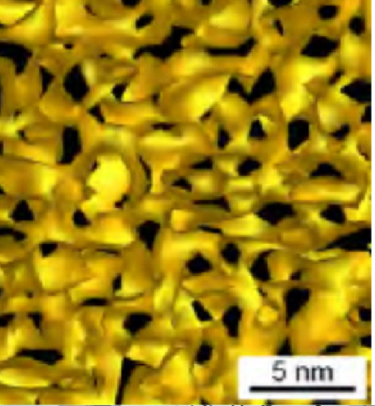

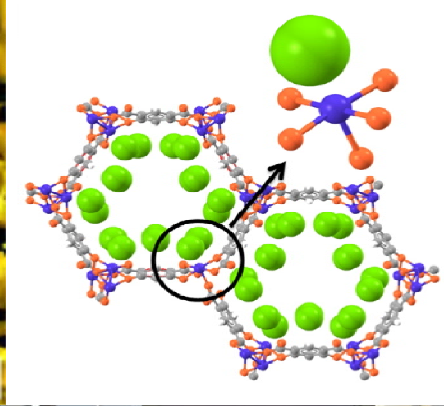

U.S. DEPARTMENT OF
ENERGY

Hydrogen and Fuel Cells Program

2015 Annual Merit Review and Peer Evaluation Report

June 8–12, 2015
Arlington, VA

DOE/GO-102015-4730 **October 2015**

About the Cover

Photo collage (from top to bottom, left to right):

A cryogenic transmission electron microscopy three-dimensional reconstruction of hydraded Nafion. *Image courtesy of Lawrence Berkeley National Laboratory.*

A unit cell of a coordinatively unsaturated metal center Co_2(*m*-dobdc) structure dosed with three deuterium molecules (green) per open metal site. The circled inset shows a section of the unit cell that has been enlarged in the upper right, showing the location of the deuterium with respect to an open cobalt site. *Image courtesy of C. Ahn, U.S. Department of Energy, based on M.T. Kapelewski et al.,* J. Am. Chem. Soc.*, 2014, 136, 12119−12129.*

The California State University, Los Angeles, station was the first in the United States to receive a seal of approval for the consumer sale of hydrogen on a per-kilogram basis. The right portion of the image shows an enlarged version of the approval seal. *Photo courtesy of California State University, Los Angeles.*

The **H**ydrogen **F**ueling **I**nfrastructure **R**esearch **S**tation **T**echnology (H2FIRST) project is designed to address the technical challenges of hydrogen station deployment in the early market.

Fuel cell cargo tractors are demonstrated at the Memphis International Airport by Plug Power with Fuel Cell Technologies Office partner FedEx. *Photo courtesy of FedEx.*

An optical reflectance image showing automated (not manual) detection of particulates on the electrode surface of a gas diffusion electrode. The individual images of the particles inside the yellow boxes are magnified 10 times. *Image courtesy of the National Renewable Energy Laboratory.*

Photo on right:

U.S. Capitol Building. *Photo courtesy of Dollar Photo Club.*

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NOTICE

Prologue

Dear Colleague:

This document summarizes the comments provided by peer reviewers on hydrogen and fuel cell projects presented at the fiscal year (FY) 2015 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting (AMR), held in conjunction with DOE's Vehicle Technologies Office Annual Merit Review on June 8–12, 2015, in Arlington, Virginia. In response to direction from various stakeholders, including the National Academies, this review process provides evaluations of the DOE-funded projects in applied research, development, demonstration, and analysis of hydrogen and fuel cell technologies. Under Secretary for Energy and Science Franklin Orr opened the joint plenary session with more than 1,000 attendees, followed by a keynote address from former Senator Byron Dorgan (D-ND). The joint plenary also included overview presentations from the Fuel Cell Technologies Office, the Vehicle Technologies Office, and the Basic Energy Sciences Program. A plenary for Hydrogen and Fuel Cells Program participants included overviews on each of the eight sub-programs: Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Technology Validation; Safety, Codes and Standards; Market Transformation; and Systems Analysis.

DOE values the transparent, public process of soliciting technical input on its projects and overall programs from relevant experts with depth and breadth of knowledge across a number of broad areas. The recommendations of the reviewers are taken into consideration by DOE technology managers in generating future work plans. The table in this report lists the projects presented at the review, evaluation scores, and the major actions to be taken during the upcoming fiscal year (October 1, 2015–September 30, 2016). The projects have been grouped according to sub-program and reviewed according to the appropriate evaluation criteria. The weighted scores for all of the projects are based on a four-point scale, with half-point intervals. To furnish principal investigators (PIs) with direct feedback, all of the evaluations and comments are provided to each presenter; however, the authors of the individual comments remain anonymous. The PIs are instructed by DOE to fully consider these summary evaluation comments, along with any other comments by DOE managers, in their FY 2016 plans. In addition, DOE managers contact each PI individually and discuss the comments and recommendations as future plans are developed.

In addition to thanking all participants of the AMR, I would like to express my sincere appreciation to the reviewers for your strong commitment, expertise, and interest in advancing hydrogen and fuel cell technologies. You make this report possible, and we rely on your comments, along with other management processes, to help make project decisions for the new fiscal year. We look forward to your participation in the FY 2016 AMR, which is presently scheduled for June 6–10 in Washington, DC. Thank you for participating in the FY 2015 AMR.

Sincerely,

Sunita Satyapal
Director
Hydrogen and Fuel Cells Program
U.S. Department of Energy

Hydrogen Production and Delivery

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-014	Hydrogen Delivery Infrastructure Analysis *Amgad Elgowainy; Argonne National Laboratory*	3.8	X			According to reviewers, the model developed in this project is robust and will be a valuable asset to the U.S. Department of Energy (DOE) and the state of California in establishing funding priorities. The reviewers praised the model for its basis in near-term costs, its variety of external checks and reviews, and its use of data from vendors and California Energy Commission solicitations. They also commended the project's analyses of the cost impacts of variables such as market penetration and station configuration. Reviewers suggested that future efforts involve increased collaboration with car companies, investors, and municipalities. In addition, they suggested expanding the model to simulate hybrid stations and station expansions.
PD-021	Development of High-Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery *Don Baldwin; Hexagon Lincoln*	3.4			X	Reviewers praised this project for its approach; relevance to the near-term fuel cell vehicle market; and collaboration with the American Bureau of Shipping, the U.S. Department of Transportation, Argonne National Laboratory, and Powertech. Reviewers commented that the design of 540 bar trailers would also be significant to the near-term market, and that the project should include the design of such trailers. They suggested codifying the project's designs to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XII if appropriate, and they noted that technologies to reduce the cost of carbon fiber are needed. Reviewers indicated that the project might fit better as a technology validation project, rather than a production and delivery research and development (R&D) project. This project is being completed in fiscal year 2015.
PD-022	Fiber-Reinforced Composite Pipelines *George Rawls; Savannah River National Laboratory*	3.5	X			Reviewers praised the project for its approach in codifying fiber-reinforced pipeline and for including testing of dry-wrap piping capable of on-site manufacture. Reviewers noted that the project has great relevance to lowering hydrogen delivery costs. Reviewers recommended expanding efforts to educate consumers on the adoption of the pipeline technology and searching for further ways to facilitate improvements to the technology and/or its installation and operation.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-025	Hydrogen Embrittlement of Structural Steels *Brian Somerday;* *Sandia National Laboratories*	3.3	X			Reviewers praised this project for its technical robustness and calculation of the appropriate thickness of hydrogen pipelines, but they also emphasized the need for better interaction with stakeholders. Specific recognized strengths include the use of high-pressure test capabilities to simulate service conditions, the study of friction stir welds, and the accounting of residual stress. Reviewers suggested that future work include (1) a greater sample size of welds to ensure that results are representative of industry; (2) a greater range of temperatures and pressures to better simulate real-world pipeline conditions; and (3) greater interaction with pipeline operators and ASME to ensure the work is relevant to industry needs.
PD-031	Renewable Electrolysis Integrated System Development and Testing *Mike Peters;* *National Renewable Energy Laboratory*	3.2	X			The reviewers commended the near-term industrial relevance of this project for hydrogen production from renewable sources. They commented that the facilities, staff, organization, and approach are well suited to meet project its objectives. As a suggestion to strengthen the project, reviewers recommended that the team perform additional evaluations to determine the effect of load variability on long-term electrolyzer performance. They also recommended stronger engagement with outside experts.
PD-088	Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage *Zhili Feng;* *Oak Ridge National Laboratory*	3.3			X	Reviewers commended the project for manufacturing a representative prototype, and they praised the approach of developing finite element models that will be verified with cyclic testing. However, they stated that the project does not sufficiently address the vessel's relative cost benefit compared to existing technologies, and that the team has not adequately explained the role of concrete in the design. Reviewers suggested that the team better assess the lifetime of the tank, taking into account the impact of low volumes of hydrogen on the vent holes, as well as the properties of concrete.
PD-096	Electrolyzer Component Development for the Hybrid Sulfur Thermochemical Cycle *William Summers;* *Savannah River National Laboratory*	2.7	X			Reviewers commended the project's progress in developing the sulfur-depolarized electrolysis membranes and catalysts for the hybrid sulfur thermochemical cycle, and they appreciated the efforts on system analysis. The reviewers criticized the complexity and potential high cost of combining this thermochemical process with concentrated solar energy. Reviewers recognized the relevance of the work, but they expressed concern over the project approach's potential to meet hydrogen production cost goals. The reviewers recommended collaborating more extensively with experts in the solar thermal industry to better understand the long-term feasibility of this approach.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-101	Cryogenically Flexible, Low-Permeability Hydrogen Delivery Hose *Jennifer Lalli;* *Nanosonic*	3.6	X			Reviewers commended the project's approach, accomplishments, and relevance to lowering the cost of dispensers. Specific strengths mentioned include: (1) developing a material that can tolerate the expected service conditions (e.g., temperature range, pressure range, solvents, and abrasion), (2) developing a novel means of adhering the hose to fittings, and (3) collaborating with relevant stakeholders. Reviewers suggested that the research team study the hose compatibility with hydrogen and polymer electrolyte membrane (PEM) fuel cells (e.g. the potential for off-gassing, leaching, and particulate formation), obtain guidance from standards development organizations to ensure the hose is tested for all relevant conditions, and obtain guidance from hose manufacturers on potential challenges related to crimping the hose to fittings.
PD-102	Analysis of Advanced Hydrogen Production Pathways *Brian James;* *Strategic Analysis, Inc.*	3.4	X			Reviewers commended the project team's development of analytical case studies for high-temperature solid-oxide electrolysis and fermentation, and they praised the approach, noting that it involves gathering information from research organizations and industry through quantitative questionnaires. The reviewers saw the results of the analyses as a necessary part of determining the feasibility of the evaluated technologies. The reviewers commented that it would be extremely valuable to evaluate near-term, low production volume costs in conjunction with the projected cost values based on high production volume. They also recommended that the team clearly articulate and document the current technical barriers to both solid oxide electrolysis and fermentation.
PD-103	High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis *Hui Xu;* *Giner, Inc.*	3.5			X	Reviewers commended the project for making progress toward lowering the platinum-group-metal catalyst loading in PEM electrolyzers (compared with commercial baselines) while maintaining electrolyzer performance and durability. The reviewers were pleased that all project milestones are being met, and they felt extremely optimistic that this work could have a significant near-term impact on PEM electrolysis performance and cost. They suggested placing more emphasis on efforts to gain a better molecular-level understanding of the catalyst surface structure reconstruction during operational conditions.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-106	Reference Station Design *Daniel Terlip; National Renewable Energy Laboratory*	3.4			X	Reviewers commended the project for its thoroughness and strong relevance to near-term hydrogen station needs. They praised the project's clear identification of the economic challenges of station deployment and important potential value to the codes and standards communities in studying station risks. Reviewers suggested expanding the project to include designs of larger stations that may be valuable long-term investments, designs for fleets of material handling equipment, and designs for stations with on-site hydrogen production.
PD-107	Hydrogen Fueling Station Pre-Cooling Analysis *Amgad Elgowainy; Argonne National Laboratory*	3.7			X	Reviewers commended the project's relevance to lowering the costs of fueling stations. They praised the project for studying the energy consumption of pre-cooling in both continuous and on-demand modes of operation, collaborating with relevant domestic and international stakeholders, and explaining the impacts of alternative hydrogen cooling technologies. Reviewers suggested that project results be incorporated into the Hydrogen Refueling Station Analysis Model (HRSAM) and/or the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) Reference Station Design activities. In addition, reviewers recommended that the team expand analysis to account for the impacts of other factors on pre-cooling requirements, including the MC Method (the fueling protocol developed by Honda), dispenser location, ambient temperature of hydrogen gas, and regional U.S. location of the station.
PD-108	Hydrogen Compression Application of the Linear Motor Reciprocating Compressor *Eugene Broerman; Southwest Research Institute*	2.9	X			Reviewers commended the project's potential to lower station costs and improve reliability if successful; however, they recommended that the researchers complete a thermodynamic energy balance analysis to validate the compressor's potential. Reviewers noted that the thermodynamic efficiency of the device should be determined to ensure it is competitive with existing technologies, and that the temperatures of the piston and coils should be calculated to ensure they are within code requirements. Reviewers suggested that the team collaborate with organizations that have experience with the design of electric motors and compressors, as well as with hydrogen safety.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-109	Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage *Zhili Feng; Oak Ridge National Laboratory*	3.3	X			Reviewers commended the project's potential to generate cost savings, if successful. They praised the project's progress to date and collaboration with experts in a wide range of areas such as material advancement, manufacturing, cost modeling, and commercialization. The reviewers expressed some concern that the technology might not be cost competitive with existing alternatives, and that the use of concrete may be unnecessary. They suggested that the research team assess the technology's maintenance costs and manufacturability, as well as complete an analysis of the strength of the vessel without concrete.
PD-110	Low-Cost Hydrogen Storage at 875 bar Using Steel Liner and Steel Wire Wrap *Amit Prakash; WireTough Cylinders*	3.1	X			Reviewers commended the project's potential to provide low-cost storage, contingent on successful achievement of project goals. Specific strengths mentioned include the approach of wire wrapping, the promising results of the burst test, and the assessment of hydrogen embrittlement risk. Reviewers noted the absence of technoeconomic modeling and expressed concern about the vessel's susceptibility to hydrogen embrittlement. They suggested expanding the project scope to include vessel acceptance by relevant codes, and partnering with station operators to better understand cost and operation requirements.
PD-111	Monolithic Piston-Type Reactor for Hydrogen Production through Rapid Swing of Reforming/Combustion Reactions *Wei Liu; Pacific Northwest National Laboratory*	3.0	X			Reviewers commended the project for achieving significant progress toward screening high-performance CO_2 sorbents for use in the swing-reactor for reforming bio-derived liquids, and they appreciated the initial efforts in technoeconomic analysis. They expressed some concern that the project does not sufficiently address the likelihood of poisoning and coking in the reforming of bio-oil. The reviewers suggested that the team expend more effort on catalyst R&D in order to reach the goals within the projected timeline.
PD-112	Reformer-Electrolyzer-Purifier for Production of Hydrogen *Fred Jahnke; FuelCell Energy, Inc.*	3.3	X			The reviewers praised the project's reformer-electrolyzer-purifier approach as a low-risk, high-impact technology with the potential to achieve <$2/kg of hydrogen in the near term. They gave specific credit to the experienced project team and its focused and realistic goals. However, the reviewers pointed out that the carbon emission of the technology was not sufficiently discussed, and that the "free" heat source that was used as an input in the Hydrogen Analysis (H2A) technoeconomic analysis was inadequately justified.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-113	High-Efficiency Solar Thermochemical Reactor for Hydrogen Production *Tony McDaniel; Sandia National Laboratories*	3.1	X			The reviewers commended the project for its relevance to long-term, large-scale renewable hydrogen production, as well as for its effective project planning and division of well-defined roles to capable partners. The reviewers specifically praised the use of Materials Genome Initiative methods in materials discovery efforts to develop optimal redox materials for the solar thermochemical systems under development. Reviewers expressed concern over the complexity and potential high cost of the solar thermochemical approach, and they strongly recommended the development of more detailed technoeconomic analysis with clear technical and economic inputs and assumptions.
PD-114	Flowing Particle Bed Solarthermal Redox Process to Split Water *Al Weimer; University of Colorado*	3.1	X			Reviewers commended the project's progress, highlighting the areas of modeling and performance prediction, constructing and upgrading test reactor systems, and redox materials discovery. They praised the update of the AspenPlus model to include experimental results as an outstanding contribution and a major strength of the project. Reviewers expressed general concern over the complexity and potential high cost of the solar thermochemical approach, and they recommended the development of more detailed technoeconomic analysis with clear technical and economic inputs and assumptions. They also recommended the project team add collaboration partners with practical, large-scale engineering experience.
PD-115	High-Efficiency Tandem Absorbers for Economical Solar Hydrogen Production *Todd Deutsch; National Renewable Energy Laboratory*	3.5	X			The reviewers commended the project for its relevance to long-term, large-scale renewable hydrogen production based on the photoelectrochemical (PEC) approach. They were impressed by the project's progress in advancing the efficiency and durability of III–V semiconductor-based PEC devices, specifically highlighting the effective use of inverted metamorphic multifunctions and Pt/Ru surface treatments. Reviewers expressed skepticism regarding one of the project's proposed designs that would use 100x concentrated sunlight with low solution penetration and low resistive loss, and they stressed the need for a more detailed schematic of the new design. They also recommended the team pay additional attention to process scale-up issues.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
PD-116	Wide Bandgap Chalcopyrite Photoelectrodes for Direct Solar Water Splitting *Nicolas Gaillard; University of Hawaii*	3.3	X			The reviewers praised the project for its focus on an important class of chalcopyrite materials that has the potential to meet long-term DOE goals for PEC hydrogen production. They specifically commended the project team's ability to precisely tune the bandgap of these materials. Reviewers expressed some concern that the MoS_2 surface catalysts being developed may not be sufficient for achieving the project goal of >15% solar-to-hydrogen conversion, and that alternative approaches may be needed. They also recommended that the project team perform detailed technoeconomic analysis that considers the technology scale-up of chalcopyrite-based PEC systems.
PD-117	High-Temperature, High-Pressure Electrolysis *Cortney Mittelsteadt; Giner, Inc.*	3.3	X			The reviewers commended the project for screening and selecting candidate membranes that show long lifetimes (>30,000 hours) and high conductivity to permeability rations (>2) for use in membrane-based electrolyzers designed to operate under high pressures and high temperatures. The reviewers highlighted that this work contributes significantly to overcoming barriers related to electrolysis operated under these conditions to reduce the cost of delivered hydrogen. They recommended that the team develop a detailed cost analysis that clearly compares the cost of hydrogen prepared by high-pressure, high-temperature methods with the cost of hydrogen produced by low-pressure electrolysis coupled with a compressor.

Hydrogen Storage

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-001	System-Level Analysis of Hydrogen Storage Options *Rajesh Ahluwalia; Argonne National Laboratory*	3.4	X			Reviewers commended the project team's strong expertise in modeling thermodynamic, kinetic, and heat transfer phenomena and its development of a comprehensive and rigorous set of tools and methodologies that enable detailed predictions of materials and system performance. Reviewers also commended the project team for developing and understanding data from multiple research and development (R&D) efforts and integrating that data into cogent analyses from a wide spectrum of technical areas. Reviewers also noted the results of the relationship between high-density polyethylene (HDPE) liner properties and liner failure in Type IV tanks at cryo temperatures. Reviewers recommended the continued use of experimental data whenever available to test and benchmark models.
ST-004	Hydrogen Storage Engineering Center of Excellence *Don Anton; Savannah River National Laboratory*	3.5			X	This project is part of the Hydrogen Storage Engineering Center of Excellence (HSECoE). Overall, the reviewers commented that the HSECoE is well managed and appreciated the approach taken and progress made. The reviewers praised the down-selection process applied and the overall accomplishments of the HSECoE. They also applauded the HSECoE for the extent and quality of the collaboration and coordination among the partners and its relevance to the Hydrogen Storage sub-program. However, the reviewers expressed disappointment in the delays in evaluating the two prototype systems and felt the issues should have been solved more quickly.
ST-005	Systems Engineering of Chemical Hydrogen, Pressure Vessel, and Balance of Plant for Onboard Hydrogen Storage *Kriston Brooks; Pacific Northwest National Laboratory*	3.3			X	This project is part of the HSECoE. The reviewers commented that the project is well organized and executed. Reviewers cited the development and posting of the chemical hydrogen system model, evaluation of the liquid-nitrogen-cooled tank wall concept, and design of the consolidated valve block as noteworthy accomplishments. Reviewers commented positively on the collaboration to validate the cost analyses.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-006	Advancement of Systems Designs and Key Engineering Technologies for Materials-Based Hydrogen Storage *Bart van Hassel; United Technologies Research Center*	3.5			X	This project is part of the HSECoE. The reviewers commended the United Technologies Research Center (UTRC) for its work on the publicly available hydrogen storage material system models. In particular, reviewers praised UTRC's work on the graphical user interface and the development of standard Simulink platforms for easy comparison across the various material-based storage systems. The reviewers were also pleased with UTRC's openness and flexibility in identifying and reacting to the host of challenges discovered throughout the life of the HSECoE. While reviewers applauded the work on the adsorbent system filters in relation to UTRC's generation of filter pressure drops at service flow rates, they mentioned that the cost analysis for these filters could use additional review.
ST-008	System Design, Analysis, and Modeling for Hydrogen Storage Systems *Matthew Thornton; National Renewable Energy Laboratory*	3.2			X	This project is part of the HSECoE. The reviewers commended the project for its effort in validating and making the framework system models that integrate vehicle, fuel cell, and storage system models with a user-friendly graphical interface that is publicly available to the research community. Reviewers also praised the extensive and highly coordinated collaboration between the project and the other HSECoE partners.
ST-010	Ford/BASF-SE/UM Activities in Support of the Hydrogen Storage Engineering Center of Excellence *Mike Veenstra; Ford Motor Company*	3.3			X	This project is part of the HSECoE. Overall, the reviewers commended the team for its work over the past year involving the evaluation of impurity effects, identification and mitigation of potential system failures, and maximization of metal-organic framework (MOF)-5 properties by compaction and enhancement in thermal conductivity. The reviewers expressed some concern about whether the results of the system model developed for MOF-5 can translate to other types of sorbent materials.
ST-044	Savannah River National Laboratory Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence: Design and Testing of Adsorbent Storage *Bruce Hardy; Savannah River National Laboratory*	3.1			X	This project is part of the HSECoE. The reviewers commended the project team on its approach to designing, fabricating, and evaluating prototype hydrogen adsorbent systems. However, the reviewers also noted the delays in progress due to the leak issues encountered. Reviewers praised the strong collaborations between the project and the other HSECoE partners. Reviewers stated that the HSECoE should make a recommendation between the two heat exchanger designs based on its evaluation.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-046	Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage *Kevin Drost; Oregon State University*	3.1			X	This project is part of the HSECoE. The reviewers noted that the Modular Adsorption Tank Insert (MATI) heat exchanger design is innovative and addresses critical issues of cryo-adsorbent systems such as weight, volume, and charging time, while also addressing the impact on cost. While the reviewers were encouraged by the overall design concept, multiple reviewers raised concerns regarding the multiple setbacks and project delays observed during the last year of the project that significantly limited the project's progress. Specifically, they noted that the lack of any initial data from the system testing is particularly disappointing, given that the project is nearly over.
ST-063	Reversible Formation of Alane *Ragaiy Zidan; Savannah River National Laboratory*	3.0	X			Most reviewers found the project to be targeting appropriate barriers to lowering the cost of alane production. Several reviewers suggested that the project team include more computational guidance and use a design of experiments approach. Reviewers noted that this material is more appropriate for low-to-medium-power applications. Reviewers recognized the close collaboration between project partners. They also recommended avoiding duplicative efforts.
ST-093	Melt-Processable PAN Precursor for High-Strength, Low-Cost Carbon Fibers *Felix Paulauskas; Oak Ridge National Laboratory*	3.0		X		Reviewers commented that the project has a good potential to reduce cost. They expressed concern about the significant delay due to staffing and engineering issues. Reviewers commended the project for reaching out to previous BASF engineers and equipment vendors in dealing with the engineering issues. Reviewers suggested that the project develop a contingency plan and obtain additional external assistance to resolve the engineering issues. Reviewers also commented that the project needs to consider evaluating composite properties in addition to fiber properties. Reviewers recommended updating the cost model to better understand cost drivers.
ST-100	Hydrogen Storage Cost Analysis *Brian James; Strategic Analysis, Inc.*	3.4	X			Reviewers commented that the project is very relevant and has completed cost analyses for all key hydrogen storage systems under development to assist with the U.S. Department of Energy's R&D portfolio evaluation. Reviewers also commended the project's strong and close collaboration with national laboratories, original equipment manufacturers, and tank manufacturers. Reviewers noted that the project has done a good job in identifying major contributors to overall cost as well as pathways for cost reduction. Reviewers noted the need to provide cost uncertainties in general and include the range of possible costs for both sorbent systems analyzed for better comparison between them.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-101	Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks *David Gotthold; Pacific Northwest National Laboratory*	3.1	X			Reviewers praised the team's progress in predicting and validating tank model performance, as well as in validating lower-cost resin performance through actual tank burst tests. Reviewers also commended the strong collaboration among multiple partners with a variety of areas of expertise. They noted that these partners have contributed in useful ways. Reviewers suggested increasing the fiber supplier's participation. Reviewers also identified the need to consider the effect of the operating temperature during cycling, as well as the potential failure modes and the effect of loss of thermal insulation for cold gas operation.
ST-111	Thermomechanical Cycling of Thin-Liner, High-Fiber-Fraction Cryogenic Pressure Vessels Rapidly Refueled by Liquid Hydrogen Pump to 700 bar *Salvador Aceves; Lawrence Livermore National Laboratory*	3.3	X			This is a joint project funded by the Hydrogen Storage, Technology Validation, and Hydrogen Delivery sub-programs. The reviewers noted that the project is highly relevant because cryo-compressed hydrogen storage has been estimated as having high volumetric and gravimetric capacities. Pressure and temperature cycling is still needed to provide confidence in the technology. The reviewers also complimented the team for the physical installation of the cryo-pump and the associated hardware as well as the emphasis on ensuring safety during testing. The reviewers noted that the progress has been a bit slow and that future milestones could be harder to reach, but they expressed hope that the pace of progress will speed up as important aspects related to infrastructure and safety approval are completed. Reviewers noted that the team should put more emphasis on dormancy, better define project partners' roles in the project, and be more open regarding the potential liner materials.
ST-113	Innovative Development, Selection, and Testing to Reduce Cost and Weight of Materials for Balance-of-Plant Components *Chris San Marchi; Sandia National Laboratories*	3.3	X			Reviewers commended the project's combined experimental and computational approach for focusing on critical barriers. They emphasized the need to better integrate the experimental and computational work for model validation and prediction. Reviewers also praised the project's experienced and appropriate mix of partners, noting that the partners include balance-of-plant component and steel manufacturers as well as a fatigue testing organization.
ST-114	Next-Generation Hydrogen Storage Vessels Enabled by Carbon Fiber Infusion with a Low-Viscosity, High-Toughness Resin System *Brian Edgecombe; Materia*	2.9	X			Reviewers commented that the project has made good progress as a new project. They also noted the need for the team to consider sizing for the Materia resin and to focus on demonstrating the Materia resin in a pressure vessel configuration with 35% less fiber content. Reviewers also stressed the importance of including the additional costs associated with the vacuum-assisted resin transfer molding process, such as resin cost, cycle time, additional processing, and winding efficiency, in the cost analysis.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
ST-115	Achieving Hydrogen Storage Goals through High-Strength Fiber Glass *Hong Li; PPG Industries, Inc.*	3.0	X			Reviewers commended the project's potential for achieving cost savings by using high-strength glass fiber. They also emphasized the need to quantify the impact on gravimetric capacity. In addition, reviewers recognized the technical challenges presented by the high melting temperature and recommended considering countermeasures. Reviewers also commended the partners' well-balanced capabilities, noting that they range from modeling to experimenting to manufacturing.
ST-116	Low-Cost α-Alane for Hydrogen Storage *Richard Martin; Ardica*	2.7	X			The reviewers recognized the relevance of the project's focus to reduce the cost of alane production and investigate scale-up of the synthesis process for portable power applications. They questioned the project's potential for transportation applications. The reviewers expressed concern with the lack of details presented on the cost analysis and suggested that an independent organization verify the analysis. Reviewers praised the close coordination between project partners, but they identified knowledge transfer between partners as an area for improvement.
ST-117	Boron-Based Hydrogen Storage: Ternary Borides and Beyond *John Vajo; HRL Laboratories, LLC*	3.0	X			The reviewers found this project to be highly relevant. They acknowledged the success of the combined experimental and modeling efforts to effectively and rapidly screen and characterize many new materials. They noted that the results do not thus far show great potential to demonstrate reversible hydrogen storage. Reviewers recognized the close collaboration and integration between the project partners, theorists, and experimentalists as a strength of the project.
ST-118	Improving the Kinetics and Thermodynamics of $Mg(BH_4)_2$ for Hydrogen Storage *Brandon Wood; Lawrence Livermore National Laboratory*	2.9	X			The reviewers applauded the project team for its combined theory (i.e., density functional theory and phase-field modeling conducted at multiple length and time scales), synthesis, and characterization. They described this approach as a rational method to better understand kinetic limitations and address rate-limiting steps. The reviewers also indicated that the project has not completely addressed how it plans to handle the critical issue of multiple-phase formation during reactions, and they expressed concern that the team's work on validating models based on the Li-N-H system is distracting the researchers from their efforts on the Mg-based system. Reviewers suggested that the team test some of the models using existing literature data on nano-confined Mg-based systems instead of Li_3N.

Fuel Cells

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
FC-007	Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes *Bryan Pivovar; National Renewable Energy Laboratory*	3.0			X	Reviewers commented that the approach of making extended, continuous Pt nanostructures is promising based on previous results with similar structures. They commended the project for its progress toward generation of high-mass-activity electrocatalysts that are also durable against potential cycling. However, they expressed concern that the results have been demonstrated in only rotating disk electrodes (RDEs) and not in membrane electrode assemblies (MEAs). In addition, they were concerned that the membrane deactivation due to leached transition metal ions such as Ni^{+2} is not a major consideration. The reviewers had mixed recommendations, with some recommending that the project end on schedule with no additional work, and others suggesting that the project focus all remaining resources on getting the fuel cell test results that provide "proof" that the new electrocatalyst materials are worth pursuing.
FC-008	Nanosegregated Cathode Catalysts with Ultra-Low Pt Loading *Vojislav Stamenkovic; Argonne National Laboratory*	3.2			X	Reviewers stated that the outstanding capabilities of the world-class team in electrocatalyst synthesis and the partnership with world-class MEA fabrication and fuel cell testing entities have led to world-leading advancements in fuel cell catalyst design ability for performance and stability. They also noted that the project's very basic scientific approach to fundamental studies of the factors leading to high oxygen reduction reaction (ORR) activity and durability have been critical to developments throughout the field. Reviewers stated that the project would benefit from assessments in MEAs, but that industry collaboration may be required for these assessments.
FC-009	Contiguous Pt Monolayer Oxygen Reduction Electrocatalysts on High-Stability, Low-Cost Supports *Radoslav Adzic; Brookhaven National Laboratory*	3.3			X	Reviewers were particularly impressed by the novel approaches to catalyst synthesis that have been developed by this knowledgeable team of collaborators from industry, academia, and national laboratories. They noted that these novel approaches have resulted in "extremely high activities" in electrochemical cells. Reviewers suggested that additional collaboration with industry is required to improve MEA performance.
FC-017	Fuel Cells Systems Analysis *Rajesh Ahluwalia; Argonne National Laboratory*	3.5	X			Reviewers commented that the project's complete fuel cell system model demonstrates an ability to predict the system-level impact of component-level changes. They stated that this ability comes from the project's great collaboration among highly qualified team members. Reviewers expressed concern that the model relies on performance and durability validation data that lack consensus and recommended that the team validate the system against stack and system data.

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FC-018	Fuel Cell Vehicle and Bus Cost Analysis *Brian James; Strategic Analysis, Inc.*	3.5	X			Reviewers were universally impressed with this project's approach. They stated that the project incorporates learning and feedback into future work, provides a systematic and effective framework for providing cost projections, and uses exemplary detailed and methodical approaches at all levels of the analysis. Reviewers expressed concern about the project's real-world applicability, including its model validation, benchmarking, and transferability.
FC-020	Characterization of Fuel Cell Materials *Karren More; Oak Ridge National Laboratory*	3.6	X			Reviewers commended this characterization project for being well integrated into the portfolio of DOE projects, having a highly collaborative nature and an excellent team, and making excellent progress with characterizing the ionomer layer of MEAs. Reviewers had few recommendations for the project, but one reviewer stated that a user-accessible database for distribution of data would be helpful.
FC-021	Neutron Imaging Study of the Water Transport in Operating Fuel Cells *Muhammad Arif; National Institute of Standards and Technology*	3.5	X			Reviewers stated that the project's unique approach and technique for identifying water in polymer electrolyte membrane fuel cells are its greatest strength. They also agreed that NIST facilities represent a significant focal point for diagnostics related to in situ water content analysis and provide a key technique for the fuel cell community. Reviewers recommended a greater focus on size and time resolution to capture dynamic processes.
FC-026	Fuel Cell Fundamentals at Low and Subzero Temperatures *Adam Weber; Lawrence Berkeley National Laboratory*	3.3			X	Reviewers were impressed with the team's expertise in most, if not all, of the critical areas that could lead to an understanding of water distribution in the cell and unanimously lauded this project for its collaboration among laboratories, universities, and industry. They found the project to be well designed with in situ and ex situ testing and praised the solid progress on integrating gas diffusion layer (GDL) properties into the transport model. Some reviewers commented that the project has still not produced insights regarding nanostructured thin-film (NSTF) electrodes during cold start.
FC-048	Effect of System Contaminants on Polymer Electrolyte Membrane Fuel Cell Performance and Durability *Huyen Dihn; National Renewable Energy Laboratory*	3.3			X	Reviewers stated that the project had demonstrated good progress, particularly in developing gas chromatography mass spectrometry (GCMS) methods to quantify contaminant concentrations. In addition, reviewers were impressed with the user-friendly and interactive website displaying the contaminants studied by the team and with the strength of the project team's collaboration. Reviewers noted that the project would benefit from a more rapid screening approach and from greater consideration to environmental effects such as heat and ambient environment.

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FC-052	Technical Assistance to Developers *Tommy Rockward; Los Alamos National Laboratory*	3.4	X			Reviewers unanimously lauded LANL's capabilities, facilities, and support for the fuel cell community. They were impressed by the number of projects LANL is able to support under the project's budget.
FC-065	The Effect of Airborne Contaminants on Fuel Cell Performance and Durability *Jean St-Pierre; Hawaii Natural Energy Institute*	3.0			X	Reviewers found the approach to be "reasonable," "correct," "well balanced," and "effective." They provided mixed comments on the effort to determine the effect of acetonitrile intermediate or reaction products on membrane conductivity, with some reviewers finding this work particularly interesting and others expressing concern that the degradation rate in reference conditions creates doubt regarding the reliability of the acetonitrile impact findings. Multiple reviewers expressed concern that an in-depth description of the mechanisms is not yet available.
FC-081	Fuel Cell Technology Status: Degradation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.4	X			Reviewers stated that the project has provided a valuable service in collecting, analyzing, and communicating real-world data through its good relationships with fuel cell developers. However, they also stated that the project is limited in its ability to identify accurate trends by the voluntary nature of the data collection.
FC-097	Stationary and Emerging Market Fuel Cell System Cost Analysis—Primary Power and Combined Heat and Power Applications *Vincent Contini; Battelle*	3.0	X			Reviewers praised the strength of the collaboration partners. However, they expressed a number of concerns regarding the approach, stating that the project has not considered several real-world aspects such as the combined heat and power efficiency of low-temperature proton exchange membrane fuel cells and the cost of support after sale.
FC-098	A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications *Max Wei; Lawrence Berkeley National Laboratory*	3.2	X			Reviewers liked the Total Cost of Ownership Model approach. They also noted that the Manufacturing Cost Model shows that solid oxide fuel cell (SOFC) systems are close to DOE cost goals. Reviewers were concerned that the project does not provide sufficient direction for research and development efforts.
FC-103	Roots Air Management System with Integrated Expander *Dale Stretch; Eaton Corporation*	2.8			X	Reviewers stated that the project is of great relevance because compressor cost is a key contributor to fuel cell system cost, and that the project includes collaborations among relevant partners such as a fuel cell integrator. They expressed concern, however, that the project has not met all of its targets and that there does not appear to be a path for meeting the targets. They recommended conducting integrated system testing and minimizing efforts on plastic component fabrication to focus more on closing performance gaps.

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FC-104	High-Performance, Durable, Low-Cost Membrane Electrode Assemblies for Transportation Applications *Andrew Steinbach; 3M*	3.1	X			Reviewers commented that the project brings together an excellent team of well-managed collaborators to address a critical challenge facing DOE—development of catalysts with inherently excellent performance and durability. They stated that the best-of-class MEAs exhibit promising results. However, the reviewers were concerned about the durability of the membrane, and that performance is still 10%–15% below 2020 targets. The reviewers expressed concern regarding the fundamental architecture of the NSTF catalyst layer structure and whether NSTF systems could ever be operationally robust.
FC-106	Rationally Designed Catalyst Layers for Polymer Electrolyte Membrane Fuel Cell Performance Optimization *Deborah Myers; Argonne National Laboratory*	3.1	X			Reviewers were impressed that the project has met almost all of the go/no-go milestones and that ANL has provided meaningful data on the effects of ionomer content and the type of organic solvent in ink. They commented that the project is well designed by a well-coordinated team of strong partners. However, reviewers expressed various concerns about the approach (e.g., engineering processes are ignored) and accomplishments (e.g., the performance-limiting property has not been identified). One reviewer recommended that the project team consider a PtCo catalyst because the project may be in a good position to clarify the leaching tendencies of Co versus Ni from a dealloyed catalyst.
FC-107	Non-Precious-Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design *Piotr Zelenay; Los Alamos National Laboratory*	3.3	X			Reviewers stated that the project's creative, capable, and collaborative team has made incremental progress in performance this year. They were impressed with the project's characterization accomplishments, including the Nafion mapping and x-ray absorption spectroscopy on Fe-only catalysts. Reviewers recommended additional durability studies.
FC-108	Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells *Bryan Pivovar; National Renewable Energy Laboratory*	3.0			X	Reviewers agreed that the project's approach to utilize perfluoro polymer electrolytes is sound and worth exploring. They also stated that despite a diverse and strong project team, the project has made little progress this year due to setbacks in synthesis.
FC-109	New Fuel Cell Membranes with Improved Durability and Performance *Michael Yandrasits; 3M*	3.5	X			Reviewers stated that this project is relevant based on its potential for achieving performance and durability improvements and for cost reductions in the balance of plant (BOP). They lauded the project's key achievement, exceeding 0.1 S/cm at 50% relative humidity (RH), noting that this is a fivefold improvement over previous materials. Reviewers were concerned about a lack of data at high temperatures (90°C–120°C) and high humidity (100% RH).

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FC-110	Advanced Hybrid Membranes for Next-Generation Polymer Electrolyte Membrane Fuel Cell Automotive Applications *Andrew Herring; Colorado School of Mines*	2.8	X			Reviewers appreciated that this project's innovative approach using heteropoly acid (HPA) functionalized membranes is the only DOE project focusing on potentially game-changing PEM concepts. Despite this promising approach, reviewers expressed concern about the lack of progress to date and the inability of the project team to make reproducibly quality films. Reviewers recommended that the project team begin testing swelling, mechanical properties, low-RH performance, and durability.
FC-114	High-Throughput Synthesis, Oxygen Reduction Reaction Activity Modeling, and Testing of Non-Platinum-Group-Metal Polymer Electrolyte Membrane Fuel Cell Cathode Catalysts *Deborah Myers; Argonne National Laboratory*	2.9			X	Reviewers stated that the project team consists of strong team members who are collaborating well on a good theoretical approach to understanding the ORR active sites of a non-platinum-group-metal (PGM) catalyst. However, they expressed concern that the project team has not defined how much throughput is required and has too wide of a focus, noting that this has led to limited accomplishments.
FC-115	Affordable, High-Performance, Intermediate-Temperature Solid Oxide Fuel Cells *Bryan Blackburn; Redox Fuel Cells, Inc.*	3.1	X			Reviewers found that the project has made reasonable progress, including a power density of 0.95 W/cm^2 at 600°C. Reviewers also commented that the approach is appropriately structured with clearly defined go/no-go decision points. However, reviewers expressed concern that there has been no durability testing and that the project team has not planned for durability testing.
FC-116	Smart Matrix Development for Direct Carbonate Fuel Cells *Chao-yi Yuh; FuelCell Energy, Inc.*	3.2	X			Reviewers commented that the project team brings extensive experience in molten carbonate fuel cells and has demonstrated improved pore structure and durability. They also noted that the presentation did not include sufficient information on how existing accelerated testing would demonstrate 80,000-hour durability.
FC-118	Novel Non-Platinum-Group-Metal Catalysts from Rationally Designed Three-Dimensional Precursors *D.J. Liu; Argonne National Laboratory*	3.0			X	Reviewers stated the project team demonstrated good material synthesis, activity, and performance. Reviewers further commented on the remarkable activity and encouraging MEA data. Reviewers also recommended that the project team begin testing and improving durability. Reviewers also recommended that the project continue investigating Fe-free non-PGM catalysts

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FC-119	Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells *Hector Colon-Mercado; Savannah River National Laboratory*	2.7			X	Reviewers commented that the project includes good input from industry and advances the state of the art for non-PGM catalysts. They expressed concern about the project team's approach, noting that catalyst evaluation relies on RDE measurement, the project team needs much more familiarity with this technique, and the RDE activity targets for this project were not revised as they were for other projects. Reviewers recommended that the project team establish collaborations with experts in catalyst theory and characterization.
FC-120	High-Performance and Durable Low-Platinum-Group-Metal Cathode Catalysts *Yong Wang; Pacific Northwest National Laboratory*	2.9			X	Reviewers found this project to feature good collaboration among laboratories to address DOE's goals for reduced cost. They stated that while RDE results have been good, there have been no MEA results. In addition, the reviewers commented that the project team has not provided a rationale for why indium tin oxide will improve durability.
FC-121	Magnetic Annealing of Pt-Alloy Nanostructured Thin-Film Catalysts for Enhanced Activity *David Cullen; Oak Ridge National Laboratory*	2.7			X	Reviewers stated that the strengths of this project are the technical skills of the group of collaborators it has assembled and the execution of the stated work. Reviewers commented that the electrochemical surface area (ECA), specific activity, and mass activity achieved for magnetically annealed Pt-alloy catalysts are all lower than for the catalyst as received. They recommended that the project team focus on addressing the existing problems rather than on sophisticated modeling and analysis.
FC-122	High-Conductivity, Durable, Anion-Conducting Membranes *Tom Zawodzinski; Oak Ridge National Laboratory*	2.7			X	Reviewers noted that the project has met its conductivity goals. However, they expressed concern that there is insufficient data to support the goal claims and that 0.1 Ohm/cm^2 is an insufficient goal. In addition, the reviewers commented that the approach is not sufficiently described, there is little evidence of collaboration, and the future work is overambitious. They recommended that the project team test whether the anion exchange membranes (AEM) lose KOH and thus conductivity during extended fuel cell operation at wet conditions.
FC-123	Advanced Hydroxide-Conducting Membranes *Yu Seung Kim; Los Alamos National Laboratory*	3.4			X	Reviewers stated that the approach of investigating multiple backbone chemistries is good and provides reduced risks. They also commented that the project team has made good progress in the number of membranes synthesized and analyzed and in meeting project milestones.
FC-124	High-Temperature and Low-Humidity Membranes *Cy Fujimoto; Sandia National Laboratories*	3.3			X	Reviewers stated that the project team has done good evolutionary work with existing membrane chemistry, demonstrating conductivity almost double that of Nafion at 120°C and ~30% RH. However, reviewers recommended that the project team focus on testing stability and mechanical properties.

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FC-125	Engineered Low-Pt Catalyst Layers *Mahlon Wilson; Los Alamos National Laboratory*	3.4			X	Reviewers noted that performance results exceed the milestone target of 550 mV at 1 A/cm^2 and 100% RH for MEAs with less than 0.05 mg Pt/cm^2. They stated that engineering a catalyst/ionomer interface with better oxygen utilization is a very good approach to meeting DOE cost targets and the modeling provides good guidance for the project.
FC-126	Semi-Automated Membrane Electrode Assembly Fabrication with Ultra-Low Total Platinum-Group-Metal Loadings *Stoyan Bliznakov; Brookhaven National Laboratory*	2.7			X	Reviewers were impressed that the project team has successfully engineered, developed, and deployed an automated system for the fabrication of electrodeposited catalysts directly on GDLs in a short period of time. However, they expressed concern about the poor air performance in MEAs and that plans to improve this performance probably do not go far enough. Reviewers recommended that the project team focus future efforts on diagnosing and resolving this poor performance.
FC-127	Durability Improvements through Degradation Mechanism Studies *Rod Borup; Los Alamos National Laboratory*	3.3			X	Reviewers found that this project aligns well with Fuel Cell Technologies Office barriers and that it exhibits excellent collaboration among strong team members. In addition, they commented positively on the balance between experiments and theory and on the team’s ability to identify new accelerated stress test protocols. The reviewers noted that the project does not use state-of-the-art materials in some cases, such as in its carbon corrosion activities.

Manufacturing R&D

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MN-001	Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development *Michael Ulsh; National Renewable Energy Laboratory*	3.4	X			Reviewers noted that the approach for the project is very good and that collaboration with industry and other partners has been, and continues to be, very good. Reviewers also noted that the National Renewable Energy Laboratory (NREL) made significant progress this year in further developing the reactive impinging flow technique, increasing its scale at high moving rates. The reviewers encouraged NREL to determine the statistical performance of each approach and increase its focus on correlating defect size (as detected in a webline) with fuel cell performance.

Technology Validation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
TV-001	Fuel Cell Electric Vehicle Evaluation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.3	X			The reviewers believe that continuing to validate fuel cell vehicle performance and compare findings to technical targets remains essential to reaching the U.S. Department of Energy's goals, and that these insights are useful to a variety of stakeholders. Reviewers also praised the project staff for maintaining the cooperation of several automotive companies, and they suggested that these partners continue to provide data during increased rollout and commercialization. Reviewers suggested segmenting data based on vehicle model year, disaggregating vehicle classes, collecting data for fuel efficiency at one-quarter and full power for newer model vehicles, looking more closely at fuel cell stack vintage, and evaluating the effects of climate on vehicle performance.
TV-008	Fuel Cell Bus Evaluations *Leslie Eudy; National Renewable Energy Laboratory*	3.9	X			The reviewers noted that this project serves as the only consistent source of fuel cell electric bus (FCEB) data in the United States, and that evaluations use transparent and accurate methodologies to evaluate technical targets. Reviewers commended the coordination and cooperation with transit agencies over the many years, and they saw the focus on obtaining feedback from both bus drivers and passengers as highly valuable in gauging technology adoption. Reviewers suggested that the project: include hybrid diesel and battery-electric technology buses for comparison, investigate the effect of larger numbers of FCEBs at a single site, consider other geographic areas and fleets, and examine climate impacts on bus performance.

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TV-017	Hydrogen Station Data Collection and Analysis *Sam Sprik; National Renewable Energy Laboratory*	3.5	X			Reviewers noted that the project's efforts in data collection and data evaluation on hydrogen refueling stations have provided a long history of reliable information and greatly advanced knowledge on station characteristics and performance. Reviewers especially found data on maintenance to be valuable and relevant in deriving preventive operations and maintenance schedules in order to maximize the availability of stations and reduce costs. Reviewers recommended that the project team start identifying next-generation "open" retail stations in data reporting separately from previous-generation non-retail stations, as well as evaluate the correlation between usage of station and compressor failure events.
TV-019	Hydrogen Component Validation *Daniel Terlip; National Renewable Energy Laboratory*	3.0	X			Reviewers recognized the need for reliable data on the performance and failure modes of compressors and viewed this effort as important in the deployment of commercial hydrogen stations. While reviewers acknowledged that the team has generated useful data and made significant progress in the evaluations, they also noted that there has been limited operational data and run time. Reviewers suggested performing more hours of compressor testing, evaluating other compressor types, investigating the impact of start-up mode and frequency on compressor performance and failure modes, and adding a separate mass flow sensor to confirm the calculation of the mass flow.

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TV-020	Validation of an Advanced High-Pressure Polymer Electrolyte Membrane Electrolyzer and Composite Hydrogen Storage, with Data Reporting, for SunHydro Stations *Larry Moulthrop; Proton OnSite*	3.2	X			Reviewers indicated that the project has contributed considerable data in demonstrating hydrogen station performance. They also found the project to have a solid plan to reduce the cost of hydrogen through a combination of increasing efficiency and standardizing packaging of station components. They suggested that the project team document lessons learned related to station siting and approvals; consider how the project is supported by, and will support, automakers introducing fuel cell electric vehicles on the East Coast; and engage in additional collaborations with U.S. DRIVE Partnership tech teams. Reviewers further added that the data collected from this project should feed into engineering models such as the Macro-System Model (MSM) and Hydrogen Analysis (H2A) model to provide early market cost and performance data.
TV-021	Material Handling Equipment Data Collection and Analysis *Chris Ainscough; National Renewable Energy Laboratory*	3.8	X			Reviewers saw this project as having the potential to identify optimization potentials for commercialization of fuel cells in key early markets. Reviewers stated that major strengths of the project are the people working on it, the background knowledge, and interaction in the field. Reviewers stated that the project has shown excellent coordination with a variety of relevant industrial partners. Reviewers noted that suppliers are still voluntarily providing data which is a testament that they find the compiled results useful. Reviewers also noted that including fueling and operation times adds value to the data set, and that data collection on fueling behavior should continue.

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TV-025	Performance Evaluation of Delivered Hydrogen Fueling Stations *Ted Barnes; Gas Technology Institute*	3.4	X			Reviewers saw the involvement and contributions of capable partners as a strength, and they praised the progress achieved to date. Reviewers viewed the completion of the West Sacramento site data acquisition system and submission of initial quarterly data as significant project accomplishments, but they cautioned that the project team should focus intensively on working with permitting authorities for the final three project sites. They noted that having data from five stations will help validate the technology, and that project partners should document lessons learned to aid the industry in overcoming barriers for future hydrogen station installations. Reviewers further suggested that the project team address cost barriers.
TV-026	Development of the Hydrogen Station Equipment Performance (HyStEP) Device *Terry Johnson; Sandia National Laboratories*	3.6	X			Reviewers praised the project for being well designed and achieving significant accomplishments in a relatively brief time period. Reviewers viewed the organizations involved as having significant expertise, and they commended the collaborations with these partners. Reviewers cautioned the team about the potential changing standardization requirements (CSA HGV 4.3) and revision of SAE International J2601, and they remarked that it may be prudent to synchronize completion of this project with the publication of the revised standards. Reviewers further remarked that other stakeholders should also be informed of project progress, perhaps through SAE.

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TV-027	Station Operational Status System (SOSS) 3.0 Upgrade *Ben Xiong; California Fuel Cell Partnership*	3.4	X			Reviewers saw this project as valuable in addressing the barrier of public acceptance and as having the potential to contribute to the more rapid acceptance of fuel cell technology by consumers. Reviewers commended the project team's efforts in working with most stations to add real-time data, and they noted that integration with all stations is essential for the success of the project. Reviewers identified key project strengths as the adaptability of the system to different station configurations, the mobile app providing easy access to real-time station status, and the strong support from the members of the California Fuel Cell Partnership. Reviewers suggested that it would be useful to also include a customer feedback mechanism in the app design in order to gauge customer satisfaction and obtain feedback for enhancements.
TV-029	Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump *Salvador Aceves; Lawrence Livermore National Laboratory*	3.4	X			Reviewers noted that this project has demonstrated progress and generated useful operational data. They found the safety analysis conducted by the project team to be very thorough and capable of serving as a model plan, as well as a demonstration of the quality work done by the project team. Reviewers commented that the partners on the project possess complementary expertise and are well chosen for their ability to contribute. Reviewers suggested that the project team obtain further input from vehicle manufacturers (especially to evaluate whether the increased volumetric hydrogen density is worth the added cost and complexity of a cryogenic system), more fully specify performance benchmarks (e.g., cryo pump degradation over time and anticipated heat leaking into the thinly insulated vessel), identify the cost of the system, and analyze the economics and pressure excursions during dormancy. Reviewers noted the lack of a broader liquid hydrogen research community and stakeholders to share knowledge with, and thus also recommended that more emphasis should be put on collaborating with institutions outside the consortium.

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TV-030	Fuel Cell Technologies Office INTEGRATE Stack Test Bed and Grid Interoperability *Kevin Harrison; National Renewable Energy Laboratory*	3.4	X			Reviewers noted that this project provides a unique effort to adapt electrolyzers to the grid in an efficient and synergistic manner, allowing for better utilization of time-variable renewable energy sources. They commended the amount of progress the project has demonstrated in a short time frame on both electrolyzer technology and communications. Reviewers advised that the project could be enhanced by including utilities and Independent System Operators in order to obtain feedback on their experiences in incorporating renewables, as well as their needs.

Safety, Codes and Standards

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SCS-001	National Codes and Standards Deployment and Outreach *Carl Rivkin; National Renewable Energy Laboratory*	3.2	X			Reviewers praised this project for acknowledging the importance of efforts beyond the completion of the initial codes and standards. They saw the lack of outreach to states' authorities having jurisdiction (AHJs) through state fire marshals and building inspectors as a weakness. Reviewers recommended closer collaboration and better coordination with both domestic and international stakeholders to maximize the impact of this work.
SCS-002	Component Standard Research and Development *Robert Burgess; National Renewable Energy Laboratory*	2.4		X		Reviewers commended this project for developing a knowledge base of the hydrogen component reliability and component testing efforts that are key for commercialization. However, they noted that closer collaboration with other laboratories would permit those laboratories to better leverage their expertise and limit redundant efforts. Reviewers recommended investigating the operational wear of components previously in service and collaborating with industry and third-party testing entities.
SCS-004	Hydrogen Safety, Codes and Standards: Sensors *Eric Brosha; Los Alamos National Laboratory*	3.8			X	Reviewers applauded the project team's collaboration, citing the importance of sensor work and the focus on proper deployment. They noted the need for further collaboration with instrument makers and commercialization partners for more field testing. Reviewers recommended that the team place additional focus on testing in different environments and engage with major manufacturers.
SCS-005	Research and Development for Safety, Codes and Standards: Materials and Components Compatibility *Brian Somerday; Sandia National Laboratories*	3.8	X			Reviewers praised the technical expertise and collaborative efforts with industry stakeholders through the American Society of Mechanical Engineers. However, they identified the lack of more direct engagement with industry and coordination to harmonize standards at the international level as a weakness. Reviewers recommended better harmonization with activities taking place in the International Partnership for Hydrogen and Fuel Cells in the Economy and investigation of other alloy steels and stainless steels.
SCS-007	Hydrogen Fuel Quality *Tommy Rockward; Los Alamos National Laboratory*	3.6	X			Reviewers applauded the project team's technical competence and critical work in addressing key technical barriers to infrastructure and vehicle deployment. They noted the lack of collaboration and communication with academic laboratories as project weaknesses. Reviewers encouraged closer collaboration with domestic laboratories, code development organizations (CDOs), and standards development organizations (SDOs).

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SCS-011	Hydrogen Behavior and Quantitative Risk Assessment *Katrina Groth; Sandia National Laboratories*	3.6	X			Reviewers commended this project for its engagement with industry and its approach to addressing key technical barriers. They felt that the project's main weakness is the need for acceptance by AHJs and a path to adoption for regulations, codes, and standards activities. Reviewers recommended expanding the focus on liquid hydrogen in the Hydrogen Risk Assessment Model (HyRAM) and increasing the direct collaboration with industry groups to develop code change proposals and standard requirements for risk-informed decisions.
SCS-017	Hands-On Hydrogen Safety Training *Salvador Aceves; Lawrence Livermore National Laboratory*	2.9		X		Reviewers saw the project's focus on hands-on training and tools for education about interacting with hydrogen as its main strength. They identified the project's main weakness as the lack of understanding about whether the tools are effective in transferring knowledge during trainings. Reviewers' recommendations include examining other audiences (e.g., technical colleges and gas utilities) for these trainings and considering a certification element to validate the knowledge transfer during the trainings.
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources *Nick Barilo; Pacific Northwest National Laboratory*	3.7	X			Reviewers praised the quality of the safety training content and safety knowledge tools and the coordination of the project's early adoption efforts. They identified the project's main weakness as the difficulties involved in accomplishing widespread adoption and deployment of the tools to ensure the appropriate level of training for all stakeholders. Reviewers recommended that the team expand video resources, improve leveraging of the Hydrogen Safety Panel (HSP), and evaluate the quantitative and qualitative impact of these resources.
SCS-021	National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory *Bill Buttner; National Renewable Energy Laboratory*	3.5	X			Reviewers praised the technical competence and expertise of the project team. However, they also noted the lack of communication with industry (directly or through a standard committee) to broadly share research. Reviewers encouraged the project team to couple the work with risk assessment tools to develop guidance on optimal sensor placement, installation, and maintenance.
SCS-022	Fuel Cell & Hydrogen Energy Association Codes and Standards Support *Morry Markowitz; Fuel Cell & Hydrogen Energy Association*	3.6	X			Reviewers commended this project for coordinating and facilitating communication with key stakeholders, both domestically and internationally. However, they identified the lack of engagement with ongoing research activities as a weakness. Reviewers suggested the project take on the role of interfacing between normative and research activities, as well as explore integrating efforts with H2 Tools and HSP to provide centralized access to information.

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SCS-024	Hydrogen Contaminant Detector *Daniel Terlip; National Renewable Energy Laboratory*	3.4			X	Reviewers praised this project for its evaluation of currently available technologies and related technical gaps, and for developing the associated requirements for cleanliness and testing of hydrogen fuel. They cited the lack of relevant collaborations and the approach to addressing barriers and technical challenges as weaknesses. Reviewers recommended interfacing with CDOs and SDOs to bolster data requirements and initiating outreach to instrument manufacturers to investigate a path forward.
SCS-025	Enabling Hydrogen Infrastructure through Science-Based Codes and Standards *Chris LaFleur; Sandia National Laboratories*	3.6	X			Reviewers complimented the project team's strategic interfaces with stakeholders and approach to addressing industry needs. They identified the lack of an outreach strategy for adoption of performance-based design methods by AHJs as the project's main weakness. Reviewers recommended demonstrating the results of a real case to encourage adoption among targeted stakeholders and focusing outreach on states with central jurisdiction (e.g., New York) to accelerate acceptance of the methodology.

Market Transformation

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
MT-008	Hydrogen Energy Systems as a Grid Management Tool *Richard Rocheleau; Hawaii Natural Energy Institute*	3.4	X			Reviewers stated that this project will have an impact on the ability to use renewables by mitigating the grid instability caused by those renewables. Reviewers recommended continuing the project but noted that more attention is needed on data collection and determining a business case. They identified not having an operating system installed as a weakness. They stated that more economic analysis showing cost breakdowns of component equipment and operating expenses is an immediate need.
MT-011	Ground Support Equipment Demonstration *Jim Petrecky; Plug Power*	3.4	X			Reviewers reported that the plan to complete this project is reasonable and that progress to date is on schedule, scope, and budget. However, they mentioned that the cost of delivered hydrogen was not reported, which makes it impossible to understand the value proposition. Also, reviewers were concerned that the data set for fleet operations was not reported, since this data is critical for identifying further technology improvements.
MT-013	Maritime Fuel Cell Generator Project *Joe Pratt; Sandia National Laboratories*	3.5	X			Reviewers noted that this project seeks to develop, design, and test a hydrogen fuel cell generator for maritime power. They stated that the project continues to do an outstanding job of coordinating efforts among the fuel cell supplier, fuel cell customer, infrastructure support, and relevant regulatory agencies. They felt that good progress has been made to date; however, they noted that more attention is needed on cost analysis and potential markets.
MT-016	Fuel Cell Hybrid Electric Delivery Van Project *Jason Hanlin; Center for Transportation and the Environment*	2.3	X			Reviewers stated that while this is a good project in concept, it has fallen behind schedule because of supplier issues and other problems. Reviewers commented that the project has a good strategy and plan for implementation; however, they also noted that it has failed to deliver on its commitments to obtain the required cost-share resources. (This project has an upcoming go/no-go decision point.)

Systems Analysis

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-033	Analysis of Optimal Onboard Storage Pressure for Hydrogen Fuel Cell Vehicles *Zhenhong Lin; Oak Ridge National Laboratory*	3.1			X	Reviewers observed that the project approach is reasonable but felt it should examine fueling pressures in a continuum. They stated that the project would benefit from additional input and review from the original equipment manufacturers (OEMs). Reviewers noted that future consideration should be given to examining the impact of potential incentives, such as the Low Carbon Fuel Standard and Zero Emissions Vehicle programs.
SA-035	Employment Impacts of Infrastructure Development for Hydrogen and Fuel Cell Technologies *Marianne Mintz; Argonne National Laboratory*	3.5	X			Reviewers acknowledged the project is well developed and uses a sound approach of applying “input/output” modeling. They stated that the project has benefited from good collaboration with industry and academia, and that this collaboration makes the project useful for policymakers to understand the societal benefits of fuel cell electric vehicles (FCEVs) and the development of hydrogen infrastructure. Reviewers noted that the project team should consider expanding the model to include larger capacity stations, liquid delivery, and net job analysis.
SA-036	Pathway Analysis: Projected Cost, Life Cycle Energy Use, and Emissions of Emerging Hydrogen Technologies *Todd Ramsden; National Renewable Energy Laboratory*	3.5	X			Reviewers commented that the project is critically important and provides a clear and transparent understanding of current and future hydrogen pathway costs. They reported that the project collaboration is good but should be expanded to include input from industry stakeholders with specific technology expertise. They found that the pathway analysis and Macro-System Model (MSM) benefits from the linkage of multiple sub-program models to deliver a systems-approach for cost and greenhouse gas (GHG) assessment.
SA-039	Life Cycle Analysis of Water Consumption for Hydrogen Production *Amgad Elgowainy; Argonne National Laboratory*	3.6	X			Reviewers agreed the project has established a good fundamental understanding of water consumption associated with hydrogen pathways, and that this understanding is essential for comparing multiple fuel pathways and resource analysis. They noted that the project would benefit by expanding collaboration to multiple stakeholders, including the international community. They also recommended expanding the model to include mid-to-low–Technology Readiness Level hydrogen production technologies and a regional water assessment.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-044	Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost *Aymeric Rousseau; Argonne National Laboratory*	3.5	X			Reviewers observed that the project strategy is sound and uses the well-respected ANL Autonomie model to assess the impact of future fuel cell improvements on FCEV cost and performance. They noted that the project results are extremely useful and relevant to the Fuel Cell Technologies Office (FCTO) in developing future research and development strategies. They recommended expanding the project to include sensitivity and parametric analyses of the complex issues of crosscutting vehicle performance and cost.
SA-045	Analysis of Incremental Fueling Pressure Cost *Amgad Elgowainy; Argonne National Laboratory*	3.6			X	Reviewers complimented the project's approach of including multiple refueling protocols and identifying the main cost drivers, such as the precooling requirements for multiple pressure levels. They found the analysis to be technically sound and robust. Reviewers felt the project would benefit from input from additional stakeholders, such as industrial gas companies. They recommended that the project team consider the price elasticity of refueling time for the consumer in its future work.
SA-047	Tri-Generation Fuel Cell Technologies for Location-Specific Applications *Brendan Shaffer; University of California, Irvine*	3.2			X	Reviewers stated that the project approach is reasonable but should have expanded the co-location strategy to include the benefits of integrating hydrogen with electricity and heat. Reviewers noted that the project provides good insight on the benefits of tri-generation and should be expanded to other regions.
SA-050	Government Performance and Results Act Analysis: Impact of Program Targets on Vehicle Penetration and Benefits *Zhenhong Lin; Oak Ridge National Laboratory*	3.3	X			Reviewers commented that the project includes an exhaustive comparison of FCEVs to other relevant powertrains to understand petroleum use and GHG emissions. They reported that the project has made excellent progress in assessing many scenarios of FCEV penetrations but has not fully explained the project goal of evaluating FCTO targets. They suggested that the project team consider expanding collaboration to multiple OEMs. Reviewers recommended that future work include scenarios based on FCEV rollout announcements from OEMs and other forecasts from the California Air Resources Board.
SA-051	Infrastructure Investment and Finance Scenario Analysis *Marc Melaina; National Renewable Energy Laboratory*	3.6			X	Reviewers applauded the project's progress and accomplishments in developing the Internet-based model to answer investor questions about hydrogen infrastructure decision-making. They noted that the tool is relevant to DOE goals, especially for engaging the financial, policy, and regulatory communities for risk and cost assessments. Reviewers suggested that the project team consider adding a few "standard" cases to the model as a starting point as well as regional factors.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-052	The Business Case for Hydrogen-Powered Passenger Cars: Competition and Solving the Infrastructure Puzzle *Robert Rosner; University of Chicago*	3.0	X			Reviewers noted that the project is in the early stages of development and analysis, but that it would benefit from gathering data and input from multiple stakeholders. They felt the project team should elaborate on the project's value and applicability. The reviewers stated that the project's value would improve with input and review by industry stakeholders such as the financial community, OEMs, and industrial gas suppliers.
SA-053	Retail Marketing Analysis: Hydrogen Refueling Stations *Kent Schlesselman; Kalibrate*	3.4			X	The reviewers observed that the project team has a clear understanding and expertise in siting fueling stations, and they noted that this is relevant to projecting future hydrogen refueling infrastructure. They felt that the results of the project are limited by restricted access to the proprietary model and the lack of an accompanying user-friendly software tool that could be used by station developers. Reviewers reported that the project would benefit from additional input and calibration from hydrogen infrastructure providers, such as industrial gas suppliers. They recommended that the team consider expanding the analysis to other regions of the United States where there are plans to introduce FCEVs.
SA-054	Performance and Cost Analysis for a 300 kW Tri-Generation Molten Carbonate Fuel Cell System *Shabbir Ahmed; Argonne National Laboratory*	3.5			X	Reviewers acknowledged that the project's approach is comprehensive and effective in analyzing the actual costs and performance, with modeled fuel cell performance to assess opportunities for cost reduction. They observed that the project has made excellent progress and that the parametric analysis of multiple variables is well done. They noted that the project would benefit from additional input from industry stakeholders. Reviewers recommended improving the explanation of the project results and findings to accurately explain the inherent trade-offs between electricity, heat, power, and hydrogen.
SA-055	Hydrogen Analysis with the Sandia ParaChoice Model *Dawn Manley; Sandia National Laboratories*	3.1	X			Reviewers commented that the project has a good approach but is limited by the quality of the input data. They stated that the project team should improve the data quality, accuracy, and relevance by adding industry collaboration. Reviewers noted that the project team needs to differentiate between the project's efforts and models and other DOE models. They felt that FCTO will benefit from parametric analysis of multiple cases and scenarios from the ParaChoice model, but that data input and selection need to be refined to increase confidence in the model's output. They suggested that the project would benefit from additional collaboration with industry stakeholders.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed	Summary Comments
SA-056	Status and Prospects of the North American Non-Automotive Fuel Cell Industry: 2014 Update *David Greene;* *University of Tennessee*	3.6			X	Reviewers complimented the project on its approach and accomplishments in assessing how current and future policies support and accelerate the commercialization of non-automotive fuel cell technologies. They noted that the results of the analysis provide insight on early market behavior to two diverse industries—material handling equipment and backup power—and on industry acceptance of the technologies without market scale. Reviewers stated that the project has an adequate level of collaboration and input from key stakeholders. They recommended that the team refine the “learning curves” with data and calibration and consider adding supply chain, export markets, and market segmentation.

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Introduction

The fiscal year (FY) 2015 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) Annual Merit Review and Peer Evaluation Meeting (AMR), in conjunction with DOE's Vehicle Technologies Office Annual Merit Review, was held June 8–12, 2015, at the Crystal Gateway Marriott and Crystal City Marriott in Arlington, Virginia. This report is a summary of comments by AMR peer reviewers about the hydrogen and fuel cell projects funded by DOE's Office of Energy Efficiency and Renewable Energy (EERE). Projects supported by other DOE offices (including the Office of Science [Basic Energy Sciences] and Advanced Research Projects Agency – Energy [ARPA-E]) in areas relevant to hydrogen and fuel cells were also presented at the FY 2015 AMR. DOE uses the results of this merit review and peer evaluation, along with additional review processes, to make funding decisions for upcoming fiscal years and help guide ongoing performance improvements to existing projects.

The objectives of this meeting include the following:

- Review and evaluate FY 2015 accomplishments and FY 2016 plans for DOE laboratory programs; industry/university cooperative agreements; and related research, development, and demonstration (RD&D) efforts.
- Provide an opportunity for stakeholders and participants (e.g., fuel cell manufacturers, component developers, and others) to provide input to help shape the DOE-sponsored RD&D program in order to address the highest-priority technical barriers and facilitate technology transfer.
- Foster interactions among the national laboratories, industry, and universities conducting RD&D.

The peer review process followed the guidelines in the *Peer Review Guide* developed by EERE. The peer review panel members, listed in Table 1, provided comments about the projects presented. Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells, and they represented national laboratories; universities; various government agencies; and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest as prescribed by the *Peer Review Guide*. A complete list of the meeting participants is presented as Appendix A.

Table 1: Peer Review Panel Members

No.	Name	Organization
1	Abdel-Baset, Tarek	Fiat Chrysler Automobiles
2	Adzic, Radoslav	Brookhaven National Laboratory
3	Afzal, Kareem	PDC Machines, Inc.
4	Ahmed, Shabbir	Argonne National Laboratory
5	Ainscough, Chris	National Renewable Energy Laboratory
6	Antoni, Laurent	CEA (Alternative Energies and Atomic Energy Commission [France])
7	Ardo, Shane	University of California, Irvine
8	Autrey, Thomas	Pacific Northwest National Laboratory
9	Ayers, Katherine	Proton OnSite
10	Balema, Viktor	Sigma-Aldrich
11	Barbosa, Nicholas	National Institute of Standards and Technology
12	Barilo, Nick	Pacific Northwest National Laboratory
13	Baturina, Olga	U.S. Navy, Naval Research Laboratory
14	Benjamin, Thomas	Argonne National Laboratory
15	Boillot, Lionel	European Commission, Fuel Cells and Hydrogen Joint Undertaking
16	Bonhoff, Klaus	NOW GmbH
17	Bonner, Brian	Air Products and Chemicals, Inc.
18	Bordeaux, Christopher	Bordeaux International Energy Consulting LLC
19	Borup, Rod	Los Alamos National Laboratory
20	Bouwkamp, Nico	California Fuel Cell Partnership
21	Bowden, Mark	Pacific Northwest National Laboratory
22	Bowerson, Dan	Fiat Chrysler Automobiles

No.	Name	Organization
23	Bowman, Robert	Oak Ridge National Laboratory
24	Boyd, Robert	Boyd Hydrogen LLC
25	Brandon, Erik	National Aeronautics and Space Administration, Jet Propulsion Laboratory
26	Brown, Craig	National Institute of Standards and Technology
27	Bunnelle, Eric	Exxon Mobil Corporation
28	Burgunder, Albert	Praxair, Inc.
29	Cai, Mei	General Motors
30	Cairns, Julie	CSA Group
31	Centeck, Kevin	U.S. Army, TARDEC (Tank Automotive Research, Development and Engineering Center)
32	Chapman, Bryan	Exxon Mobil Corporation
33	Choudhury, Biswajit	DuPont Fuel Cells
34	Collins, William	Consultant
35	Contini, Vince	Battelle
36	Cullen, David	Oak Ridge National Laboratory
37	Curry-Nkansah, Maria	Argonne National Laboratory
38	Dale, Nilesh	Nissan Technical Center North America, Inc.
39	Dillich, Sara	U.S. Department of Energy
40	Dinh, Huyen	National Renewable Energy Laboratory
41	Dixon, David	University of Alabama
42	Dornheim, Martin	Helmholtz-Zentrum Geesthacht
43	Eckerle, Tyson	State of California
44	Eisman, Glenn	Rensselaer Polytechnic Institute
45	Erlebacher, Jonah	Johns Hopkins University
46	Esposito, Dan	Columbia University
47	Eudy, Leslie	National Renewable Energy Laboratory
48	Ewan, Mitch	University of Hawaii, Manoa
49	Fenske, George	Argonne National Laboratory
50	Fisher, Allison	Cella Energy US
51	Fritz, Katrina	KM Fritz LLC
52	Ganesan, Prabhu	University of South Carolina
53	Garzon, Fernando	University of New Mexico
54	Gennett, Thomas	National Renewable Energy Laboratory
55	George, Paul	Battelle
56	Gervasio, Don	University of Arizona
57	Gittleman, Craig	General Motors
58	Graetz, Jason	HRL Laboratories
59	Grassilli, Leo	Consultant
60	Greene, David	University of Tennessee, Knoxville
61	Gross, Tom	Energy Planning and Solutions
62	Grot, Stephen	Ion Power
63	Gupta, Ram	Virginia Commonwealth University
64	Haight, Andrea	Composite Technology Development, Inc.
65	Halevi, Barr	Pajarito Powder LLC
66	Hall, Karen	Fuel Cell and Hydrogen Energy Association
67	Hamdan, Monjid	Giner, Inc.
68	Hamilton, Jennifer	California Fuel Cell Partnership
69	Hanlin, Jason	Center for Transportation and the Environment
70	Hardis, Jonathan	National Institute of Standards and Technology
71	Harris, Aaron	Air Liquide Advanced Technologies US
72	Hartman, Brent	CSA Group

No.	Name	Organization
73	Harvey, David	Ballard Power Systems
74	Hennessey, Barbara	U.S. Department of Transportation
75	Herring, Andy	Colorado School of Mines
76	Hirano, Shinichi	Ford Motor Company
77	Holladay, Jamie	Pacific Northwest National Laboratory
78	Hua, Thanh	Argonne National Laboratory
79	Huang, Xinyu	University of South Carolina
80	Jacobson, David	National Institute of Standards and Technology
81	James, Brian	Strategic Analysis, Inc.
82	Jaramillo, Thomas	Stanford University
83	Jensen, Craig	University of Hawaii, Honolulu
84	Jensen, Torben Rene	Aarhus University
85	Jerram, Lisa	Navigant
86	Keller, Jay	Consultant
87	Khalil, Y. (John)	United Technologies Research Center
88	Kienitz, Brian	Consultant
89	Klebanoff, Lennie	Sandia National Laboratories
90	Knights, Shanna	Ballard Power Systems
91	Kocha, Shyam	National Renewable Energy Laboratory
92	Kongkanand, Anusorn	General Motors
93	Kopasz, John	Argonne National Laboratory
94	Krause, Theodore	Argonne National Laboratory
95	Kreller, Cortney	Los Alamos National Laboratory
96	Kurtz, Jennifer	National Renewable Energy Laboratory
97	Lakshmanan, Balsu	General Motors
98	Levy, Michael	Aaqius
99	Liu, Di-Jia	Argonne National Laboratory
100	Ludlow, Daryl	Ludlow Electrochemical Hardware
101	Lymperopoulos, Nikolaos (Nikos)	European Commission, Fuel Cells and Hydrogen Joint Undertaking
102	Markovic, Nenad	Argonne National Laboratory
103	Martinez, Andrew	California Air Resources Board
104	Masten, David	General Motors
105	McDonald, Rob	Energetics Incorporated
106	McWhorter, Scott	Savannah River National Laboratory
107	Melaina, Marc	National Renewable Energy Laboratory
108	Mergel, Jurgen	Forschungszentrum Julich GmbH
109	Miller, James	Argonne National Laboratory
110	Minh, Nguyen	University of California, San Diego
111	Mittelsteadt, Cortney	Giner, Inc.
112	Mohtadi, Rana	Toyota Motor Corporation
113	More, Karren	Oak Ridge National Laboratory
114	Moretto, Pietro	European Commission, Joint Research Centre
115	Motyka, Ted	Savannah River National Laboratory
116	Mukerjee, Sanjeev	Northeastern University
117	Myers, Charlie	Trenergi Corporation
118	Myers, Deborah	Argonne National Laboratory
119	Nguyen, Nha	U.S. Department of Transportation
120	Niangar, Ellazar	Nissan Technical Center North America, Inc.
121	Nicholas, Mike	University of California, Davis
122	O'Brien, James	Idaho National Laboratory
123	Odgaard, Madeleine	IRD Fuel Cells LLC

No.	Name	Organization
124	Olson, Gregory	Consultant
125	Ott, Kevin	Los Alamos National Laboratory
126	Owejan, Jon	Alfred State, SUNY College of Technology
127	Parks, George	FuelScience LLC
128	Patel, Pinakin	Fuel Cell Energy, Inc.
129	Pecharsky, Vitalij	Iowa State University
130	Penev, Michael	National Renewable Energy Laboratory
131	Perret, Robert	Nevada Technical Services LLC
132	Perry, Mike	United Technologies Research Center
133	Pietrasz, Patrick	Ford Motor Company
134	Pivovar, Bryan	National Renewable Energy Laboratory
135	Ramsden, Todd	National Renewable Energy Laboratory
136	Resende, William	BMW
137	Rhodes, Bill	National Nuclear Security Administration
138	Richards, Mark	FuelCell Energy, Inc.
139	Rinebold, Joel	Connecticut Center for Advanced Technology, Inc.
140	Rose, Bob	Breakthrough Technologies Institute
141	Rufael, Tecle	Chevron Corporation
142	Sandrock, Gary	Oak Ridge National Laboratory
143	Schneider, Jesse	BMW
144	Serre-Combe, Pierre	CEA (Alternative Energies and Atomic Energy Commission [France])
145	Siegel, Don	University of Michigan, Ann Arbor
146	Snyder, Joshua	Drexel University
147	Sofronis, Petros	University of Illinois, Urbana-Champaign
148	Song, Min-Kyu	Washington State University
149	Soto, Herie	Shell Oil Company
150	Spitler, Mark	U.S. Department of Energy
151	Stamenkovic, Vojislav	Argonne National Laboratory
152	Steinbach, Andy	3M
153	Stolten, Detlef	Forschungszentrum Julich GmbH
154	St-Pierre, Jean	University of Hawaii, Manoa
155	Swartz, Scott	NexTech Materials, LTD
156	Thomas, C.E. (Sandy)	Clean Car Options
157	Toughiry, Mark	U.S. Department of Transportation
158	Trabold, Tom	Rochester Institute of Technology
159	Trocciola, John	SRA International, Inc.
160	van der Vliet, Dennis	3M
161	van Hassel, Bart	United Technologies Research Center
162	Vanderborgh, Nicholas	Los Alamos National Laboratory (retired)
163	Veenstra, Mike	Ford Motor Company
164	Verduzco, Laura	Chevron Corporation
165	Wagner, Frederick T.	General Motors
166	Waldecker, James	Ford Motor Company
167	Walk, Alex	SGL Group
168	Wang, Conghua	TreadStone Technologies, Inc.
169	Warren, Dave	Oak Ridge National Laboratory
170	Weber, Adam	Lawrence Berkeley National Laboratory
171	Wei, Max	Lawrence Berkeley National Laboratory
172	Wheeler, Douglas	DJW Technology LLC
173	Williams, Mark	National Energy Technology Laboratory
174	Wilson, Mahlon	Los Alamos National Laboratory

No.	Name	Organization
175	Woods, Stephen	National Aeronautics and Space Administration
176	Xu, Hui	Giner, Inc.
177	Yandrasits, Michael	3M
178	Zelenay, Piotr	Los Alamos National Laboratory
179	Zhu, Yimin	OneD Material, LLC

Summary of Peer Review Panel's Crosscutting Comments and Recommendations

AMR panel members provided comments and recommendations regarding selected DOE hydrogen and fuel cell projects, overall management of the Hydrogen and Fuel Cells Program, and the AMR peer evaluation process. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by sub-program. Comments about sub-program management are provided in Appendix B.

Analysis Methodology

A total of **117** Fuel Cell Technologies Office (FCTO) projects were reviewed at the meeting. As shown in Table 1, **179** review panel members participated in the AMR process, providing a total of **704** project evaluations. These reviewers were asked to provide numeric scores (on a scale of 1–4, including half-point intervals, with 4 being the highest) for five aspects of the work presented. Sample evaluation forms are provided in Appendix C. Scores and comments were submitted using laptops (provided on-site) to an online, private database, allowing for real-time tracking of the review process. A list of projects that were presented at the AMR but not reviewed is provided in Appendix D.

For the Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Safety, Codes and Standards; and Systems Analysis sub-programs, scores were based on the following five criteria and weights:

Score 1: Approach to performing the work (20%)
Score 2: Accomplishments and progress toward overall project and DOE goals (45%)
Score 3: Collaboration and coordination with other institutions (10%)
Score 4: Relevance/potential impact on DOE Program goals and RD&D objectives (15%)
Score 5: Proposed future work (10%)

For each project, individual reviewer scores for each of the five criteria were weighted using the formula in the box below to create a final score for each reviewer for that project. The average score for each project was then calculated by averaging the final scores for individual reviewers. The individual reviewer scores for each question were also averaged to provide information on the project's question-by-question scoring. In this manner, a project's final overall score can be meaningfully compared to that of another project.

Final Overall Score = [Score 1 x 0.20] + [Score 2 x 0.45] + [Score 3 x 0.10] + [Score 4 x 0.15] + [Score 5 x 0.10]

A perfect overall score of "4" indicates that a project satisfied the five criteria to the fullest possible extent; the lowest possible overall score of "1" indicates that a project did not satisfactorily meet any of the requirements of the five criteria.

For the Market Transformation and Technology Validation sub-programs, scores were based on the following five criteria and weights:

Score 1: Relevance/potential impact on DOE Program goals and RD&D objectives (15%)
Score 2: Strategy for technical validation and/or deployment (20%)
Score 3: Accomplishments and progress toward overall project and DOE goals (45%)
Score 4: Collaboration and coordination with other institutions (10%)
Score 5: Proposed future work (10%)

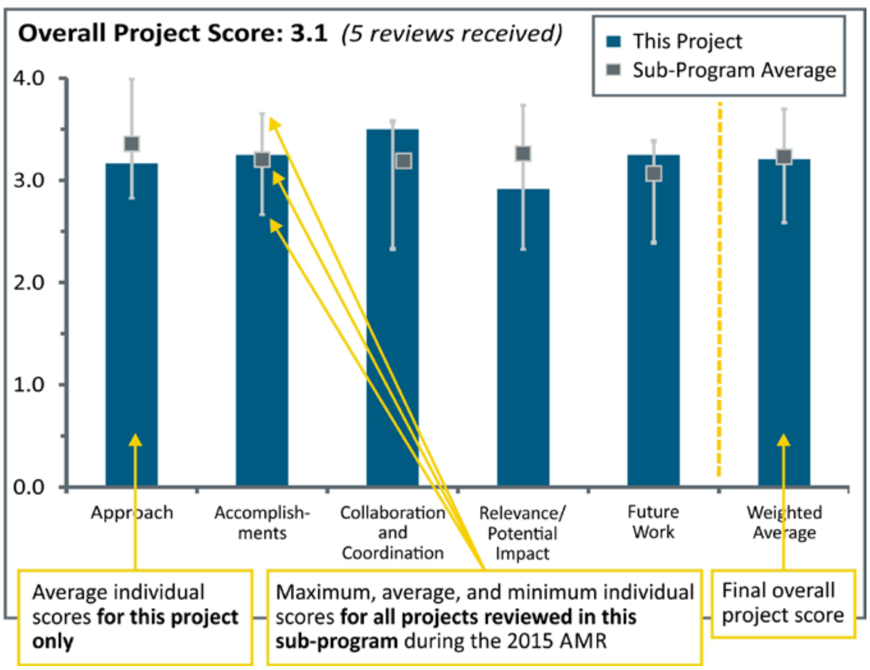
For all sub-programs, reviewers were also asked to provide qualitative comments regarding the five criteria, specific strengths and weaknesses of the project, and any recommendations relating to the work scope. These comments were also entered into the online, private database for easy retrieval and analysis.

Organization of the Report

The project comments and scores are grouped by sub-program (Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Technology Validation; Safety, Codes and Standards; Market Transformation; and Systems Analysis) in order to align with FCTO's planning scheme. Each of these sections begins with a brief description of the general type of research and development or other activity being conducted. Next are the results of the reviews of each project presented at the 2015 AMR. The report also includes a summary of the qualitative comments for each project, as well as a graph showing the overall project score and a comparison of how each project aligns with all of the other projects in its sub-program. A sample graph is provided in Figure 1.

Projects are compared based on a consistent set of criteria. Each project report includes a chart with bars representing that project's average scores for each of the five designated criteria. The gray vertical hash marks that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all of the projects in the same sub-program.

Figure 1: Sample Project Score Graph with Explanation



For clarification, consider a hypothetical review in which only five projects were presented and reviewed in a sub-program. Table 2 displays the average scores for each project according to the five rated criteria.

Table 2: Sample Project Scores

	Approach (20%)	Accomplishments (45%)	Collaboration and Coordination (10%)	Relevance/ Potential Impact (15%)	Future Work (10%)
Project A	3.4	3.3	3.3	3.2	3.1
Project B	3.1	2.8	2.7	2.7	2.9
Project C	3.0	2.6	2.7	2.8	2.9
Project D	3.4	3.5	3.4	3.2	3.3
Project E	3.6	3.7	3.5	3.4	3.4
Maximum	3.6	3.7	3.5	3.4	3.4
Average	3.3	3.2	3.1	3.0	3.1
Minimum	3.0	2.6	2.7	2.7	2.9

Using this data, the chart for Project A would contain five bars representing the values listed for that project in Table 2. A gray hash mark indicating the related maximum, average, and minimum values for all of the projects in Project A's sub-program (the last three lines in Table 2) would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

Final Score for Project A = [3.4 x 0.20] + [3.3 x 0.45] + [3.3 x 0.10] + [3.2 x 0.15] + [3.1 x 0.10] = 3.3

2015 — Hydrogen Production and Delivery
Summary of Annual Merit Review of the Hydrogen Production and Delivery Sub-Program

Summary of Reviewer Comments on the Hydrogen Production and Delivery Sub-Program:

This review session evaluated hydrogen production and delivery research and development (R&D) activities in the U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy. The hydrogen production projects reviewed represented a diverse portfolio of technologies to produce hydrogen from renewable energy sources. Production project sub-categories included thermal and thermo-electrochemical conversion of bio-derived feedstocks, advanced water splitting, direct solar thermochemical (STCH) and photoelectrochemical (PEC) water splitting, biological hydrogen production, and hydrogen production pathway analysis. The hydrogen delivery projects reviewed included R&D for low-cost, reliable delivery technologies (pipelines and tube trailers) and forecourt components (compression, storage, and dispensing), as well as technoeconomic analysis of stations.

The reviewers recognized the Hydrogen Production and Delivery sub-program as focused, effective, well managed, and having a clear strategy to achieve DOE goals and objectives. Reviewers commented positively on the relevance of delivery projects to near-term priorities and needs, and they commended the achievements of production projects in enhancing materials efficiency and durability and in innovative systems design. Reviewers encouraged more detailed studies of both near-term and future costs of production and delivery technologies, especially those at lower Technology Readiness Levels (TRLs), and they recommended broader leveraging of relevant technical expertise and greater collaboration with other domestic and international government agencies. Continued and strengthened emphasis on industrial collaboration and stakeholder engagement was strongly recommended. Reviewers also emphasized that fundamental science R&D needs to continue in parallel with the system-level applied R&D.

Hydrogen Production and Delivery Funding:

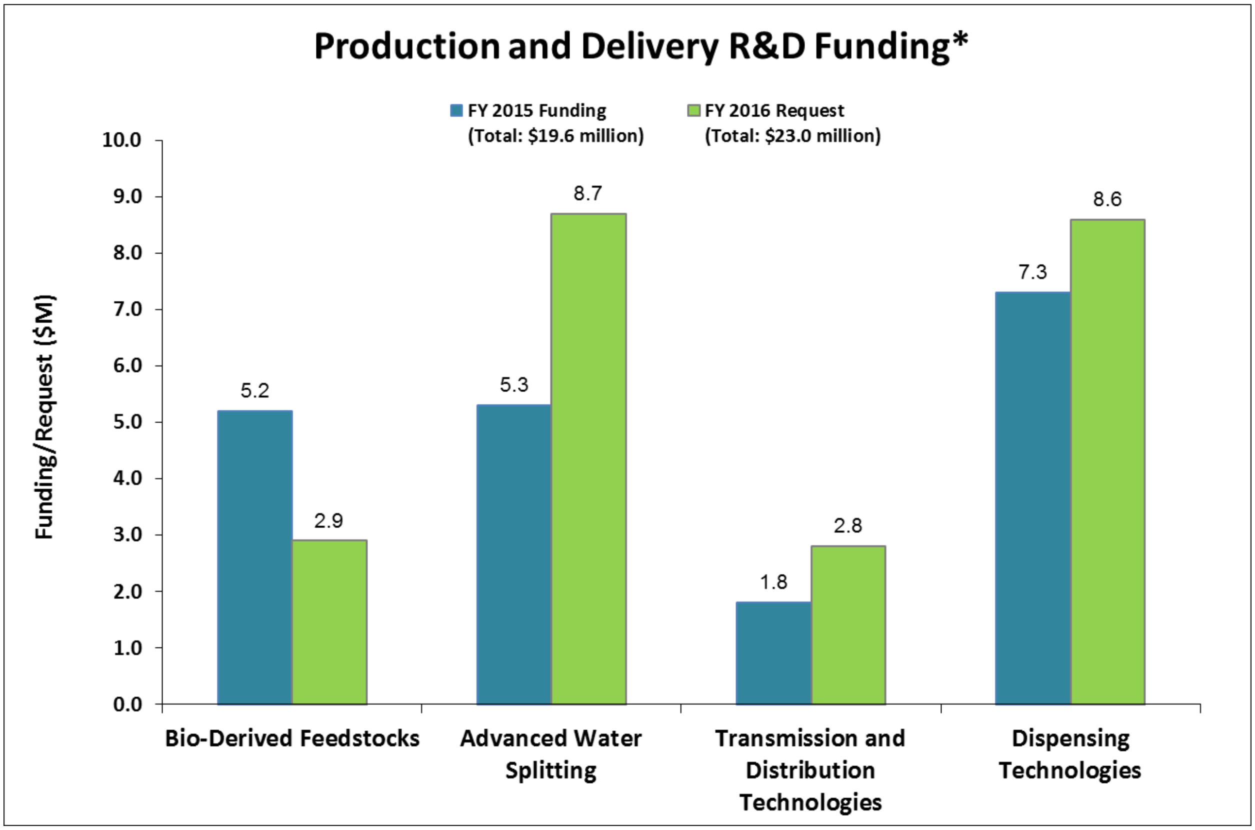
The fiscal year (FY) 2015 appropriation for the Hydrogen Production and Delivery sub-program was $19.6 million, as shown in the chart on the following page. Funding was distributed approximately evenly between hydrogen production and hydrogen delivery, consistent with previous years. The production portfolio funding focus in FY 2015 was on mid- to long-term renewable pathways such as advanced water splitting; bio-derived feedstock conversion; and STCH, PEC, and biological hydrogen production. This emphasis will change in FY 2016 with a shift in focus to advanced water splitting pathways such as STCH, PEC, and other electrolysis technologies. FY 2016 will also include the addition of new fermentative hydrogen production projects competitively selected in FY 2015. FY 2016 planning is based on a $23 million budget request (~$11.5 million apportioned to production R&D). A consortium approach to accelerated development of renewable hydrogen production pathways is also planned. The delivery portfolio emphasis in FY 2015 was on reducing near-term technology costs, such as those associated with storage vessels and dispensing hoses, and on identifying additional low-cost, early market delivery pathways that are viable. This emphasis will continue in FY 2016 with ~$11.5 million apportioned from the budget request, with an additional focus on the reliability of critical components, such as forecourt compressors and meters, as well as the performance of technologies relevant to mature markets, such as hydrogen liquefaction.

Majority of Reviewer Comments and Recommendations:

Twenty-two projects were reviewed, receiving above-average to high scores (2.7–3.8), with an average score of 3.3. The scores are indicative of the technical progress that has been made over the past year in the hydrogen production and delivery R&D portfolio.

Production Projects

Hydrogen Production Pathway Analysis: One project was reviewed in the area of hydrogen production pathway analysis. The project received a score of 3.4. Reviewers commended the project team’s approach to developing



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area.

analytical case studies for solid oxide electrolysis cells (SOEC) and fermentation, which involved gathering information from research organizations and industry through quantitative questionnaires. The results of the analysis were seen as a necessary part of determining the feasibility of these technologies. The reviewers commented that it would be extremely valuable to evaluate near-term current costs in conjunction with the projected cost values based on high production volume. The reviewers recommended that the current technical barriers to both SOEC and fermentation be clearly articulated and documented. Reviewers also noted that the project's proposed case studies for next year focus largely on low-TRL pathways. They suggested that additional case studies of higher-TRL technologies, such as biomass gasification and pyrolysis, should be considered.

Advanced Electrochemical Water Splitting: Three projects in the area of hydrogen production from advanced electrochemical water splitting were reviewed, receiving an average score of 3.3. Projects included efforts to decrease the platinum group metal (PGM) loading of the electrolysis cell electrodes, efforts to understand electrolysis under variable electrical load, and efforts to develop membranes with advanced durability under high-temperature and high-pressure conditions. Reviewers praised the progress made toward developing low-PGM electrodes while maintaining performance and durability compared to commercial baselines with higher-PGM electrodes. They also commended progress made toward membrane testing for high-temperature/high-pressure electrolysis. All projects in the category have completed or are on track to completing major milestones. Reviewers recommended performing additional studies to better understand the long-term hydrogen cost ramifications of their improvements and technologies, as well as studies to better understand the molecular nature of the catalyst surface during operational conditions.

Bio-Derived Feedstock Conversion: Two projects were reviewed in the area of bio-feedstock conversion, and these received an average score of 3.2. Reviewers commended the bio-derived liquid reforming project for achieving significant progress towards CO_2 sorbent screening and for its initial technoeconomic analysis. They expressed some concern that the project does not sufficiently address the likelihood of poisoning and coking in the reforming of bio-oil. The reviewers also suggested that more effort be spent on the catalyst R&D in order to reach goals within the projected timeline. The reviewers complimented the reformer-electrolyzer-purifier project as being a low-risk, high-impact technology that could have the greatest chance of achieving <$2/kg of hydrogen in the near term, giving credit to the experienced project team for its focused and realistic goals. The reviewers pointed out that the carbon emission of the technology was not sufficiently discussed, and that the “free” heat source as an input in the Hydrogen Analysis (H2A) technoeconomic analysis was inadequately justified.

PEC Hydrogen Production: Two PEC projects were reviewed, receiving an average score of 3.4. Reviewers felt that projects in this area are well aligned with DOE objectives, with a focus on developing the most-promising PEC material systems and prototypes, such as those based on highly efficient III–V semiconductor and chalcopyrite thin-film materials. Projects were rated highly for advancing the efficiency and durability of PEC materials and interfaces. Reviewers highlighted the excellent collaborative successes of the projects involving the DOE PEC Working Group. Recommendations for future work included more detailed technoeconomic analysis of scaled-up technologies and more detailed schematics of proposed commercial PEC cell designs.

STCH Hydrogen Production: Three projects were reviewed in the area of STCH hydrogen production, with an average score of 3.0. Two of the projects focus on two-step, metal-oxide-based reaction cycles, and the third addresses a hybrid sulfur (HyS) reaction cycle, which includes an electrolysis step. Reviewers praised the innovative approaches and achievements in all three projects, including the (1) design of perovskite and hercynite reaction materials and the new reactor concepts for the metal-oxide STCH cycles, and (2) screening and characterization of advanced membranes and electrocatalysts for the HyS cycle. Reviewers expressed concern about the complexity of the integrated reactions and reactors for all three systems, and they recommended that project emphasis be placed on materials R&D to obtain the kinetics, durability, and other properties needed to achieve the hydrogen cost goal. Reviewers also recommended continued updating of technoeconomic analysis for the technologies, specifically including realistic capital costs.

Delivery Projects

Hydrogen Delivery Technoeconomic Analyses: Three projects were reviewed in this area, with an average score of 3.6. These projects studied the energy consumption of hydrogen pre-cooling; developed a model to characterize the forecourt costs of hydrogen delivery; and developed a report that describes in detail the costs, design, and layouts of hydrogen stations expected to be relevant in the near term. Projects were praised by reviewers for their technical robustness and relevance to DOE objectives. Recommendations were made for projects to integrate results with one another, and to collaborate more closely with potential end users (such as authorities having jurisdiction and station developers). Reviewers also recommended that analyses be expanded to include stations that may be viable in the mid term, such as those that support pipelines and tube trailers, have large capacities, or are located in different regions of the United States.

Hydrogen Delivery Technologies: Three projects were reviewed in the areas of hydrogen pipelines and tube trailers, receiving an average score of 3.4. The pipeline projects were praised for technical robustness (testing in high-pressure environments, studying welds, accounting for residual stresses, and testing multiple types of fiber reinforced pipeline). The project on tube trailers was praised for its potential for near-term cost reduction. Reviewers suggested that (1) the steel pipeline project collaborate more closely with industry to ensure real service conditions are represented, (2) the tube trailer project focus on codification where appropriate, and (3) the project on fiber-reinforced pipelines educate consumers on technology adoption.

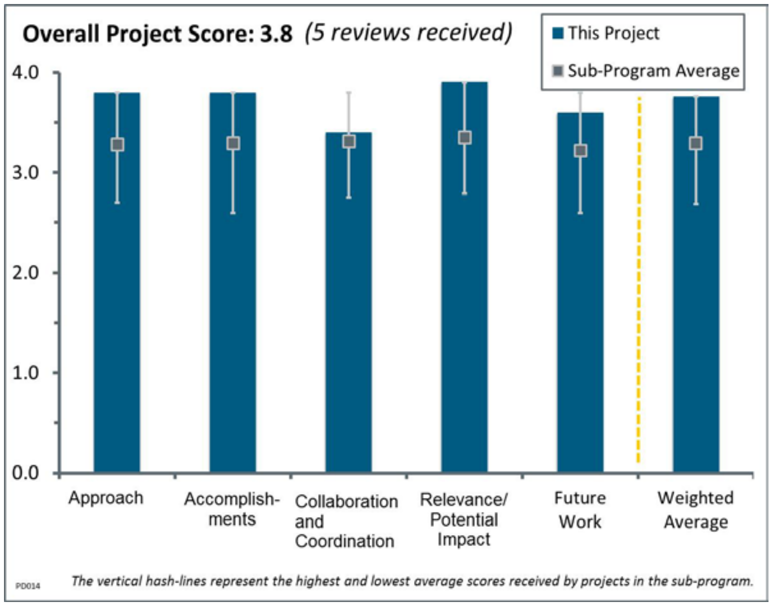
Forecourt Technologies: Five projects were reviewed on hydrogen dispensers, compression, and storage, and these received an average score of 3.3. The project on dispensing hoses was praised for its technical approach, which included developing a thorough understanding of the material’s ability to withstand the chemical and mechanical stresses it will face in service. Reviewers suggested that the team collaborate with standards development organizations to ensure that all service conditions are accounted for, and with manufacturers to ensure that challenges with joining the hose to fittings are understood. The project on linear motor reciprocating compression was praised for its potential to lower station costs and improve reliability if successful. Reviewers expressed concern over the project’s thermodynamic efficiency compared to incumbent technologies, and they suggested that the team obtain guidance from experts in electric motors and compression. The projects on steel concrete composite vessels (SCCVs) for hydrogen storage were praised for the development of a prototype that passed a burst test, and for their progress to date. Reviewers suggested that the team compare the cost of the SCCV to existing competitors and assess the strength of the vessel without concrete. The hydrogen storage project on wire wrapping Type I vessels was commended for its approach and promising burst test results. Reviewers suggested that the cost of this technology be assessed in greater detail, and that the team focus on acceptance of the technology by relevant codes.

Project # PD-014: Hydrogen Delivery Infrastructure Analysis

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to (1) assess impacts of delivery and refueling options on the cost of dispensed hydrogen by (a) modeling refueling costs in early fuel cell electric vehicle markets, (b) evaluating the impact of design and economic parameters, (c) identifying cost drivers of current technologies, and (d) developing estimates of delivery and refueling cost reduction with market penetration; (2) assist with Fuel Cell Technologies Office planning; and (3) support existing U.S. Department of Energy-sponsored tools.



Question 1: Approach to performing the work

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

- The principal investigator continues to do great work. In California, focus is needed on near-term costs, and this effort does that. It is a welcome change from earlier models, which looked at the potential for long-term success. This is a great platform to facilitate ongoing learning. In California, it can be used to help determine what near-term costs should be, and it provides tools to prioritize funding.
- Early market uncertainties were well addressed. Infrastructure cost is better understood, given the learning curves, which were developed using solid data from vendors and vetted using California Energy Commission solicitations. It is very useful to finally have a cost analysis that reflects the conditions of the early market instead of assuming high volumes of component production and high market penetration.
- The work is appropriately aimed at modeling the cost associated with various hydrogen refueling station options in order to select the most cost-effective pathways and to identify areas to focus cost-reduction efforts. The use of a wide variety of external checks and reviews establishes the validity of the estimates.
- The project takes a proper approach for the analysis work by complementing the modeling work with current cost and designs of key refueling components to look into several options to identify areas for refueling cost reduction.
- The team members' efforts to understand potential options, quantify the strengths and weaknesses of each option, and assess the impact of various option configurations are impressive. It is also clear they understand how technology and market demand play into technical solutions.

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

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

- The development of tools and models to estimate the cost of delivery and refueling has allowed the focus of production and delivery funding to be on critical barriers. The identification of ramp-up and economies of scale as critical factors should lead to further work in mitigating risks associated with the realization of profitable refueling stations.
- The most valuable accomplishment is the project's ability to clearly summarize the outcome of various liquid and gas solutions and show the impact as variables change. This work can immediately serve both policy initiatives and installation projects that will soon be built. The optionality for gas hydrogen delivery

by trailer is starting to change. Future reviews accounting for supplies delivered at 250 and 180 bar are happily anticipated.

- The development of the Hydrogen Refueling Station Analysis is an outstanding accomplishment. It is a great tool that will enable the development of the hydrogen and hydrogen fuel cell vehicle market by being released in the public domain. Another significant accomplishment is the development of a very comprehensive analysis of refueling component costs and of the impacts of utilization and economies of scale on hydrogen costs.
- The project is on target to assess impacts or liquid and gaseous delivery. There are already results in the Hydrogen Analysis (H2A) Hydrogen Delivery Scenario Analysis Model (HDSAM)that can be used by industry to better understand the cost of infrastructure today and potential future cost reductions.
- No progress can be made without a complete understanding of the near-term challenges and opportunities—this model does just that.

Question 3: Collaboration and coordination with other institutions

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

- The H2A Refueling Station Analysis Model has been scrutinized through the years, and it continues to stand up to this scrutiny. Clearly, inputs came from industry, which is incredibly helpful—the model appears to reflect reality.
- It is appropriate and particularly important that suppliers and vendors were interviewed to provide information on station components. It is good that the results of the model will be integrated into the Macro System Model and H2A.
- There probably should be more collaboration effort established with the car companies, station investors, and municipalities. In doing so, the project may gain insight into various challenges that exist and should be factored into the model (e.g., delivery of product by large or small trailers). Such collaboration would also accelerate the understanding that forecourt parties need to comprehend the interplay of variables that affect the success of a station and begin to forecast future evolution.
- Collaboration appears to be strong but not uniform across sectors. It is hard to tell how much input from end users has been included. The approach section mentions that reviews took place but not how well the work matched the reviews or how much “end-user” review was accessed.
- Collaboration looks appropriate for this project. The team may benefit if some collaboration with hydrogen and hydrogen station providers is also included.

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

This project was rated **3.9** for its relevance/potential impact.

- The hydrogen infrastructure analysis is an extremely low-cost approach to understanding how to optimize fuel supply to fuel cell vehicles and prepare for the industry’s growth. This is vital work, and the team has proven its ability to keep pace with the market.
- This work helps DOE set near-term targets, which are incredibly important outreach and communication tools. It also benefits California planning efforts by helping stakeholders understand the state of the industry and what can be achieved with a variety of funding approaches.
- This type of analysis work is key to enabling the initial roll-out of hydrogen refueling stations and identifying options and opportunities for further cost reductions on hydrogen infrastructure.
- This project has a very practical and clear application for the implementation of additional hydrogen stations.
- The work will continue to strongly influence progress toward the goals and objectives of the Hydrogen and Fuel Cells Program (the Program).

Question 5: Proposed future work

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

- The outline presented at the Annual Merit Review will be challenging. The only recommendation is to increase the focus on collaboration to “spread the news” and receive relevant feedback from live developments.
- The model will improve with time. Of particular interest is the impact of individual components on station performance and cost through time. Anything that can be done to increase reliability and help the industry plan to keep stations online is helpful. It would be very helpful to understand the economic impact of planning for expansion vs. funding new stations.
- Including station footprint as part of this analysis will be extremely valuable to this work, as one of the main challenges right now is the space constraints within existing refueling sites.
- Future work is appropriate. It would be interesting to know how project economics may vary regionally, particularly in places where hydrogen refueling infrastructure is more likely to be deployed in the early years.
- It is great to see plans to work closely with the Codes and Standards Technical Team and other working groups. It would be helpful to continue to make models as accessible to stakeholders as possible. Providing tools with the ability to adjust or explore variables as needed would enable further exploration of the options available.

Project strengths:

- This project is aligned to needs and goals and has a variety of inputs and collaborations.
- The project’s relevance and ability to evolve with technology are strengths.
- The focus on near-term costs and targets is a strength.
- The project has appropriate stakeholder engagement.

Project weaknesses:

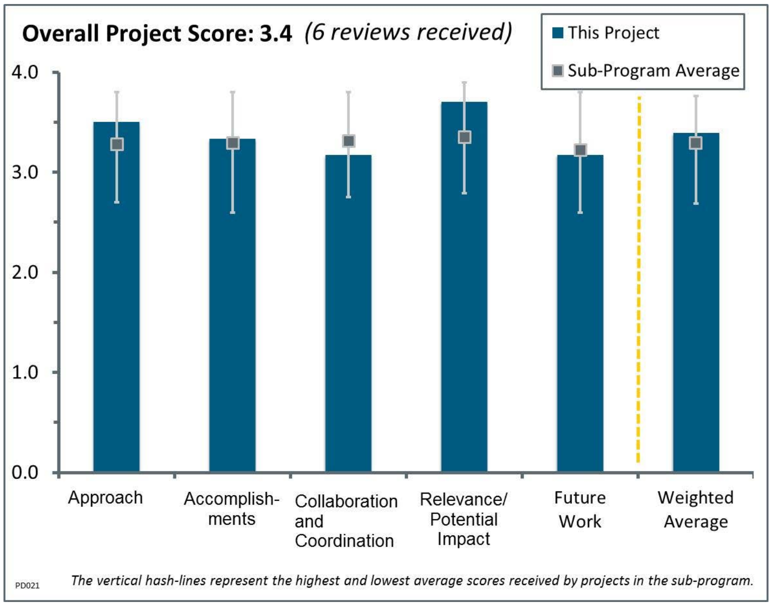
- Continued work to further engage and maintain stakeholder engagement should be a priority.
- The work should be used to bring forecourt personnel to a high level of understanding.
- Any weaknesses can be addressed by additions.

Recommendations for additions/deletions to project scope:

- The project should consider regional deep dives, i.e., how cost will be different in regions where hydrogen stations may be deployed in the next few years. Also, although tube trailer delivery for pre-compression has great project economics, it is not always practical in all situations, particularly where real estate is at a premium. Other options should be considered.
- It would be helpful to better understand the cost and impact of expansion of stations. If possible, it would be helpful to understand the impact of component reliability on operations and maintenance costs—and identify ways to invest where needed and cut costs where possible.
- The project should consider hybrid options to help handoff between early- and late-stage costs (liquid pumping vs. gas compression).

Project # PD-021: Development of High-Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

Don Baldwin; Hexagon Lincoln



Brief Summary of Project:

The overall objective of this project is to reduce the cost of a near-term means of transporting gaseous hydrogen from the production or city gate site to the stations. Hexagon Lincoln will design and develop the most effective bulk hauling and storage solution for hydrogen in terms of cost, safety, weight, and volumetric efficiency. This will be done by developing and manufacturing a tank and corresponding International Organization for Standardization (ISO) frame that can be used for the storage of hydrogen in a stationary or hauling application.

Question 1: Approach to performing the work

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

- This was a very practical and productive project. The project team stayed focused on meeting practical objectives established by U.S. Department of Transportation (DOT) regulations, market requirements, and the physical manufacturing of the vessels. It is necessary for the U.S. Department of Energy (DOE) to fund a portfolio of projects but exciting when a few in the portfolio are market-ready.
- Hexagon Lincoln has taken a well-planned and logical approach to optimizing trailer capacity, using good engineering practices to increase capacity while maintaining compliance with DOT regulations.
- The project team has taken a very effective and consistent approach throughout the entire timeline of this work. It has been clearly defined and successfully executed.
- The approach is sound.
- This seems to be more of a Market Transformation or Technology Validation project in that it is testing trucks on the road and using compressed natural gas (CNG). The containers have been deployed. Some of the project goals (pressure) do not meet the DOE targets, and it is not clear that the project is offering a pathway to the DOE goals. The project is doing both hydrogen and CNG. The cycle testing is very important, and it will be interesting to see the results. The research aspect seemed to be more about engineering scale-up rather than the usual research and development (R&D) done in production and delivery work. It is not clear what the project is doing to address Barrier I: “Other fueling site/terminal operations.”
- The approach seems to be out of the realm of DOE R&D and into the commercial space. It seems unlikely that the project will produce a 540 bar system, and the 350 bar improvements are very incremental. A technical breakthrough may not be needed for the 540 bar to occur—perhaps only a business case and DOT approval. The discussion should be focused on the technical requirements to achieve project objectives.

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

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

- The evolutionary work performed by Hexagon to achieve an optimal design for the market is very impressive—especially the work on the ISO frame to drive down weight and vessel configurations to maximize volume.
- Design and assembly of trailers has been carried out effectively. Current testing of Titan tanks with hydrogen is a good final step to this project.
- The technical accomplishments and the progress are impressive.
- The progress has mainly been incremental; however, with such large volumes, the incremental progress can have large impacts. The project should normalize to a materials cost so that market adjustments are not affecting the cost. The project needs to focus on the technical challenges to reach the 540 bar mark.
- It was difficult to tell what was accomplished in previous years compared to the current evaluation. The project has been going since 2008. Project team members have scope for cost reduction studies, but it was not clear what the results were. The team presented some generalities, but more specifics on the cost studies would have been helpful in the evaluation. The market the team describes cannot use the 540 bar system since, according to Hexagon, their clients rarely use the full capabilities of the 350 bar system. While this may be true for CNG, the hydrogen filling stations operate above 300 bar, and the vehicles are going to 700 bar; so it seems that the hydrogen market will be able to handle, and would probably prefer, the higher gas pressure. The on-road testing is impressive, but it was CNG. It was not clear that the project would be doing on-road testing with hydrogen. The team sort of showed a pathway to some of the DOE goals, but it was not clear.
- The new presentation did not show significant differences in the accomplishments of this work when compared to accomplishments presented in 2014. The only major difference in this year's accomplishments was the development of the hydrogen deep cycle test plan to be executed at Powertech. It was shown that some of the initial tests were conducted in April/May 2015, but initial findings were not presented.

Question 3: Collaboration and coordination with other institutions

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

- Collaboration is a little tough when the project is just ahead of market need. That said, Hexagon's work in natural gas gives the team very practical feedback from real-time users of the system. The collaborations performed with DOT, American Bureau of Shipping (ABS), Argonne National Laboratory (ANL), and Powertech were vital and clearly contributed to the success of the project.
- The project used outside testing very well at Powertech Labs and Stress Engineering Services. The presenter stated that the project had discussions and input to ANL for Hydrogen Refueling Station Cost Reduction studies; some details on these would be interesting and strengthen the collaboration score.
- The project has benefitted tremendously from "internal collaboration" with Hexagon Lincoln's natural gas transportation business.
- The ongoing collaboration with DOT on this project is very valuable to the success of this work. The addition of Powertech Labs for the testing activities will be very beneficial to the project.
- The collaboration with Powertech to perform deep cycle testing should show some technical improvements, and the coordination with DOT and ABS are appropriate to meet the project goals.
- The collaboration and coordination with other institutions are appropriate for this type of project.

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

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

- The project is focused on one of the main barriers to fuel cell vehicle deployment by helping to decrease the cost of the hydrogen infrastructure and improve the hydrogen transportation opportunities. This has broad impacts beyond the Fuel Cell Technologies Office into areas such as merchant hydrogen transportation for petroleum and aerospace applications, as well as CNG and other gas delivery.
- As the early hydrogen market develops, high-pressure tube trailers will be the most cost-effective pathway for delivery of hydrogen to retail sites. Delivering at high pressures will provide more reliability and flexibility to the hydrogen retail stations, so reducing the costs for this transportation pathway is essential to the initial rollout of hydrogen fuel cell vehicles and refueling stations.
- Tube trailer delivery appears to be a low-cost delivery strategy, and Hexagon Lincoln has done an excellent job of maximizing trailer capacity to enable this delivery pathway.
- The relevance and potential impact are enormous for an alternate gaseous fuels infrastructure.
- This is a great project to demonstrate leading-edge relevance when delivery of gaseous hydrogen is required to serve a functional market. Unfortunately, the market for fuel cell vehicles has not kept pace with Hexagon’s effort. As for impact, Titan will become a vital component in the early supply of hydrogen to the fuel cell vehicle market. What is unclear is the sustainability of this delivery solution over the next two decades.
- The project has been impactful, and *if* the team can get approval for the 540 bar system, then that could be very impactful for the rollout of fuel cell electric vehicles. However, perhaps the approval should have been separate from this project so that the project could focus on technical challenges, if there are any. The presenter mentioned that valves and controllers could be an issue at the 540 bar level, so emphasis should go to the design and manufacturing of these components.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The cycle testing is very important. The project should reach out to more hydrogen fueling stations and fuel cell vehicle original equipment manufacturers to better understand the timing and needs of hydrogen fueling stations.
- The deep cycle testing at Powertech should add some benefit to the technical community, and the results should be shared.
- Future work proposed seems appropriate towards the development of this project, but it is the same as what was previously presented.
- The proposed future work is appropriate for this type of project.
- It appears this project is complete at this point.
- The project is nearing completion at this point.

Project strengths:

- Hexagon is a leader in composite tanks for gas delivery in the United States. An excellent company was included to do the real-world testing of tanks on the road.
- The project is doing good fundamental engineering and continuous improvement to optimize hydrogen transport.
- The project strength is the design and fabrication team.

Project weaknesses:

- There are no notable project weaknesses.

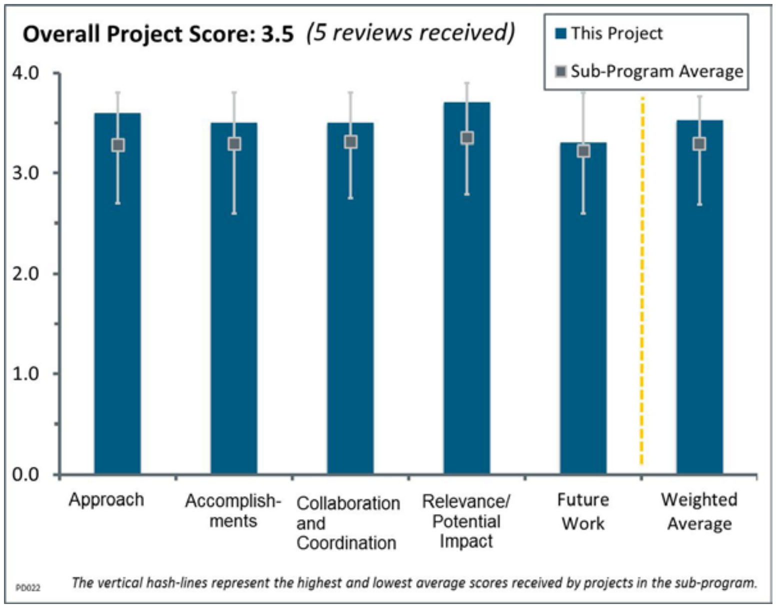
- The project seems more focused on CNG than hydrogen. There was not enough discussion of the market analysis or the cost savings. No details were given on construction, etc.

Recommendations for additions/deletions to project scope:

- In giving the presentation, the PI noted the unit capital cost for a Titan has escalated from $500/kg to $800/kg because of the cost of carbon fiber. Funding technologies to reduce the cost of fiber manufacturing will be necessary. There may be push-back from existing manufacturers, but if carbon fiber becomes a critical commodity to the development of fuel cell vehicles, funding in this area can make an impact by helping to drive down cost.
- It is suggested that these design advances be included in ASME Boiler and Pressure Vessel Code, Section XII (transport vessels), if viable. Additionally, it would be good to know what happens with the local authorities having jurisdiction if this pallet is removed from trailers and used as station storage without an ASME stamp.
- This project seems more like a Technology Validation or Market Transformation project than a Hydrogen Delivery project. The research aspect was not clear; it seemed to be more engineering design work.

Project # PD-022: Fiber-Reinforced Composite Pipelines

George Rawls; Savannah River National Laboratory



Brief Summary of Project:

The objectives of this project are to (1) provide data to support a technical basis for fiber-reinforced piping in hydrogen service, and (2) have fiber-reinforced piping integrated into the American Society of Mechanical Engineers (ASME) B31.12 Hydrogen Piping and Pipeline Code by 2015. Composite pipeline technology has the potential to reduce installation costs and improve reliability for hydrogen pipelines.

Question 1: Approach to performing the work

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

- The purpose of this work is to obtain data on fiber-reinforced piping for the ASME code development activities. The ASME approach—to produce an appropriate safety factor over and above non-hydrogen service using a holistic approach, start to finish, considering all processes— is the correct approach. The goal is to codify this technology. Good-quality solid data are extremely valuable to the codification process. The approach taken here is appropriate. The goal for this work is clear, the execution is on target, and progress made to completing the goal is spot on.
- This project has immense relevance for the distribution of high-pressure hydrogen to a wide variety of end users. The project team is very focused on finding and validating a commercially available product that is capable of being deployed in the near term. In doing so, the team is applying rigorous test methods and effective inspection techniques.
- The investigators are proceeding well with their work to qualify fiber-reinforced piping for use in hydrogen transportation. The incorporation of dry-wrap piping suitable for use in on-site manufacturing is a good addition to the project.
- The project clearly addresses barriers around the use of steel pipelines for hydrogen transport, including changes to the B31.12 code regulating the use of hydrogen pipelines.
- The approach is sound. It follows the standard industry practices—this is an industry with a high level of safety and a high level of intolerance for failure.

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

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

- The project is building on significant accomplishments. Smart Pipe supplied a new system to the project—a dry-wrap-system-reinforced thermoplastic pipe. The burst pressure was higher than required; the burst was not at the joint but along the pipe, indicating robust joints. Permeation leaks were lower than required. The project has made progress in codification efforts, having passed the B31.12 committee—the standards committee is next—so the team is moving this along at a nice pace. Most of the comments from this committee are editorial, not particularly technical. This experience demonstrates the necessity of requiring solid data/analysis for successful movement through the codification process. This project is simply doing an excellent job to codify technologies. The team is doing its job.

- The project's evolution is very impressive in terms of the selection and evaluation of distinct generations of thermoplastic pipe. The team is now working with a long-length manufacturer, which is very important in reducing the number of couplings (hence cost) for a commercial investment. The team also recognized the C-wrap product's importance in terms of its ability to be sleeved by hard-shell pipe. This is innovative and has the potential to be extremely cost effective.
- Acceptance for use as part of a domestic pipeline requires inclusion in an ASME B31 Code section. The project has successfully helped the code case for inclusion of fiber-reinforced plastic piping. This is a four-step approval process. The product has passed the first step, the B31.12 Section Committee, and it has moved up to the B31 Code Committee.
- The work addresses the critical questions associated with the safe implementation of this cost-effective steel pipe alternative. The investigation of the dry-wrap pipe provides additional support for the use of fiber-reinforced piping for hydrogen transport via pipelines.
- Work with the code committee has been on time and well organized. Work to understand the dry-wrap pipe was carried out well, although it was not part of the original work plan.

Question 3: Collaboration and coordination with other institutions

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

- The work given to securing codification under ASME B31.12 is outstanding and satisfies the value of collaboration for a project of this nature.
- The work has been guided through collaboration with the ASME code committee, resulting in the initial stages of successful balloting. It is not clear whether the list of partners or collaborators fully represents the stakeholders.
- This activity includes several manufacturers and ASME. With acceptance by ASME, this should meet U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration regulations.
- This project works with the appropriate collaborators. This year, a new partner defined the technology for the current codification exercise.
- The work with pipe manufacturers and ASME is good.

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

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

- This solution may be required for all "end delivery" of hydrogen to various use points across the country. Therefore, the relevance is immense. It also represents an outstanding economic solution that may potentially deliver value for 50 years.
- Fiber-reinforced pipe—especially on-site manufactured pipe—has real potential to lower pipeline costs. This project began as a high-risk, high-reward effort to eliminate the high costs associated with welding steel pipelines. It is nice to see it reaching these milestones.
- The hydrogen community needs to get the technologies codified in the appropriate standards/codes bodies before significant deployment can occur. This project is perfectly aligned with that need.
- The work provides the technical basis to implement a single, cost-effective steel pipe alternative.
- This has the potential to reduce pipeline installation costs.

Question 5: Proposed future work

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

- Once the codification work is successfully achieved, the team should consider playing a role in educating commercial users to rapidly adopt the technology and look for ways to improve the technology in the form of the product, installation, and/or use.
- This project is on target to get this technology codified, just about as fast as possible.

- The project is proceeding well toward completion.
- The future work appears to be focused on wrapping up the project.
- The proposed future work is appropriate for this task.

Project strengths:

- This work has a clear, well-defined goal, and the principal investigator is performing the work necessary to achieve that goal in a clean, systematic manner. It is clear that performing high-quality analysis, experiments, and measurements before approaching the code committees makes the codification process much more efficient. That is exactly the approach. The bottom line is that this work is accomplishing its goal and doing the work that is necessary.
- This is solid work that will almost surely result in access to fiber-reinforced piping as a hydrogen transport option in the near future.
- The project has strong interactions with pipe manufacturers and standards agencies.
- Industry involvement and oversight (i.e., ASME B31.12) are project strengths.
- The project's usefulness is its strength.

Project weaknesses:

- No weaknesses can be seen.
- The couplings are proprietary designs. There is the potential for mixing and matching fittings (e.g., hose to fitting or fitting to fitting). This is often an issue with non-commodity designs.

Recommendations for additions/deletions to project scope:

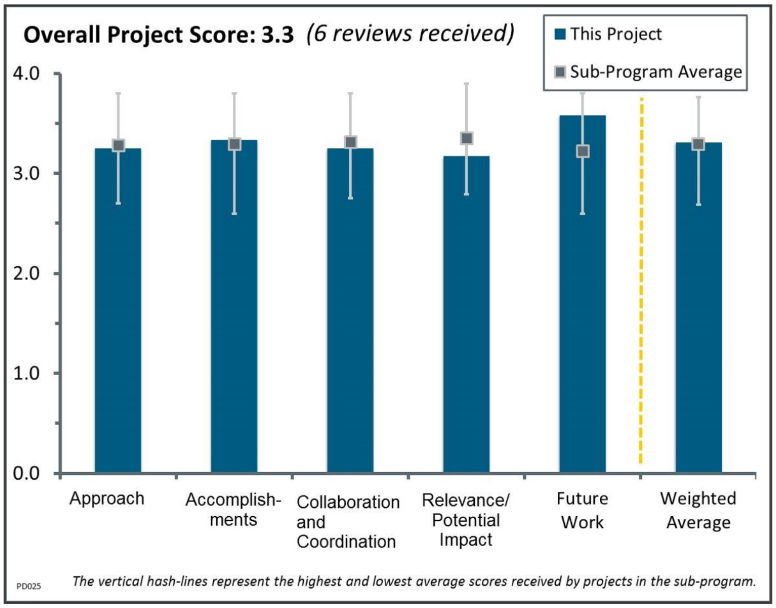
- The project should keep up the great work.
- More funding is recommended.
- The project should address the concern about mixing and matching fittings in a proprietary design.

Project # PD-025: Hydrogen Embrittlement of Structural Steels

Brian Somerday; Sandia National Laboratories

Brief Summary of Project:

The objectives of this project are to (1) enable data-informed design safety factors for hydrogen pipelines, which affect both reliability/integrity and cost, and (2) answer specific questions about steel hydrogen pipelines. Sandia National Laboratories (SNL) will quantify fatigue crack growth aided by hydrogen embrittlement in pipeline steels, particularly for welds.



Question 1: Approach to performing the work

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

- The use of the established high-pressure fatigue laboratories in existence at SNL is critical for this investigation. Indeed, this capability enables the investigation of failure through fatigue crack growth rate mechanics (laws)—the appropriate analysis for this investigation. The results from this work will be published in the scientific peer-reviewed literature—nothing less is to be expected of this work. Experiments are performed in high-pressure hydrogen environments representative of service conditions. The experiments are coupled with fracture fatigue analysis to improve understanding of the experimental results. This approach provides unique, valuable data and understanding of the fatigue crack growth experience in welds. This is world-class, outstanding work.
- The approach being applied to perform this work, in the form of theoretical analysis and physical testing, appears very rational and robust. The work performed on both friction and girth welding is very impressive.
- The approach is focused on answering the critical questions relevant to the implementation of steel pipeline for hydrogen transport. The addition of the forward-looking advanced pipeline material will likely enhance long-term cost savings.
- Researchers are using state-of-the-art techniques for evaluating crack growth in steels. It would perhaps be better to do more measurements on several welded pipes to determine the variability within a single method of welding. A single weld on just one pipe may or may not be representative of that specific welding technique.
- Although the approach may be great, the presenter had difficulty communicating key concepts to the review team. Throughout the presentation, it was unclear whether the principal investigator (PI) had fed back any learnings to stakeholder groups, including the American Society of Mechanical Engineers (ASME). The approach uses perfect pre-cracks placed in the material; there did not seem to be a correlation between similar real-world crack types and what the project has been testing (or it was not stated).
- The fatigue life analysis should also be performed over a range of temperatures that correspond to possible use conditions of a steel pipeline.

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

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

- These experimental measurements were carefully performed. A residual stress analysis was performed and removed from the data, highlighting the fatigue crack growth as a function of the stress applied—this is outstanding work. The result provided data that were then used to improve the understanding of crack growth in weld regions. They were also used to calculate an effective wall thickness based on predicted crack growth, which is a very nice addition to this work and traditional for this PI. This calculation shows the wall thickness can be reduced from traditional calculations while maintaining the same level of safety—again, this is outstanding work.

- Completing work on both validating fatigue crack growth laws and performing physical sampling facilitates the opportunity for meaningful dialogue during peer review of papers and helps to form the technical policy to guide the construction of future high-pressure pipelines. Although laborious, this groundwork will no doubt be helpful to future generations of engineers and ensure safe operation for the general public.
- A credible and effective analytical system has been assembled to assess the embrittlement of steel under exposure to hydrogen gas—a system that is backed by a credible model. The examination encompasses the pipe and the all-important seals and welds at a microscopic level.
- The completion of the friction stir weld work is critical to the implementation of the technique to minimize the cracking susceptibility associated with conventional welds. Analysis to account for residual stress is valuable to appropriately interpreting fatigue crack data and minimizing costs while maintaining safety.
- The determination of appropriate pipe wall thicknesses is a significant development that adds value to the project.
- One huge factor is out of place: all testing occurred at 295K (71°F). In real-world pipeline situations, -40°C to 40°C can be realized. In lower-temperature cases, this crack will propagate at accelerated rates, and the data presented would not be predictive. This is a very significant point to which there seemed to be no response. It is interesting that welds do not seem to be more susceptible to accelerated fatigue crack growth than the base metal. It is not clear whether there is a significant sample size to confirm this analysis.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration/coordination is spot on for this project, including the international collaboration with the International Institute for Carbon-Neutral Energy Research (I^2CNER) in Japan.
- Based on comments from the 2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review, the team has demonstrated expanded collaboration activities. The notably increased interaction with ASME will help ensure the work is relevant to actual pipeline operating conditions.
- There was collaboration with Oak Ridge National Laboratory, which was evident during the question-and-answer period.
- The collaborations are sufficient to enable progress. They could be used as a source for real-use conditions of pipes in pipelines to determine whether the scope of the embrittlement problem is larger than this laboratory exercise.
- It is great to see the interaction with Exxon Mobil on securing samples, but the depth of interaction with a variety of commercial leaders in the pipeline industry requires more work. The project should identify the top five leaders in the high-pressure pipeline industry (even if they do not use hydrogen) to solicit opinions of the work performed to date and recommendations for ongoing work. The project appears to be too insulated by academic thinking.
- The project had good collaboration inside the national laboratory system and with the ASME, but there has been little interaction with industry.

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

This project was rated **3.2** for its relevance/potential impact.

- It is too early to determine relevance, but the objectives of the project are extremely meaningful and fully justify the required investment. There is potential relevance in both the development of the fatigue crack growth theory and the application of this work in the construction (materials and methods) of future pipelines.

- This work and other work on steel's compatibility with hydrogen is critical for the safe, low-cost implementation of hydrogen technologies.
- This project on steel pipes is a very necessary exercise on a conservative approach to solving the hydrogen pipeline problem.
- Steel is not a dominant cost for pipelines, so material cost reductions are unlikely to yield large reductions in pipeline costs.
- The fact that testing (for such a long project) has occurred only at 295K is concerning and not a great example of a real-world possibility.

Question 5: Proposed future work

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

- The proposed work for 2015 includes vital steps to expand awareness of the subject matter and to start a broad discussion on its relevance and improvements. The work for 2016 expands the scope to new materials and methodologies that serve to cultivate refinements and best practices. This work should be funded for decades.
- The future direction represents appropriate growth for this work. Nothing less is to be expected than getting this work into the technical peer-reviewed literature, so clearly the focus to complete refereed papers is appreciated—this is a good focus. Working with the appropriate ASME pressure committees ensures rapid dissimulation into the relevant code language. This PI and group have historically had a significant impact on ASME code language; it is good to see that continuing.
- The future work contains a good combination of focus on today's implementation challenges and forward-thinking future work to maintain the long-term viability of the use of steel pipelines for cost-effective hydrogen transport.
- The fiscal year 2015 work seems appropriate. It would be great to add cyclic testing with additional temperature gradients to find out what effect temperature has on crack growth and the K factor for areas where pipelines could experience wildly swinging ambient temperature conditions.
- The proposed work is still a laboratory project. Extrapolation to the behavior of pipes in the field does not appear to have been made.

Project strengths:

- The project uses triplicate tests to get repeatable data, resulting in good consistency of the data. Calculations presented show good data for calculating wall thickness, and this will be a key factor in the overall cost of the pipeline. Such variation in thickness will make a huge impact on pipeline cost.
- Project strengths include the carefully thought-out experiments, excellent execution, clear understanding of the physics involved, and application of that knowledge in providing thoughtful analysis. The team casts the information in such a manner as to make the fundamental data immediately valuable to the community.
- Project strengths include the granular insight on the performance of high-pressure pipelines over long use and methods to ensure the community is safe.
- The project has great balance between its science and engineering aspects. Collaboration has increased.
- The PI projects competence in handling the technical aspects of the problem and is aware of the dimension of the challenges.
- The team has strong expertise in crack propagation mechanics.

Project weaknesses:

- Data are collected only at static temperature. Because there are pipelines in dynamic climates, this could be a key factor in determining the long-term costs for pipelines as a delivery method for hydrogen. Determining what the real pressure swings could be is also a key factor; it is unclear whether pipeline operators have shared this information.

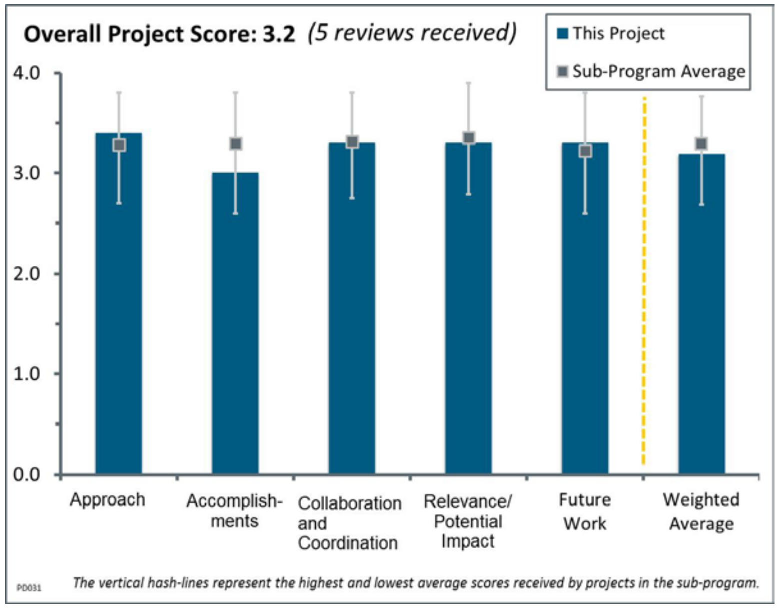
- This group needs to extend the temperature operating range to be consistent with the service conditions of -40°C to +85°C.
- It is doubtful that the full range of necessary laboratory work for this project can be done at a national laboratory with this low of a budget. Such a limitation inhibits the commitment of the PI to the intellectual aspects of the project.
- The project must continue to leverage various facilities to perform the needed number of tests for implementation.
- More dialogue with commercial players is needed.
- The work is unlikely to yield large reductions in pipeline costs.

Recommendations for additions/deletions to project scope:

- The project should keep going.
- This laboratory really needs to develop a temperature capability to enable temperature ranges consistent with service conditions of ambient down to -40°C and SAE International J2601 conditions of up to +85°C.
- More pipe samples should be examined to account for the variability in welding procedures.
- A credible attack on this problem requires expansion of the laboratory work, with a concomitant increase of resources to support such an expansion.

Project # PD-031: Renewable Electrolysis Integrated System Development and Testing

Mike Peters; National Renewable Energy Laboratory



Brief Summary of Project:

The objectives of this project are to (1) provide independent performance testing of advanced electrolyzer stacks and systems for the U.S. Department of Energy (DOE) and industry; (2) develop electrolyzer stack and subsystem components and optimize performance using grid and, especially, variable renewable energy; and (3) leverage large active area stack testing platform and balance of plant (BOP) to develop system efficiency improvements.

Question 1: Approach to performing the work

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

- The project utilizes experience and facilities developed over a number of years. The barriers addressed are the degradation of polymer electrolyte membrane (PEM) electrolyzer stacks under variable loads and the reduction of hydrogen loss due to drying. The simultaneous testing of stacks under variable and constant loads is the ideal testing environment for such an analysis; it is a pity that the stacks did not have the same run times at the start of the experiment. The tests on different approaches for drying the hydrogen are well planned but hampered by the accuracy of the dew point sensors.
- The project evaluates PEM electrolyzer performance in critical applications (wind and solar to hydrogen) with attention to the necessary details for high-fidelity results. An ancillary benefit is that it also provides hydrogen for NREL efforts on the hydrogen delivery front.
- The approach to the effort was well organized and well thought-out with DOE targets clearly in mind.
- NREL is working with several industrial partners to provide independent testing of advanced water electrolyzers and integrated systems coupled to grid and renewable power sources. The work includes evaluation of several hydrogen drying technologies based on pressure swing adsorption (PSA). This is primarily a development and demonstration project, rather than a basic research project.

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

This project was rated **3.0** for its accomplishments and progress.

- The project team has made sound choices regarding the focus areas: the impact of intermittency on long-term performance of electrolyzer stacks and how to minimize loss of hydrogen in dryers.
- Electrolyzer stack performance and degradation were evaluated using three Proton OnSite stacks under constant and variable-power operating conditions over long test periods (i.e., 5,500 hours for two of the stacks and 2,500 hours for the third). The effect of variable operation on degradation is not completely clear from the results, but it does not appear to have a significant effect on the degradation rate. The project has developed the ability to simulate typical variable-demand profiles to simulate wind and photovoltaic power sources. PSA dryers were evaluated with the goal of optimizing the electrolyzer BOP under variable operation conditions. Dryer performance was evaluated using dew point sensors. The target moisture of the hydrogen product is <5 ppm.

- The project contributes to the DOE target of increased hydrogen from renewable energy sources. The stack decay rate was measured to be almost the same under constant and varying loads. Alternative drying processes still need to be verified; however, the facility is well designed.
- The effort to improve electrolyzer efficiency by optimizing electrolyzer BOP operation under variable conditions seemed to have merit; however, the approach was not adequately outlined in the presentation.

Question 3: Collaboration and coordination with other institutions

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

- This is somewhat of a stand-alone effort, but existing relationships with PEM electrolyzer providers should serve to strengthen that market.
- Partners include Xcel Energy (providing an ongoing wind-to-hydrogen demonstration project); Proton OnSite (providing 40 kW and 120 kW electrolyzers and a drying skid); and Giner, Inc. (providing 150 kW PEM electrolyzer stacks). The collaborative efforts with these companies appear to have been quite close and mutually beneficial.
- Collaboration is limited to project partners. The project also interacts with NREL's Integrated Network Testbed for Energy Grid Research and Technology Experimentation (INTEGRATE) project.
- The issues with the dew point sensors seemed to resonant with the audience. However, the lack of collaborations and coordination with experts in this field is concerning. Clearly, the data collected from these critical instruments affects resultant conclusions, etc. It is recommended that subject matter experts be brought in to address this apparently long-term problem.

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

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

- The project greatly supports advances toward increased penetration of renewable energy technologies in the energy system, aiming at the storage of excess energy from renewables.
- Electrolytic hydrogen production can be coupled with renewable energy (wind and solar) for hydrogen production. This technology can also support grid stabilization with increasing penetration of renewables. Because it is based on relatively mature technologies, this work has the potential to have a significant short-term impact on the integration of renewables into the energy mix, as well as on hydrogen production for use as vehicle fuel or for other applications.
- The project supports DOE's goal of lowering the cost of hydrogen, in this case by increasing efficiency and lowering costs for the existing electrolysis approach. These efforts are not likely to have a huge impact on the final cost of hydrogen, but the value of the project compared to its funding is likely high for this type of research.
- The project seems to have a near-term potential impact with regard to hydrogen savings, with logical approaches.

Question 5: Proposed future work

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

- Additional long-duration stack testing under variable-power operation and dryer testing will be completed, as well as evaluation of additional BOP improvements, such as heat recuperation. The proposed future work is a logical extension of the work completed to date.
- The future work is well planned.
- The project identified a couple of opportunities to evaluate in terms of reducing BOP costs.
- It is important to find other opportunities to use the electrolyzer BOP to improve system efficiency. A clearer message with respect to potential avenues would have been helpful. It seems that using a cooling system and H_2O dropouts to improve dryer efficiency should have been an initial focus; however, it is nice

to see it called out for future work. Capturing heat to warm up hydrogen sweeping gas to lose less hydrogen due to drying also seems logical. Finally, the effort to continue long-duration testing, comparing stack decay rates for variable- and constant-power operation, needs better fidelity with respect to expected outcomes.

Project strengths:

- Project strengths include a high level of short-term relevance for hydrogen production from renewable energy with demonstrated load-following ability and grid stabilization potential.
- Project strengths include the use of existing facilities and established expertise over a number of years. Continuous support from DOE is vital in expanding the facilities and knowledge generated, which is valuable to the United States and the international community.
- This project helps to move electrolysis further up the S-curve by improving efficiency and reliability.
- The overall organization of the project is one of the main strengths of this work.
- This project seems to have a good test facility.

Project weaknesses:

- The lack of outside expertise seems to be the one potential weakness.
- It is unfortunate that not all three stacks had the same age (i.e., operating hours) at the start of the project.
- The project has a small stack sample size for the determination of the effects of variability.
- The wind data used appears unrealistic.
- The project is not likely to dramatically lower the carbon footprint of hydrogen.

Recommendations for additions/deletions to project scope:

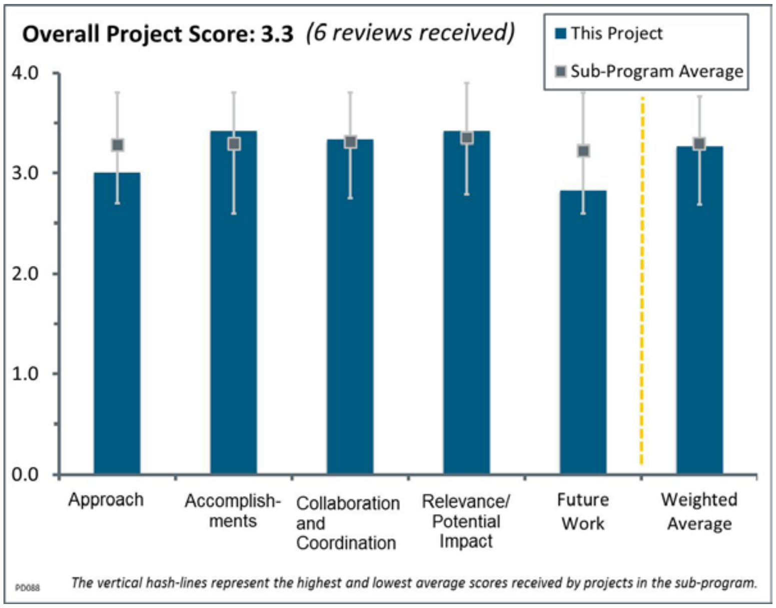
- Additional evaluations should be performed to determine the effect of load variability on long-term electrolyzer performance.

Project # PD-088: Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

Zhili Feng; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop and demonstrate the novel steel/concrete composite vessel design and fabrication technology for stationary storage systems of high-pressure hydrogen that meet the U.S. Department of Energy (DOE) technical and cost targets. Oak Ridge National Laboratory will address the significant safety and cost challenges of the current industry standard steel pressure vessel technology.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- There is intriguing integration of exiting technology with attention to cost.
  - Embrittlement-susceptible, high-tensile-strength steel is used by engineering around the embrittlement issues; the design reduces the pressure to values low enough to eliminate embrittlement concerns before the high-tensile-strength steel sees the hydrogen. This, effectively, is engineering designed leaks. The permeation leaks are below acceptable levels, and the exposed steel sees hydrogen at pressures at which embrittlement is not a concern. This is nice as long as it continues to work over the lifetime of the tank. The question was posed and addressed by the principal investigator (PI), but it would be good to see a formal response presented as part of this review.
  - The design is a bit sophisticated, making the manufacturing complex and possibly labor-intensive. Cost control is one of the goals, and the predictions are encouraging. It is clear that as this project continues, attention to manufacturing costs will remain high on the list.
  - This concept seemed, at first glance, to be a direct burial tank, in which case the tight contact with the surrounding ground would take up part of the load (if correctly designed and implemented). However, that is not the case; this is a stand-alone tank. This begs the following:
    - The concept is to use pre-stressed concrete. In this concept, the concrete is pre-stressed by steel wrappings. Concrete by itself has effectively zero tensile strength; it is great in compression but not in tension. Pre-stressed concrete, however, can handle tensile loads as long as the tensile load does not exceed the pre-stressing from the steel wrappings. In other words, the steel takes the load of pre-stressing and the pressure load of the hydrogen inside the vessel. It seems that the concrete is not necessary; indeed, this system would be a lot simpler and less costly without the concrete, and presumably the steel component can be reduced owing to the lower tensile loads.
    - This project has done a nice finite-element method (FEM) analysis, so presumably the case with and without concrete from a balance-of-plant and cost-optimization perspective has been performed. It is requested that the PI address this point in rebuttal.
- The project addresses hydrogen storage at low cost. Economic hydrogen storage in relation to tube delivery cost is an important target for the DOE Hydrogen and Fuel Cells Program, and the project is well positioned to address the relevant roadblocks. Collaborative work with industrial partners brings to the project valuable requisite expertise, such as Ben C. Gerwick, Inc., for pre-stressed concrete and Hanson Pressure Pipe for the construction of the outer concrete reinforcement.

- This is a unique approach to solving a challenging problem. There is an open question on how the small amounts of hydrogen released in the vent hole could affect the welds and materials in the micro-gaps, which causes some doubts. Likely a simple analysis could be completed to calculate the partial pressure of hydrogen experienced in the micro-gaps.
- This project has been well executed and planned. The approach of combining low-cost materials to address the cost and performance of bulk storage of hydrogen is unique. The absolute necessity of the concrete layer remains unconvincing, and the properties of the concrete used in this case should be well known, as significant degradation can occur in concrete structures that could have an impact on the vessel strength.
- As for the approach to performing the work, the project team presented a good plan and seems to be developing effective manufacturing techniques. The project is technically interesting (multi-layered vessels, stressed concrete, manifolding), but the project's value remains in question. It seems there are several proven methods to store high-pressure hydrogen below the surface at equal or lower cost. The reason for continuing to develop this concept is unclear.
- The team is making good but slow progress.

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

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

- The prototype mockup of the 90 kg tank is complete. The American Society of Mechanical Engineers (ASME) hydraulic-static test is also complete—which is a major milestone! The project will be completing cycling testing in hydrogen, which is good progress. FEM analysis has been completed to understand the stress profiles and optimize the design—this is good, solid engineering. Strain gauges were imbedded into the mockup tank and were used to ensure the tank was not overstressed during construction and initial cycling. These data need to be used to compare with the FEM calculations for model validation. This will enhance confidence in the FEM and allow it to be used in further analysis and optimization. An invalidated model is not nearly as useful as a validated one. When a question about this was posed, the PI responded that this validation is planned—which is good. This is an excellent set of accomplishments.
- Significant progress toward the final project objectives has been made. The storage structure has been completed, and concerns about hydrogen leakage and safety have been addressed according to the design concepts (vent holes) underlying the project. The project has manufactured a representative prototype vessel with appropriately placed strain gauges to test, in the near future, the real-world performance of the actual vessel; this is a significant accomplishment. Individual components have been analyzed through detailed FEM analysis to optimize design, and the scheduled testing against hydrocracking is a reliable way to study the structure's integrity under severe pressure loading. In summary, the project is well beyond the construction stage, and sound future testing procedures are in place.
- The design and mock-up of the sub-scale prototype is a significant accomplishment. It will be very interesting to see the results from testing the mock-up.
- Technology demonstration is impressive. It appears that the work will provide a successful evaluation of this technology.
- The team is making good progress with this novel technology.
- The accomplishments and rate of progress are undeniably good, but there is no effort to assess competitive environment to determine if there is value in the accomplishments and progress.

Question 3: Collaboration and coordination with other institutions

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

- Industrial partners listed on slide 19 are all relevant and chosen to assist with construction of the individual components of the project. The list of partners is comprehensive and addresses all needed expertise.
- For the most part, the collaborations and coordination between partners are appropriate. While it may be a bit late for this project, adding an expert in concrete matrices is suggested, as there is significant expertise at the national laboratory level.
- The collaborators and coordination for this project are appropriate and comprehensive.

- Collaboration is appropriate for the work.
- The team is collaborating well with key technology partners.
- The majority of the collaboration is focused on technologies integrated into the project. There appears to be little effort with external organizations that are in better positions to offer insight on the project's relevance. This effort has a likeness to historical projects that were technically amazing but commercially (or militarily) of little use.

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

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

- There is definite need for high-pressure storage systems, and current costs are too high. The susceptibility of carbon steel to hydrogen attack and low-cost structural materials makes the proposed technology very appealing.
- The project advances DOE's objectives on stationary storage at refueling stations. The significant progress toward the project completion enables DOE's plans for the introduction of the fuel cell car.
- A low-cost hydrogen storage solution is needed—if successful, this technology will be valuable to the deployment of hydrogen technologies.
- This will address an immediate cost challenge associated with hydrogen storage.
- An inexpensive bulk storage technology that can be relatively easily manufactured would have a high impact on the development of hydrogen infrastructure. It is not clear that this technology can be scaled very easily for higher manufacturing rates.
- The project team seems more interested in technology integration than relevance. No effort was made to address the cost of fielding units or the logistics of delivering a unit or whether the unit can be relocated.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Proposed future work is appropriate. The cycling with hydrogen will be expensive but is necessary. The project should run optimization on structure, with and without the concrete, and run optimization on cost, with and without the concrete. The model validation should be completed.
- Cyclic testing will be interesting. There is not enough time or funding remaining in the project to pursue other efforts, and cycling is the most appropriate. It would be good to cycle this vessel for a few years to develop a base case, and this could probably be achieved with a relatively small amount of funding.
- The proposed testing of the mockup vessel to assess performance under cyclic hydrogen loading is of crucial importance to the validation of the concept and overall design of the structure. In particular, the proposed testing can be used to ascertain the economics of the design, but no such plans have been mentioned. It is unknown whether there is a plan to revisit the design of the structure if the vessel performs well under hydro-testing but poorly under cyclic loading.
- The results of the proposed cycle testing will be very informative.
- The project appears to be in the wrap-up stages.
- The proposal for future work is weak. It seems focused on testing the mockup and building a forecourt installation. There has been no effort to evaluate the economics, no comparison to competing technologies, and no thought to evaluating the logistics of employing the technology.

Project strengths:

- Contributions from the industrial partners ensure appropriate expert input to the project execution. Strict adherence to the ASME codes for the construction of the inner steel vessel and the planned hydro-testing are both indicators that the project advances according to the available codes and standards for components operating in hydrogen. The mockup vessel is a positive step toward testing the safety and reliability of the design.

- The concept is novel, and the design approach and execution are excellent.
- The proposed technology offers hope of low-cost storage.

Project weaknesses:

- It seems possible that the codes and standards for implementation for use with hydrogen have not been fully explored.
- It is not clear why the combined steel/concrete structure reduces the cost of the overall design and ensures the safety of the structure.
    - There is no comparison with alternative designs to ascertain the role of the presence of the concrete layer. For instance, the cost of the pre-stressed concrete in relation to an outer vessel made of low-cost steel is not listed. In fact, the very role of the concrete in securing that embrittlement of the layered high-strength structural steel was not clear in the presentation. For instance, there is no study as to why load shedding on the concrete layer increases the layered structural steel's resistance to hydrogen embrittlement.
    - Slide 11 shows contour plots of S33 stress in MPa , whereas the applied pressure is given in psi. Slide 12 shows hoop stress magnitudes in ksi. This is an inconsistent use of units in the same project and the same presentation.
    - The reported stress values for S33 on slide 11 would have provided more value if information was given as to what constitutes acceptable stress levels in the concrete.
    - On slide 12, hoop stresses are reported in comparison to the code-allowable stress limits. The question is whether these are allowable stresses for the inner steel vessel relevant to hydro-testing or to hydrogen embrittlement. There is no mention as to how the inner steel is designed against embrittlement. More specifically, it is not clear in what ways the calculated stress magnitudes help with understanding the resistance of the inner steel against embrittlement.
    - The entire design is based on the plot shown on the right-hand side of slide 5—namely, that there are no substantial amounts of hydrogen in the layered structure because of the presence of the vent holes. Despite the fact that the amounts of hydrogen in the layered structure are insignificant, the steady-state profile in the inner stainless steel layer cannot be dismissed. There is no evaluation of the role of hydrogen in the inner layer.
- The weight of the storage systems seems to be too high for large tanks to be shipped to site, and the manufacturing techniques look too complex for site work.
- This overall approach is to be questioned. It is not at all clear that the use of concrete in this configuration has any value added. If, however, this could be a direct burial tank—in contact with the earth to take off some of the load, or the entire load—then this would be fine.

Recommendations for additions/deletions to project scope:

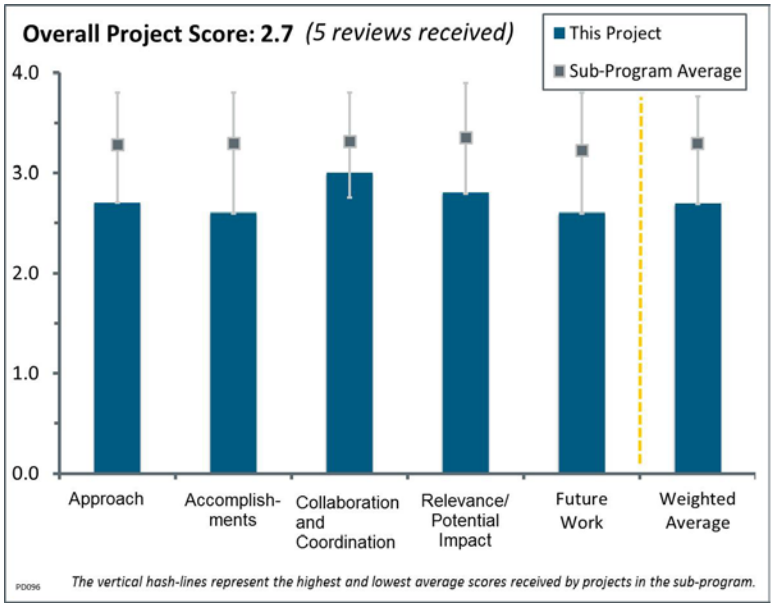
- The investigators are asked to address questions about the role of the stainless steel liner as opposed to another solution—for example, a coating on the layered steel shell could be used as a barrier to hydrogen egress. Such an alternative solution can help reduce the cost of the entire vessel significantly. The role of the concrete layer is also unclear. There is no convincing evidence that failure of the layered high-strength steel shell will be stress-driven in the presence of hydrogen. Even if failure is stress-driven, the layered shell can be constructed to bring the stress magnitudes below critical levels. No study was presented on the basis of the techno-economics of the layered shell's performance in hydrogen.
- The project should ensure that there is a thorough understanding of the codes and standards, with an emphasis on use in hydrogen.
- The project should be limited to an economic and logistic evaluation in comparison to competing technologies. Putting more money into testing seems to have little value.

Project # PD-096: Electrolyzer Component Development for the Hybrid Sulfur Thermochemical Cycle

William Summers; Savannah River National Laboratory

Brief Summary of Project:

The objectives of this project are to (1) develop highly efficient process designs for coupling the hybrid sulfur (HyS) thermochemical process with a concentrated solar energy system, and (2) demonstrate sulfur dioxide (SO_2) depolarized electrolysis using improved electrocatalysts and high-temperature (HT) proton exchange membranes (PEMs) that permit high-efficiency hydrogen production.



Question 1: Approach to performing the work

This project was rated **2.7** for its approach.

- The objective of this project is to develop and demonstrate improved component technology for the HyS thermochemical cycle, coupled to concentrated solar energy for the HT process heat requirement. The electrical energy needed for the electrolysis step can be provided by the grid or photovoltaics. The HyS process was originally developed by Westinghouse for coupling to nuclear energy (HT reactors) for large-scale hydrogen production. The HyS cycle includes an electrolytic step operating at ~120°C and a HT (850°C) H_2SO_4 decomposition thermochemical step. The electrolyzer uses a PEM-based Nafion-membrane electrolyte. Precious metal catalyst (Pt) is required on the SO_2–sulfuric acid side of the cell. Required cell voltage (~.6 V) is much lower than for water electrolysis owing to SO_2 electrode depolarization. Activation overpotentials associated with oxidation kinetics at the SO_2 electrode represent the largest magnitude (70%) loss mechanism for these cells. Testing is being performed at small scale (button cell and single-cell). Improved membranes and catalysts are needed. Cell lifetime is also an issue. Fiscal year (FY) 2015 objectives include system design and cost analysis. The conceptual system includes a HT solar receiver and thermal energy storage. A HT (130°C) high-pressure (1 MPA) button cell test capability will also be developed.
- The project approach to developing the HyS electrolyzer system itself is very good, but the merits of continuing this project are in question because it appears to depend in on a very low probability of reducing the cost of solar thermal heliostat and tower equipment. A brief literature survey indicates that the current cost of just the heliostat and power tower equipment is on the order of $4,352/kW of solar thermal energy. Assuming an annual capacity of 25% for the solar field and an annual capital recovery factor of 12%, then the price of hydrogen would have to be $7.94/kg just to recover the capital cost of the heliostat array and power tower. Thus, even if the HyS system were free, the price of hydrogen would have to be over $7.94/kg, or far above the project team's estimate of $3.13/kg to $4.23/kg. (It has been said that the U.S. Department of Energy [DOE] has instructed the principal investigator to assume very low-cost solar thermal collection systems developed under the "Sun Shot" project, but this is such a major ingredient in the overall hydrogen cost that the project should address the likelihood of achieving the Sun Shot goals for heliostat field costs.)
- The approach in this project is fair. Whereas it is generally agreed that the electrolyzer is critical to implementing this hybrid approach to hydrogen production, it is also true that integrating electrolysis with solar thermochemical processes is inherently complex and probably cost-prohibitive. The primary thrust of the work is development of the electrolysis unit and therefore consistent with priorities defined under earlier evaluations. At the same time, it is important to recognize that this effort has a long history and has

received significant funding, yet the enabling technology is still undemonstrated. Project concept design investment is insufficient to assure this reviewer that solar integration can be implemented in a way that supports the long-term program goal. In that regard, the project is inadequately integrated with outside efforts with far greater experience and knowledge in solar energy collection and use.

- The project team has identified the areas that need development, including solving the diurnal operation issue and improving the electrolysis step. It is not clear that the approach for improved membranes will work. It seems the team's favored membrane to replace Nafion is polybenzimidazole (PBI). However, PBI has well-known stability issues and challenges in consistent manufacturing, even from large, well-known chemical manufacturing companies.
- Stability and crossover attenuation using sulfuric acid-doped polybenzimidazole (s-PBI), and other membranes, are not known, and the reactor and project design rests on the assumption that such a membrane exists and/or can be made by collaborators.

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

This project was rated **2.6** for its accomplishments and progress.

- A flowsheet investigation was performed to evaluate the relative merits of vapor feed to the anode versus liquid feed (liquid feed is preferred). Solar receiver/acid decomposer options were evaluated as part of the process design activity. Three options were considered: direct solar heating of an acid decomposer, bayonet (indirect), and a falling particle receiver with thermal energy storage. The falling particle receiver and the bayonet decomposer were selected as baseline options. Electrolyzer development and testing included construction of a pressurized button cell test facility and quantification of the effect of pressure and temperature. Other HT membrane candidates will be tested. Progress over 2014 accomplishments has been modest.
- The technical accomplishments on the HyS system itself are good.
- The presenters reported significant improvements in sulfur cross-over reduction, membrane stability, and 1000-hour operation, but no data were shown to support these findings. The presenters need to show the data. The team never down-selected to a design; the design they presented can be either thermal storage or chemical storage. This option may have an impact on the cost analysis. It is not clear whether it did have an impact on the Hydrogen Analysis (H2A) results because there was not enough information about what was assumed for the H2A analysis to tell. It seems that the majority of solar HyS efficiency improvements are from work being done by the solar program, not work being done in this project. There was not enough detail provided on the H2A analysis to evaluate it. The capital cost assumptions (solar field size, heliostat costs, materials costs, etc.) are not included. Details on the operations and maintenance assumptions need to be included. It is unclear that the falling particle receiver design can achieve the 850°C operation required for the H_2SO_4 decomposer, especially if the project team plans on thermal storage to enable 24–7 operation.
- Accomplishments and progress of this project are poor to fair. This evaluation is based on historical funding for a far simpler embodiment of the HyS process in which the project team had to deal with only electrolysis and thermal decomposition of sulfuric acid. The acid decomposer was designed, developed, and demonstrated by another group, so the present team dealt only with the electrolysis process, and that process is still inadequate (although improved) to support plant-scale operations. Incorporation of solar power in lieu of nuclear power greatly complicates thermal interfaces so that the acid decomposition process might be different and therefore remains a barrier to efficient implementation.
- Very few HT studies have been reported to date, and the milestone that requires them is fast approaching.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The University of South Carolina (USC) (self-funded) is developing s-PBI membranes for HT pressurized operation. The German Aerospace Center (DLR) is participating in the system analysis task with a focus on the solar interface for direct heating of the sulfuric acid decomposer.

- The project seems to have a good collaboration with DLR and USC. While the presenters mention Sandia National Laboratories (SNL) for the falling particle receiver design, they do not mention SNL in their collaborations. Perhaps they just use literature data from SNL, but that is not clear. More collaboration with SNL on the solar receiver and solar field design is recommended, especially for the H2A cost analysis.
- The project team is good.
- Project plans indicate baseline selection of the falling particle receiver (FPR) for solar interface design. This concept has experienced some development and testing at SNL, but at-scale performance testing has not been done. Heat transfer and material durability issues accompany thermal exchange from hot particulate thermal media to process heat applications, and these have not been tested or demonstrated. Partnering with DLR for on-sun testing by direct solar heating for sulfuric acid decomposition is value-added to the project but initiates a new and untested approach to implementation of the acid decomposition process. The FPR work will require partnering with SNL. The inventory of collaborations does not include this essential element. Collaboration and coordination is poor.

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

This project was rated **2.8** for its relevance/potential impact.

- Low-cost renewable hydrogen is a needed resource. This project addresses this area. The potential impact is significant. The cycle is lower-temperature than many of the other cycles currently being investigated. It does have an electrochemical element, which means that it will need electricity. The project team currently proposes to generate electricity on-site. However, for 24–7 operation, off-site (grid) electricity would be required.
- The HT cycles have the potential to achieve higher efficiency than conventional water electrolysis. Integration with concentrated solar energy is attractive for renewable hydrogen production, but it represents a significant technical and cost challenge. Considering the technical challenges associated with the electrolytic and thermochemical steps in this process, and the coupling with concentrated solar energy, possible deployment of this technology is very long-term.
- Relevance of this work is good to excellent. Potential impact is poor to fair. Potential impact assessment is based partly on the complex (and probably costly) nature of hybrid processes. The assessment is also based partly on the project history of funded support and still-inadequate electrolysis performance. Finally, potential impact is degraded by undertaking research and development on a new and untested acid decomposition process.
- The potential impact of this project is doubtful, given the dependence on an extraordinary reduction in heliostat field costs required to make this project economically viable.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The proposed future work within the realm of the HyS technology seems reasonable.
- Proposed future work includes continued button cell testing with a focus on membrane and catalyst development. Flowsheet and cost analysis will also continue.
- The presenters said in their response to reviewers that the PBI membrane had already been shown to be stable. However, the presenters have long-term performance testing of the PBI membrane in the future work section. Either this test is redundant, or they have not performed long-term testing. They need to clarify their comments. Long-term testing of the membranes is needed. They have a performance goal of 600 mV at 500 mA/cm^2, but there is no pathway to achieve this. The data shown in FY 2015 seem to indicate that the project is a long way off in performance and that the goal of 100 mV improvement will not achieve the performance target of 600 mV. It is important for the catalyst testing to be done on real membrane electrode assemblies (MEAs) in real systems and not just rotating disk electrode testing. The team needs to complete the H2A analysis and provide details to DOE and the reviewers. The team members have yet to demonstrate an MEA that can achieve the performance goal of 600 mW at

500mA/cm^2, but they are already focusing on lowering the catalyst cost. It seems they should first get something that can meet their needs and then lower their costs. They also need to determine whether the catalyst cost is indeed a significant factor in the H2A analysis.
- Future plans are poor because the vast majority of work is directed to the electrolysis process, and no specific work is directed to resolve the acid decomposition process testing, evaluation, and selection. It is likely that this work breakdown reflects the skills and interests of the project direction, further underscoring the need for better collaboration with the solar power and solar thermochemistry communities.
- There is no clear contingency plan in the event that a higher-temperature stable membrane cannot be identified.

Project strengths:

- This is an excellent team, well-versed in the HyS process dating back to earlier times when Savannah River National Laboratory was assuming nuclear power would drive the process.
- The project has a good team with a long history of working in this area.
- Strengths are in facilities and membrane electrolysis testing and evaluation.
- Progress has been made on development of the sulfur-depolarized electrolysis membranes and catalysts, but significant performance challenges remain. Overall system analysis, including coupling to concentrated solar energy, has been performed. The project is addressing the electrolyzer issues in a logical fashion, with a go/no-go decision point of September 30, 2015.

Project weaknesses:

- The technological challenges associated with the HyS concept are very significant. Oxidation kinetics must be improved. Precious metals are required for catalysts. PBI is difficult to manufacture in large quantities and has shown large degradation. Corrosion is a significant issue for all process components that come into contact with the sulfuric acid solution. The electrolysis step has been demonstrated only at small-scale (single-cell or button cell). Additional challenges will be encountered with stack-level operation.
- The PBI membrane stability needs to be demonstrated. Simply saying it has been done is not enough; the data need to be presented. The team is focusing on lowering the cost of catalysts. It is not clear that this is the main cost driver. The project needs to provide more details on the H2A analysis.
- The project is weak in areas of solar power analysis, interface design, and thermochemical acid decomposition.
- Success depends on the drastic reduction of heliostat field costs, which seems unlikely.

Recommendations for additions/deletions to project scope:

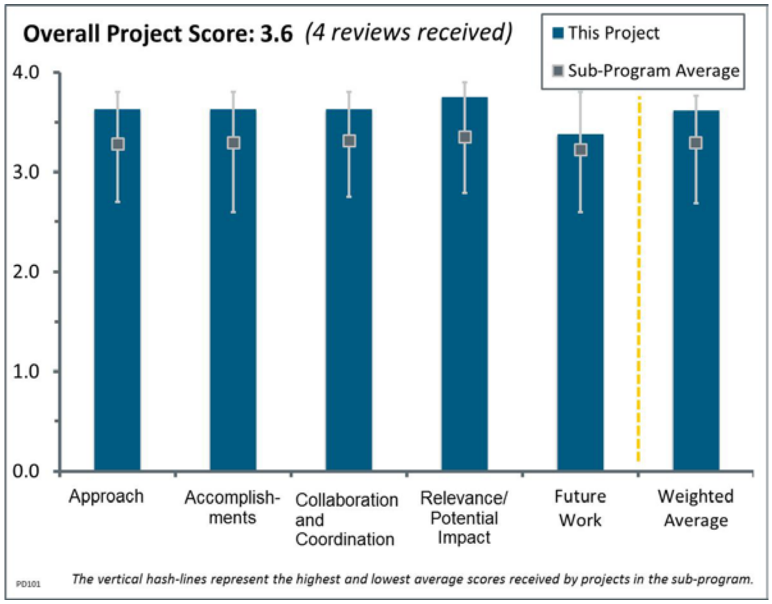
- Because the cost of the hydrogen system is so dependent on the cost of the heliostat field and solar tower, the project should add a task to determine the heliostat cost reductions needed to approach the $3.13/kg to $4.55/kg hydrogen costs quoted in this presentation. Also, the project needs to estimate the roadblocks to achieving the very low price for the heliostat field and the likelihood that the solar thermal developers will overcome those roadblocks.
- Stack operation of the SDE must be demonstrated (it is recognized that this will require additional funding).
- This project should be terminated.

Project # PD-101: Cryogenically Flexible, Low-Permeability Hydrogen Delivery Hose

Jennifer Lalli; Nanosonic

Brief Summary of Project:

The objectives of this project are to (1) develop a flexible dispensing hose to enable hydrogen delivery at <$2 per gasoline gallon equivalent; (2) demonstrate reliability at -50°C and 875 bar for H70 service; and (3) optimize ruggedness, cost, and safety for 70 fills per day and for more than two years.



Question 1: Approach to performing the work

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

- This project is well focused on program targets with well-defined go/no-go tests. The team is very focused on achieving the technical milestones needed to make this product successful. For example, the end connectors proved to be a significant challenge that, if not solved, would have been a showstopper. The project focused its attention on solving this problem and successfully did so. This is a well-thought-out, well-executed project. The team members have chosen their partners well to complement the overall team.
- The project has an excellent approach to designing a high-pressure, cryogenic hose based on a thorough understanding of the polymer chemistry required to develop a polymer to operate effectively in this regime. Both chemical and mechanical properties are understood and effectively modified to meet the barriers.
- The approach is unique. The use of nonmetal reinforcement materials for the expected pressures is novel. The comments previously supplied through the technical teams appear to have been addressed.
- The project has done well integrating suggestions from the U.S. Department of Energy and United States Council for Automotive Research Hydrogen Delivery Technical Team.

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

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

- The team has made excellent progress. This is an exciting technology about halfway through its development cycle. The team has all the appropriate metrics in sight, and it is solving critical problems. The current material appears to have the temperature range, predicted pressure range, tolerance to solvents and impurities, abrasion resistance, and minimal to zero outgassing. This looks pretty good.
- The accomplishments to date are interesting. Offgassing, leaching, and particulate formation may need to be addressed. The National Renewable Energy Laboratory (NREL), Los Alamos National Laboratory (LANL), University of Hawaii, and University of Connecticut are currently set up to test the effects of these compounds on polymer electrolyte membrane (PEM) fuel cells.
- This is a Small Business Innovation Research (SBIR) Phase II project that has made tremendous progress in developing a non-volatile, low-Tg polymer that will survive cryogenic and high-pressure service. The inability to effectively crimp the metallic connectors could be a showstopper for this material; however, the ceramic bonding agent is a creative idea and could hold promise.

- In regard to the progress in solvent resistance (slide 9), it is not clear whether Nanosonic investigated what companies owning and maintaining hydrogen stations (e.g., bus, passenger car, forklift fueling) typically use for cleaners and solvents during and after maintenance or after modifications in systems before hydrogen enters the hose for dispensing (this should be considered in addition to Canadian Standards Association [CSA] Group directions, which may not always be followed). Taking crimp manufacturing/application of the hose in-house was a strong decision, especially in combination with finding innovative ways to adhere/apply crimp to the hose. When doing the projected cost and cost savings comparisons, it is unclear whether Nanosonic considered that the German competitor may have included a significant margin on this product that results in the current pricing in U.S. and German markets. This can be expected to change when more competitors enter the market. Otherwise, the project has promising cost savings.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration/coordination is spot-on for this project.
- The company has done a great job collaborating and coordinating with different entities, such as CSA Group, NREL, New England Wire, Lillbacka, and others. It might also be good to start coordinating with the California Fuel Cell Partnership because California is leading the way in station build-out.
- The current collaboration and coordination are impressive. Working with a hydraulic hose supplier might help with hose end connection design selection. The hydraulic hose supplier would have the same problem and same pressures (i.e., above 300 psi) but different fluids.
- It is not clear whether it is realistic to account for complete county contribution at amounts ($1.1 million and $7.5 million) stated toward a DOE hose project. The New England Wire company is a good collaborator in case the project has to hand off manufacturing hoses instead of doing it in-house. It is good that the project is thinking with the future in mind.

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

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

- There remains a serious gap for the safe, cost-effective deployment of hydrogen fueling station (HFS) hoses. This project is targeted to fill that gap. This makes it spot-on for relevance and, when solved, will give the United States a hose manufacturer in this market, which will have a huge impact.
- This activity is highly relevant to the hydrogen infrastructure and has the potential to make a major impact for this effort.
- With comparison to other 70 MPa hose manufacturers in mind, this project has the potential to add a competitive U.S. manufactured product to the market—a much needed (currently missing) capability.
- While a flexible hydrogen delivery hose is a necessary component, it is not a critical component because there are composite delivery hoses that are used in high-pressure hydrogen service today. However, this particular project could show the potential to lower the cost of the hose component and could extend the service life, which could be impactful.

Question 5: Proposed future work

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

- The future work is perfect to move this project along and demonstrate success on all remaining technical milestones. The predictions look very encouraging now. The systems need to be validated by measurements. The proposed future work aligns well for this need.
- The future work addresses the problems, but resolving the issue with crimping connectors is the key issue for this project at this time.

- Future work has a good focus on hose durability and quality. It is not clear how 55 gal and 200 gal resin reactors fit into production scale-up considerations. It is not clear what is "standard" in the industry for manufacturing resin for hoses or how many meters of hose can be manufactured from one batch in either one of the reactors.
- The proposed future work is a start; however, it appears to be incomplete. First, the project team appears to be the first user of the CSA Group document, a document that needs to be validated. Second, the hose end fitting issue will be a challenge. The effort should not be underestimated. Finally, the hose material compatibility with hydrogen and PEM fuel cells may also be a challenge.

Project strengths:

- The approach and materials used are promising. The initial lessons learned and the way they were applied to the development work are excellent.
- The project strengths are the approach and the need for reliable fueling hoses for both the hydrogen and compressed natural gas vehicle industry.
- This is an exciting technology posed to enter this challenging market. When successful, this technology will provide a U.S. hose technology to compete with international manufacturers. The technology looks very good and will satisfy the technical specifications.
- Project strengths include the understanding of polymer chemistry and ability to tailor chemistry.

Project weaknesses:

- Application of the crimp-on hose is a project weakness.
- The project weaknesses are the apparent lack of recognition of all of the challenges that the project will face. However, the reviewer is confident that the challenges will be successfully met; they are not insurmountable.
- Unfamiliarity with the hydrogen delivery and the safety, codes and standards (SCS) space is a project weakness. The project team should increase its partnership with NREL SCS to help address any discrepancies with the operational characteristics of the station.

Recommendations for additions/deletions to project scope:

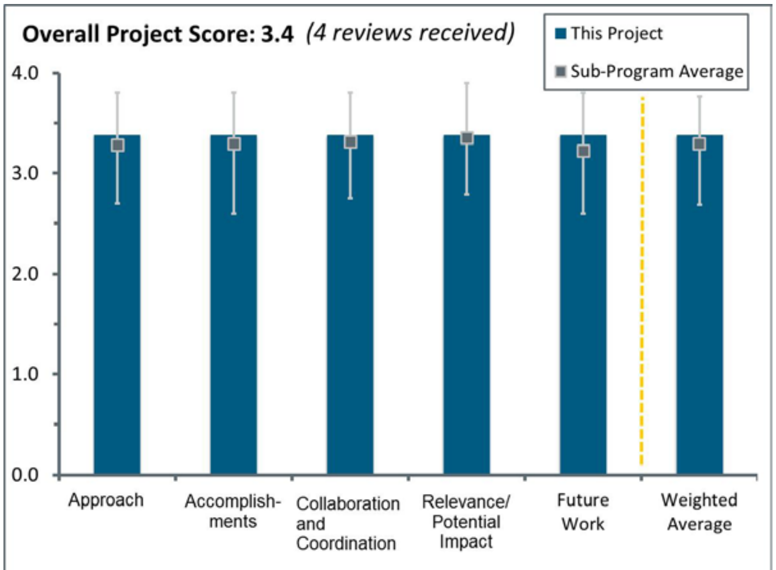
- This project should remain sufficiently well-funded to reach the goals.
- The team should consider which one of the researched materials may be easier and cheaper to manufacture (but is distinct, say, in color) in case Nanosonic wants to supply the return hose from the nozzle to the hose breakaway as a complementary product (although it is unclear what the cost of that hose is). It seems that this secondary hose does not need to meet the same qualifications/requirements, as it is not exposed to same pressures and temperatures (and will never be because it is used for venting residual hydrogen between the nozzle and the vehicle receptacle when the fueling event is completed), but it may help with revenue generation. The project should consider what future accelerated testing may look like for these hoses, using the knowledge of materials used and lessons learned from discarded materials based on testing.
- The proposed future work is a start; however, it appears to be incomplete.
    - First, the CSA Group document the team is following was not written by the hose industry, nor has an end user tried to use it. Therefore, it might not include all of the requirements. Additionally, the test methods in the documents may not be applicable or comprehensive. Providing judgment and feedback to the standards development organization (CSA Group and International Organization for Standardization) would be prudent. Using the document as a guideline at this point in time is suggested.
    - The hose end fitting issue will be a challenge; the effort should not be underestimated. Leveraging the hydraulic hose manufacturers for guidance might be worth the effort. Swagelok sells hydraulic hose assemblies, but it may not make the hoses. Parker does both. Other manufacturers that might help are Aeroquip, Teleflex, Titeflex, and Crane Resistoflex. There certainly are others. Resistoflex is in Marion, North Carolina. Teleflex and Titeflex are in the Connecticut River Valley.

- Hose material compatibility with hydrogen and PEM fuel cells may also be a challenge. The SAE J2719 standard addresses only likely contaminants caused by the formation and processing of the hydrogen. The PEM industry has yet to evaluate every compound that might adversely affect the highly dispersed and highly reactive catalysts in use, for the obvious reason that it would be prohibitively expensive. For the perspective of this project, hose offgassing, leaching, and particulate formation may need to be addressed. NREL, LANL, the University of Hawaii, and the University of Connecticut are currently set up to test the effects of these compounds on PEM fuel cells.

Project # PD-102: Analysis of Advanced Hydrogen Production Pathways

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

The objectives of this project are to (1) analyze hydrogen production and delivery (P&D) pathways to determine economical, environmentally benign, and societally feasible paths for the P&D of hydrogen fuel for fuel cell electric vehicles; (2) identify key bottlenecks to the success of these pathways, primary cost drivers, and remaining research and development (R&D) challenges; (3) assess technical progress, benefits and limitations, levelized hydrogen costs, and potential to achieve U.S. Department of Energy (DOE) P&D cost goals of <$4 per gasoline gallon equivalent (gge) by 2020; (4) provide analyses that assist DOE in setting research priorities; and (5) apply the Hydrogen Analysis (H2A) Production Model as the primary tool for projection of levelized hydrogen costs and cost sensitivities.

Question 1: Approach to performing the work

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

- Strategic Analysis, Inc. (SA) utilizes a well-developed, rational approach to cost analysis. SA uses a proven methodology for acquiring and processing information that forms the basis for cost estimates.
- The project has a well-established approach that includes gathering technical and economic data from appropriate industry and/or R&D representatives and using the submitted information as input in process and cost models, including H2A, to predict hydrogen cost, cost drivers, and sensitivities. This approach is well integrated with other modeling and analysis efforts in P&D and across the Fuel Cell Technologies Office (FCTO). Results are reviewed and vetted by the participating industry/R&D representatives. This approach would be difficult to improve significantly given the low technology readiness level of most of the production pathways under investigation and the modest funding for this effort.
- The project is well designed; however, a literature review could have been applied to complement the questionnaires/feedback from contributing partners. Additionally, questionnaires could have been sent to other institutions active in research in this area.
- The project addresses a couple of cases that will feed into H2A. It is well known that solid oxide electrolysis cells (SOECs) and bio-fermentation are currently very expensive technologies that are unable to compete with steam methane reforming. Given that, the project documents that these cases are cost-prohibitive. It is understandable that the H2A assumptions of high volume had to be followed, but currently there is very little information to accurately predict the cost of these pathways at high volume. It would be more useful to understand first where the industry is now at low-volume levels.

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

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

- The project team has made very good progress toward its goals by completing analysis of two alternative renewable energy hydrogen production pathways. The SOEC analysis complements the polymer electrolyte membrane (PEM) electrolysis study completed last year and will be a valuable resource for researchers and DOE. Similarly, the bio-fermentation study will be useful to DOE for portfolio planning. Although this is perhaps outside the scope of the current project, trade-off studies of various options in the electrolysis and biomass conversion/gasification groups would be of interest and of use to Hydrogen Production and Delivery sub-program planning.

- The project aims to facilitate the identification of R&D topics that DOE mayfund in the future. It is a well-timed action for optimizing the allocation of R&D funds.
- These two cases appear to have been done well and provide a valuable addition to the H2A suite.
- The project is on target to achieve completion within the time specified by the principal investigators, but it is inadequate to model for the n^{th} plant as opposed to using actual numbers for current technologies. It is unclear what the definition of "demonstrated advances" is in slide 6. SOECs and bio-fermentation technologies have not been deployed at large scale (50,000 kg/day). It is not clear why the team used today's cost at scale instead of modeling today's cost at low production rates and then modeling a ramp up.

Question 3: Collaboration and coordination with other institutions

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

- The project team members work well together and have been successful in identifying and enlisting industry and technology experts to participate in and inform their studies. This year's efforts addressing SOECs and bio-fermentation could be further enhanced by interactions with other DOE offices (e.g., the Office of Nuclear Energy and Bioenergy Technologies Office) to determine synergies that may favor these technologies. Examples might include an analysis of feasibility of waste heat/electricity for SOECs by co-locating them next to concentrated solar power or nuclear energy plants and an assessment of possible opportunities, geographic and otherwise, for less expensive feedstock and for R&D to enhance both concentration and hydrogen molar yield.
- SA has done a good job of working with industry and researchers to obtain the data needed for this work.
- The project has a wide network of collaborating institutions, but given the scope/structure of the project, sending contacts and questionnaires to additional institutions could have been beneficial.
- Partners and collaborators seem adequate to understand SOEC and bio-fermentation cases, although it is not clear how these partners judged the future status of the technology, given that the results do not present any variability.

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

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

- By providing analysis on cost, key barriers, and drivers for renewable hydrogen production pathways, this project provides information that allows the DOE to plan future R&D, track progress of R&D, and compare progress and the potential of various pathways. The project is critical to achieving the goal of <$4 per gge hydrogen (dispensed and untaxed) by 2020. The analysis provided is critical for the success of the production portfolio.
- The project provides support in planning future R&D topics.
- This work shows the potential for these new pathways.
- It is well known that these pathways are expensive. They will become relevant only after a major breakthrough. Furthermore, it would be useful to have current cost numbers instead of projected numbers for high hydrogen volumes.

Question 5: Proposed future work

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

- The proposed future work presents reasonable next steps for this project; however, the project team will be directed by DOE as to which pathways to investigate next. Timely production and posting of H2A cases are important for the R&D communities to benefit from the analysis.
- In terms of future pathways to be analyzed, biomass gasification and pyrolysis could also be considered.
- The future cases have merit but will be difficult because of the early stages of development.
- It is adequate to integrate the results of these cases into H2A and add new, advanced hydrogen production cases. That work needs to be done and updated with certain frequency. However, the pathways selected are very far from being commercial, and it is unclear how this information will be used. It would be helpful to ask end users to rate the usefulness of the information and which pathways are more interesting.

Project strengths:

- SA uses a strong methodology with a proven process to render consistent and reliable projections of costs.
- The project has an experienced team providing consistent analysis across the FCTO programs.
- Project strengths include the use of both the H2A modeling tool and in-house process and cost models.

Project weaknesses:

- The production pathway cost targets are quickly becoming outdated (fiscal year 2015 is almost over). Updates to the H2A tool may also be needed but should happen if/when the office cost goals are reconsidered.
- Collection of information could have been done through literature review as well as through questionnaires.

Recommendations for additions/deletions to project scope:

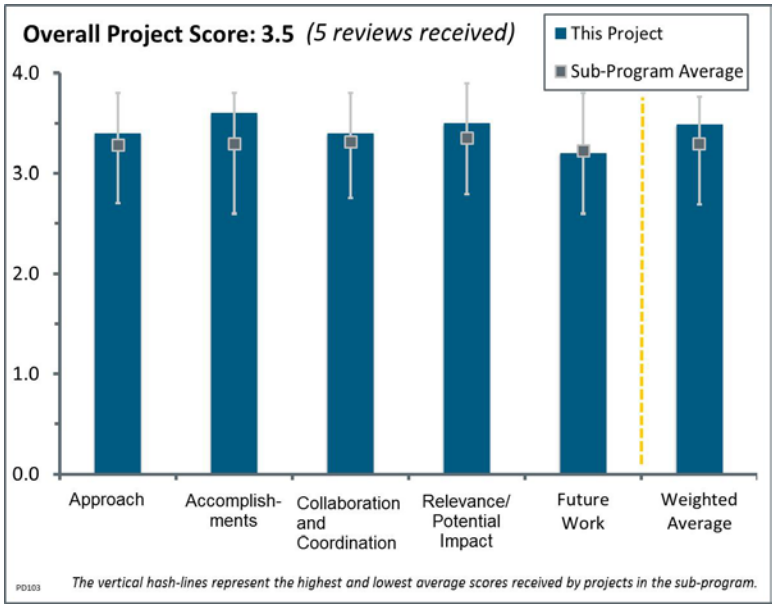
- SA should make sure that the issues around future bio-fermentation are clearly stated—specifically the fact that increasing stover concentration lowers hydrogen yield.
- An analysis of the costs and barriers for distributed or semi-central production of hydrogen via biomass conversion (e.g., wastewater treatment), possibly in tandem with microbial electrolysis cells or microbial reverse electrolysis cells, would be of interest. It may not be currently feasible because of lack of available input from researchers, industry, or municipal wastewater treatment centers, but it should be considered for future attention. A comparison of relative advantages of biomass gasification and biomass conversion processes for central production would also be of interest. In addition, the production pathway targets will need to be updated soon. While this is currently outside the scope of this project, it might be helpful if the project scope were expanded to include development of an outline of needed updates and additions to the pathway targets/cases.
- The reviewer had three recommendations:
    - It would have been useful if under "Current Case," costs were provided for both today's limited production capacity and under the theoretical mass production capacity, in case the examined technologies were commercially available today.
    - Solid oxide electrolysis, being a high-temperature process, would suffer from frequent shutdowns, starts, and general dynamic operation of the unit. This, however, is highly likely to be the case in the long term for electrolyzers when trying to operate with low-cost electricity (during times of excess renewable energy) or when operated to provide ancillary grid services. It would be useful if this could be factored into the electricity cost to make a fairer comparison with PEM or Alkaline electrolyzers.
    - In terms of future pathways to be analyzed, biomass gasification and pyrolysis could also be considered.

Project # PD-103: High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis

Hui Xu; Giner, Inc.

Brief Summary of Project:

The objectives of this project are to (1) develop advanced, low-platinum group metal (PGM) loading catalysts for high-performance, high-efficiency, and long-lifetime proton exchange membrane water electrolysis using three different catalysis approaches and (2) evaluate the impact of newly developed catalysts on proton exchange membrane electrolyzer efficiency and cost.



Question 1: Approach to performing the work

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

- The project has an excellent approach to reducing precious metal loading while maintaining the performance and durability of the electrolyzer.
- The project objective is the development of low-platinum-group-metal (PGM) catalysts (e.g., $Ir/W_xTi_{1-x}O_2$) for PEM electrolysis. Various catalyst compositions, supports, and nanostructures have been evaluated for activity and durability.
- The approach is excellent; it effectively contributes to overcoming most barriers. However, a stronger focus is suggested on gaining a molecular-level understanding with respect to the catalyst surface structure reconstruction during operational conditions.
- The project is cogently constructed with a very reasonable and straightforward approach to the experimental demonstration of three avenues to Ir loading reduction. It appears that the durability testing of the Ir nanowire approach was not conducted. It is not clear why.

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

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

- The data showing that $Ir/W_xTi_{1-x}O_2$ achieves three times higher activity than baseline Ir black (at 2.0 V) is an exciting result. A future objective should be directed toward a molecular-level understanding of this seemingly incredible result. The simultaneous stability probably would play into the molecular-level understanding. The bimetallic (IrCo and IrNi) nanowires should be studied as model systems in controlled catalytic characterization tests to understand and correlate the surface structure to performance. Because Ir is a (weak) Mossbauer element, one could conceive of an operando-type experimental campaign. Finally, the level of accomplishment, as demonstrated here, is outstanding. There is close, appropriate collaboration with other institutions, the partners appear to be full participants, and the overall strategy is very well coordinated.
- Accomplishments included preparation and testing of $Ir/W_xTi_{1-x}O_2$ catalysts with performance and durability evaluation using rotating disk electrode (RDE) and stack testing. Ir mass activity was demonstrated to increase with low loading. Stack performance with a 10x reduction in PGM loading was shown to be comparable to the standard loading case. Durability was demonstrated with a 1,000-hour test. Development and testing of nanostructured thin film (NSTF) catalyst substrates (conducted by 3M) were

completed. Performance comparable to baseline was demonstrated with 1/8 PGM loading. Durability of 1,000 hours was also demonstrated with the NSTF catalyst configuration. Development and testing of Ir/metal nanowires (conducted by the National Renewable Energy Laboratory [NREL]) were completed. Performance was shown to be about 10 times better than Ir nanoparticles.

- The project has demonstrated impressive reductions in precious metal loading (from 2–3 mg/cm^2 down to 0.25 mg/cm^2) with a minimal drop in performance, eventually leading to reduced capital cost of electrolyzers and thus hydrogen.
- Excellent progress has been achieved in fabricating and testing three classes of Ir-based catalyst. The experimental results are meaningful and appropriate.

Question 3: Collaboration and coordination with other institutions

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

- There appear to be good collaboration and division of labor among the three main team members (NREL, 3M, and Giner), and there is appropriate outside assistance for particle characterization.
- The collaboration is excellent.
- Collaborators included NREL (working on Ir/metal nanowire development as a subcontract), 3M (working on Ir NSTF catalyst development as a subcontractor), Oak Ridge National Laboratory (for the catalyst and membrane electrode assembly structure), and University of Massachusetts Lowell (for the catalyst composition and structure analysis).
- There is close collaboration, but it is limited to project partners.

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

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

- The project greatly supports the goal of reducing the cost of electrolytic hydrogen by reducing the capital cost of electrolyzers and, at the same time, reducing the use of precious materials.
- Low-cost, low-PGM high-efficiency catalysts are needed for achievement of low electrolyzer system cost. Nanostructured PGM catalysts on non-precious supports can achieve high performance with low PGM loading. This work could have a significant near-term impact on PEM electrolysis performance and cost.
- The project aligns well with the DOE Hydrogen and Fuel Cells 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 impact of reducing Ir loading by 10x is obviously beneficial, but it needs to be quantified. A cost analysis (at least a back-of-the-envelope calculation) should be conducted to suggest an Ir loading target at which point further reductions are of inconsequential benefit.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Future work on Ir nanowires appears to have been dropped in favor of focusing efforts on the other two approaches. This seems reasonable.
- Future work is well planned out.
- Future proposed work includes further study of the $Ir/W_xTi_{1-x}O_2$catalyst and selection of the best catalyst for the Giner sub-megawatt stack.
- The proposed future work does not seem to be directed at addressing a specific hypothesis. There needs to be a better, more focused effort to gain a molecular-level understanding of the surface catalysis process. This can be done by appropriately selecting and testing model catalysis systems under in situ or operando conditions.

Project strengths:

- The project appears to focus very well on the demonstration of the attributes most needing experimental assessment.
- Synthesis and testing of several advanced Ir-PGM catalysts has been completed with very promising results.
- The project has the right consortium to perform this type of work and eventually implement it in commercial products.
- Project strengths include the collaborations and accomplishments.
- The project has achieved the stated milestones.

Project weaknesses:

- The milestones might have been originally written to be lax.
- The graph on slide 19 for the Ir NSTF approach shows a polarization curve that deviates from the shape of the other catalyst curves. This should be explained. The error bars on slide 19 are considerable and obscure comparisons between the catalysts. While perhaps this amount of potential error is unavoidable, consideration should be given to how this might be improved.
- A project weakness is the lack of an approach to gain a fundamental, molecular-level understanding of the catalyst surface and its effect on performance.

Recommendations for additions/deletions to project scope:

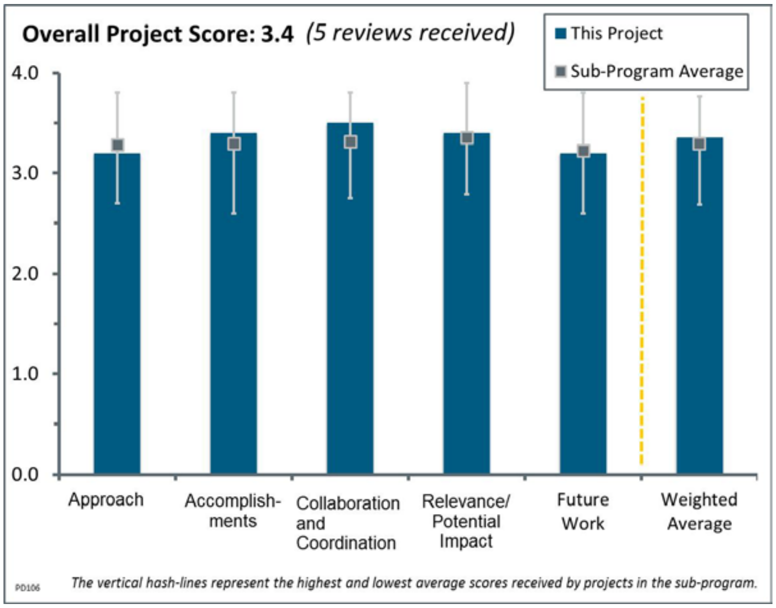
- The current project is complete. The proposed future work shown in the presentation represents a logical extension of this project.
- A basic cost analysis should be added to quantify the benefits of reduced loading.

Project # PD-106: Reference Station Design

Daniel Terlip; National Renewable Energy Laboratory

Brief Summary of Project:

The overall objective of this project is to speed the acceptance of near-term hydrogen infrastructure build-out by exploring the advantages and disadvantages of various station designs and proposing near-term optima. For fiscal year 2015, the project will (1) provide a detailed view of how these stations fit in greenfield and existing sites in relation to the National Fire Protection Agency (NFPA) 2 standard; (2) help station developers quickly evaluate the suitability of their sites for a particular station type and capacity; and (3) provide station developers and local authorities with a complete picture of the devices, components, and associated costs that make up a station.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- This approach appeared to be very thorough, systematic, and appropriate for this type of work. The results speak for themselves—they are excellent.
- The project team conducted a thorough review of current hydrogen fueling station technology.
- The presentation was informative, and the speaker was very clear and subjective in answering the questions.
- It is not clear whether relevant international efforts have been accounted for, e.g., definitions for standard capacities and performance that are used by H2 Mobility in Germany.
- It appears that most factors were considered in making the approach lead to relevant outcomes. However, it is not clear where and how municipalities and authorities having jurisdiction (AHJs) are involved in providing feedback on the work done (feedback loops were not included in the approach)—this is important, as they are identified as targeted beneficiaries of this effort.

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

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

- The project is 100% complete. The team did a good job. The direct and indirect accomplishments for this work will prove to be very valuable to hydrogen fuel station (HFS) rollout—but it will also be very valuable to the quantitative risk assessment (QRA) and code development organization/standards development organization (CDO)(SDO) community. Having a vetted “standard” design provides the ability to set examples of how to determine hazards, causes, and consequences. This was not articulated during the presentation but is an example of an ancillary accomplishment and/or value added from this work.
- This review of current technology was well conceived and well executed. The timeline was very short, and the team accomplished the goals of the project very quickly.
- The task provides a valuable set of information to support early deployment of hydrogen refueling stations (HRSs).

- The presentation provided leads, which could be a deliverable.
- Based on the reasons given for the values on slide 8, even for the near term, this effort appears to lean toward the low-capacity stations. It is acceptable that some of the participants think that having many small stations providing fuel to cover a larger area is a good idea and that the project team thought it was beneficial to include 50 kg/day stations. However, based on results and given the equipment selection assumed, it is questionable if that was a good choice. The estimated costs of hydrogen at $40–$80/kg to reach a return on investment for the station sound unrealistic for any investor, but possibly that was the reason for including it.

Question 3: Collaboration and coordination with other institutions

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

- This is an excellent example of how researchers from competitive national laboratories have come together to build an extremely effective team.
- There was good participation in the project. There were many interested stakeholders.
- Appropriate collaborations and coordination were part of this effort.
- Industry is involved via H2USA; it is not clear whether that includes sufficient component suppliers.
- It is not clear who the collaborators are from the H_2USA HFS Working Group.

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

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

- The relevance and impact are greater than originally intended. They are excellent. The benefits go beyond those articulated during this presentation; the work will be adapted in the international community as ISO / TC 197 19880-1 gets developed and published.
- The project aligns well with the DOE Hydrogen and Fuel Cells Program and DOE research, development, and demonstration (RD&D) objectives and has been a very important step in identifying the economic challenges to station deployments. The information developed by this project is critical to advancing progress toward DOE RD&D goals and objectives.
- The project increased knowledge about HRS design and cost. Dissemination will be important for further deployment.
- The project is very relevant to our future energy and environment.
- It is not clear if the project team has received any feedback about how likely it is that station implementers will actually follow these reference station designs. Because of the focus on same-size stations (100–300 kg/day capacity), the project appears to have relatively limited relevance for near-term station implementation efforts currently underway. Inclusion of larger-sized stations (500–700 kg/day) could have put outcomes in better perspective, which would be beneficial for the considerations of those willing to make a larger long-term investment.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is a natural extension of this current work—to extend beyond on-site delivery and to keep these numbers and this analysis up to date with the state of the art in the technology.
- The team seems to be open to further work, including modeling mixed-use stations and on-site production.
- The project has ended, but proposed topics for future work are relevant.
- In addition to the proposed future work in the presentation, it would be good to see reference station designs for material handling applications, medium duty vehicles, and heavy duty vehicles, as these are likely to support considerations of captive, private, and transit fleet owners—where economic considerations play a more significant role for revenue fleet adoption.

Project strengths:

- The project is an excellent and thorough effort.
- Project strengths include the team's good attempt at using a larger group of stakeholders to build an understanding of available technologies and components in the market.
- A broad database of station components and designs was created.
- The team leveraged the significant capabilities and experience of the project team very well. The team did good work to define the station size categories, which has not been done before for the U.S. market. However, the definition of station size and capacity is not complete.
- The project is adequate and will have potential for further improvements.

Project weaknesses:

- Not all station types have been modeled, and this gap includes the on-site generation options. While the team made a good effort to define station size (50, 100, 200, and 300 kg/day), it did not quantify the dispensing capacity (kilogram per hour) and sequential fill capacity for each station size.
- A hands-on demonstration would have been very helpful.
- It is important to focus on station design in the early deployment phase (low utilization) rather than recalculate fuel cell electric vehicle and HRS ramp-up.
- It is interesting that the identified areas under remaining barriers/challenges appear exactly like those that have been identified and are currently topics of DOE-supported projects. The outcomes appear to define not specific reference stations for small, medium, and large station categories but rather stations that are nearly identical in size to the stations currently being rolled out in California (except for the 50 kg/day station identified). Focus is needed on small capacity stations, which have been proven to be challenging to make work economically (which the added cost per kilogram of hydrogen dispensed clearly indicates).

Recommendations for additions/deletions to project scope:

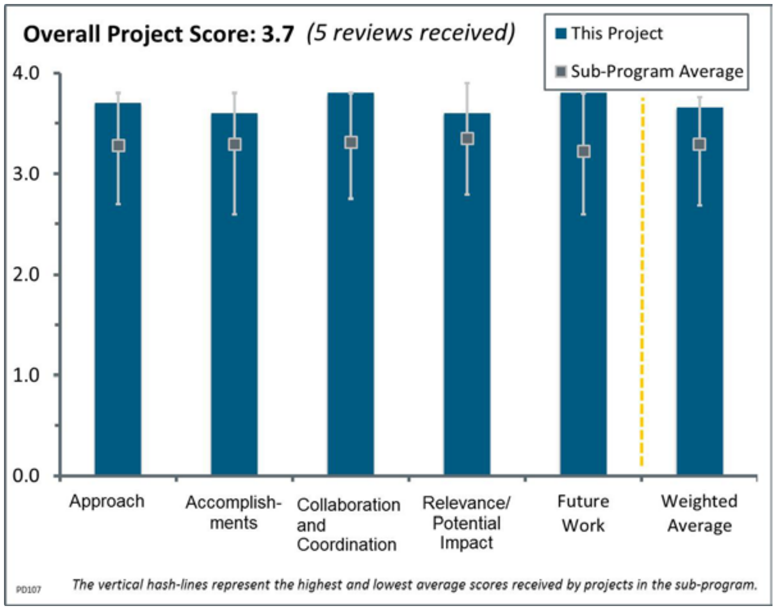
- The continuation of work as proposed should be funded.
- It would be great if the station review team could provide some further clarity to the 50 kg/day station size. It is not clear how many back-to-back fills are really needed for a small station.
- The team should invite experts from national and international SDOs, such as ISO/TC197.
- Analysis should include on-site production (especially electrolysis). The effect of low utilization on the reliability of stations should be assessed, considering different design, economics, etc.
- It is recommended that the team not show the West Los Angeles station picture anymore, as that particular station design is unrealistic from an economic perspective because of the highway overpass earthquake-grade canopy structure (which is extremely expensive). There is no point in including the California Fuel Cell Partnership Roadmap numbers; the California Air Resources Board Assembly Bill 8 report numbers are now the reference point. In addition to the project scope, consider larger capacity stations because of the delay in rollout of stations. If a station were funded today, it could be operational two years from now, when larger capacity may be needed in focus cluster regions.

Project # PD-107: Hydrogen Fueling Station Pre-Cooling Analysis

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to evaluate theoretical pre-cooling requirements at hydrogen fueling stations (HFSs), collaborate to acquire information on refueling operation and review results, examine current pre-cooling equipment design and cost, identify major drivers for pre-cooling cost and energy consumption, analyze trade-offs between different design concepts, and vet analysis results and findings.



Question 1: Approach to performing the work

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

- The project is almost done—only fiscal year (FY) 2015 work remains. The team needs to understand pre-cooling costs versus various cooling technologies and determine whether the costs can be reduced (i.e., increase the coefficient of performance [COP]/efficiency). The project should start with fundamental thermodynamics, consistent with the SAE International J2601 protocol. The thermodynamics of these processes are very well understood and readily modeled. This principal investigator is well suited to perform these analyses, and that is demonstrated in this work. This really is a very straightforward thermodynamic analysis of cooling systems. Funding was $100,000, which is appropriate for this study. The labor spent is in line with the funds expended (which is not a criticism of the value of this analysis). With that said, the outcome from this work is enlightening regarding these systems, including the impact on cost and operation of the systems to achieve the required fill characteristics. This work is very timely because station deployment is in its early stages right now. This work really needs to be incorporated in the station design activity of the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project.
- Hydrogen fueling stations are expensive compared to gasoline stations, partly because some of the components in an HFS must be custom designed and built. Pre-cooling equipment and heat exchangers can contribute significantly to the station's capital expenditures, particularly when the station is over-designed. This analysis can help address this issue.
- The approach of this analysis was excellent: developing the pre-cooling energy in both the continuous and on-demand modes of operation. It was helpful to provide these different modes in order to quantify the significant range in energy consumption that could occur.
- The analysis addresses a highly relevant topic for HFS deployment. Hydrogen cooling is relevant in terms of cost, and it has an effect on station performance, especially at low utilization.
- The approach indicates an understanding of the issue at hand and what aspects should be considered to lead to valuable results; in addition, the approach was well explained and visualized.

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

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

- The project is 100% complete—the team did a good job. This really is a very straightforward application of classical thermodynamics. The labor needed to execute this is in line with the funds expended. From a first

principles perspective, the results simply describe the classical thermodynamic results. However, the comparison of different celling schemes applicable to HFS filling at this point in the HFS deployment is extremely valuable, particularly for those who need to evaluate HFS designs. Any HFS manufacturer would do this type of analysis to optimize its own system; however, this analysis does provide people who need to evaluate HFS system performance some indications into what and how these systems can differ.
- The project was effective in providing useful conclusions and sensitivity factors, such as the heat exchanger thermal mass, back-to-back fills, station usage, and operation modes.
- The objectives of the project have been met in the sense that the theoretical pre-cooling energy requirements have been identified, which has helped in developing a method for sizing the pre-cooling equipment and heat exchanger.
- The project provides very relevant analysis.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- It appears the project had the right mix of industry experts to coordinate the assumptions and analysis.
- International experience was taken into account.
- The right stakeholders have been involved.
- The collaborators for this project are appropriate.

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

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

- This project is highly relevant to the practical implementation of stations. It is important to know about the factors that can change and influence pre-cooling energy usage because this is a critical factor in 700 bar fills.
- The project shows results that are highly relevant to optimization of HFSs, especially in the early deployment phase.
- There is a significant benefit in terms of the body of knowledge about the impact of pre-cooling hydrogen dispensed per SAE J2601.
- This analysis is very timely and needed to help the community evaluate HFS systems for performance, maintenance, and costs (capital and operating expenditures).
- It is unclear whether equipment manufacturers will make use of the resulting work, but it will be useful to incorporate the results into the Hydrogen Analysis (H2A) Refueling Station Analysis Model (HRSAM).

Question 5: Proposed future work

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

- It is necessary to continue this work to identify cost-reduction potentials and new designs or components to increase station performance (e.g., short start-up times in cases of low utilization).
- The biggest value added by this work is to make sure it is embedded into the reference station design activities to make that activity more robust.
- The work is progressing well, and the proposed future work seems appropriate to make the best use of the results.
- There are excellent suggestions based on interactions with project partners and stakeholders.
- The future work seems to involve appropriate next steps. It was interesting that some of these items (e.g., the MC Default Fill) were being covered in another project, SA-045. This connection should be noted in these slides in the future.

Project strengths:

- Detailed impacts of pre-cooling are not well understood (aside from a 10% cost impact), and this project provides industry with insight into this topic.
- Strengths include the project team's technical knowledge and modeling capabilities, as well as its stakeholder engagement.
- The project is highly useful for the practical assessment of pre-cooling for 700 bar stations.
- This is an excellent, thorough effort.
- The analysis builds on international experience.

Project weaknesses:

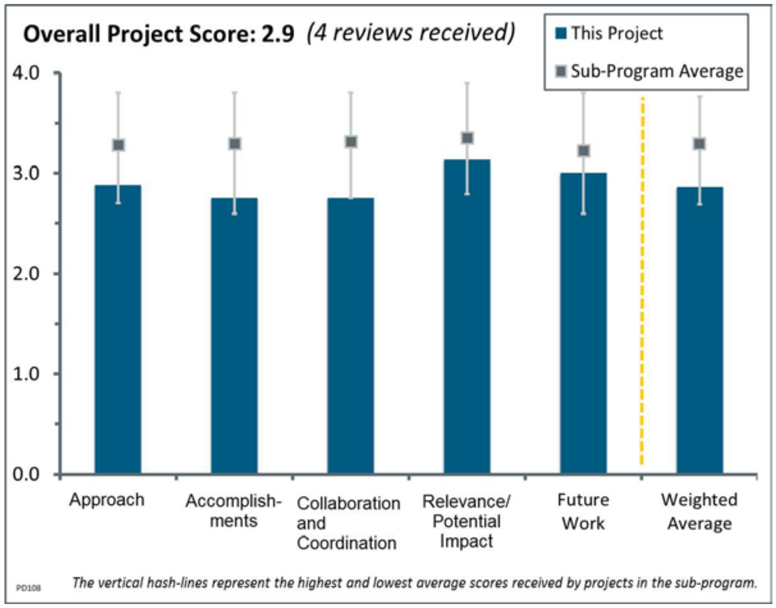
- The project does not have any weaknesses to report. Additional field data would be useful.

Recommendations for additions/deletions to project scope:

- Three additions are recommended. The project should:
  - Consider the impact of using the MC Formula on pre-cooling and the impact on hydrogen cost and power/energy needs: -33°C in 30 seconds is not necessarily needed when using a dynamic fueling process instead of a table-based one.
  - Consider the impact/benefit of lower-than-ambient-temperature hydrogen gas from buffer storage to chiller. Underground storage may result in more stable and lower gas temperature, resulting in additional economic benefits in terms of the cost of hydrogen dispensed.
  - Consider the impact of placing dispensers farther away (e.g., 50 feet versus 100 feet) from station equipment on pre-cooling cost and power needs.
- The project should merge the results with those of the other project, SA-045. As an addition, the analysis could evaluate the pre-cooling needed in different regions of the United States based on ambient temperature distributions to provide strategy guidance regarding the pre-cooling temperature and energy usage.
- Continuation is recommended—especially efforts to identify alternative pre-cooling options.
- The continuation of the work as proposed should be funded.

Project # PD-108: Hydrogen Compression Application of the Linear Motor Reciprocating Compressor

Eugene Broerman; Southwest Research Institute



Brief Summary of Project:

The objectives of this project are to (1) improve isentropic efficiency of a compressor above 95% by minimizing aerodynamic losses, (2) reduce capital costs to half those of conventional reciprocating compressors by minimizing part count, and (3) reduce required maintenance by simplifying the compressor design to eliminate common wear items.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- Initial design and modeling are proceeding well.
- The project goal is to develop a positive displacement compressor. Instead of being driven by a motor and crank shaft, the piston(s) is moved by a series of magnets generating a linear motion (linear piston). This basic concept is not new; linear hardware has been developed for other applications. This development team has extremely aggressive targets (isentropic efficiencies >95%). The path to achieving this is to optimize the fluid dynamics (aerodynamic losses). Actually, the team is attempting to optimize the thermodynamics of the process. This raises a small flag that the team has not got the thermodynamics quite right. Linear pistons have fewer moving parts compared to reciprocating machines; hence, the expectation is that reliability will go up and the cost will go down. This project is just getting started, so if the team is able to solve—or satisfy—the following issues, this could be a good project with a good outcome. These issues are the following:
    - This team needs to perform a detailed first law of thermodynamics analysis on the overall system. It may sound like a good goal to reach an isentropic efficiency >95%, but the property that drives the cost of operation is the overall first law thermal efficiency, not the isentropic efficiency. Clearly, a high first law thermal efficiency will not be achieved with a low isentropic efficiency; however, the reverse is not true. A high isentropic efficiency does not at all guarantee a high first law efficiency. This analysis should yield a figure (table) in which some measure of efficiency is identified (energy required as a function of output pressure and mass flow rate, i.e., KW = f(Mdot, MPa).
    - Linear pistons are controlled by magnets whose field is modulated, resulting in the desired piston movement. The temperature of these magnets needs to be controlled. This is easily done but results in significant heat being rejected from the system. This is a large loss term not at all reflected in the isentropic analysis. A full system thermodynamic balance is critical to determine whether this system will compete with current reciprocating machinery.
    - A much better analysis would be exergy (second law). That analysis will provide information on where in the system one should focus to improve (reduce exergy production) for optimization. This needs to be done before this project proceeds further from this point. Stopping all further work until this system energy balance has been performed is strongly recommended. Only then can one determine whether this technology will indeed yield a more efficient system than exists today.

    - In addition, there is a serious heat transfer issue. The drive piston (the one coupled to the magnetic field) is isolated physically from the "block" of the magnets. This piston has an energy source into it but no mechanism to dissipate energy. To reduce friction, this piston is presumably free-floating (air bearings). Air is a wonderful insulator and, hence, a horrible thermal conductor. The magnetic coupling is an energy source into the piston, but there is no coupling for energy to leave the piston. This system is targeted for continuous operation. The first law states that E(in) – E(out) = rate of storage; this system has E(in) >0 and E(out) = 0, so the rate of storage is >0. This could be a showstopper. This is the second analysis that must be done before this project should go further.
    - Based on this discussion, this category received a 2.5 score. This project could have potential, but these thermodynamic transport questions must be answered.
    - On a different note, the dynamic seal required to seal the compression piston from the high pressure on the piston head (85 MPa) to ambient (0 MPa) also evokes some skepticism. Success with this will be a big challenge. At this early stage in the development, this is not a showstopper—just a concern.
- The approach to the project is sound as presented and provides an appropriate work path to the project end goal. What was not presented was an assessment of where the principal investigator (PI) believes the major costs to be within compressor designs and correlate that assessment to how this specific novel design will, in fact, reduce cost. Essentially, the PI is saying that eliminating crankcases and traditional motors could halve compression costs. Some analysis on this costing is needed to understand the basis. This part was missing. Considering the stroke, force, flow, and the fact that this is a single acting design, correlations seem off for the flow rate described. The correlations seem to be an order of magnitude off (i.e., based on the stroke and force presented, the results should be 1 kg/hour rather than 10 kg/hour).
- The concept of linear pumping is very interesting in terms of system efficiency and space management. That said, the impression given is that project development is being managed on a component-by-component basis rather than as a complete system. The team is encouraged to step back to review the whole system to construct a development plan that encompasses both system development and component development. One system review has to address thermal management of the electric motors, heat of compression, and friction.

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

This project was rated **2.8** for its accomplishments and progress.

- The team has achieved much in the past eight months, but now the team members have to begin performing detailed engineering and challenging their own concepts for success. As progress continues in 2015, the team should collaborate with mentors/organizations that are knowledgeable about electric motor system design, compressor system design, and hydrogen safety. In anticipation of next year's Hydrogen and Fuel Cells Program Annual Merit Review (AMR), it would be good to see more information about the control system required to manage electric power delivery and the dynamics of a high-speed reciprocating pump and its related energy and mass.
- The project is only six months old, but it is progressing on schedule. Refrigeration energy for cooling water (interstage and magnet) should be included in efficiency calculations.
- This project is just starting. So far it is making good progress.
- There are key features missing from this design, including:
    - A distance piece to prevent hydrogen ingress into the magnet area. When asked, the PI provided comments on seals that would prevent this ingress. However, in real-world compressor applications, seal leakage in reciprocating compression equipment is key.
    - A linear actuator current of 600 amps seems extremely high (this is perhaps the biggest challenge). Several points are unclear:
        - The equivalent horsepower associated with this
        - How this compares to current compression technologies
        - Whether it affects the installed cost of the compressor
        - The surface temperatures of the coil housing

   - These temperatures in relation to requirements for hazardous area classifications of the coils

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The list of collaborators appears impressive in terms of individual technology competencies. Over time, the team is encouraged to develop additional collaborators familiar with integrated electric power systems and hydrogen compression. Collaboration on system safety should rise in importance as development progresses.
- At this stage, the project has the right mix of collaborators. Presumably Southwest Research Institute has the expertise to perform the thermodynamic and transport analysis requested as part of this review. If not, then the project team needs to reach out to an institution that does have this type of expertise (Argonne National Laboratory, Sandia National Laboratories, etc.).
- Southwest Research Institute has a good design partner in ACI Services, although partnership with national laboratories with experience in magnet materials good for hydrogen service could have been useful, given that it appears the hydrogen could leak into this area.
- Collaboration appears to be limited to material and component suppliers. The PIs should work with commercial compressor suppliers such as PDC Machines and Mitsubishi Heavy Industries to vet the project designs and assumptions.

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

This project was rated **3.1** for its relevance/potential impact.

- Current compressors are an Achilles heel for hydrogen fueling systems. Improving the operating efficiency, improving the reliability, and reducing costs are critical to the successful commercialization of hydrogen fueling systems and hydrogen technologies in the transportation sector.
- Conceptually, this technology will have relevance if it can be competitive in the areas of compression efficiency, capital management, and physical size. The next two AMR reviews will provide more detail on the project’s success. This is the type of technology that must be funded to determine whether hydrogen compression can be achieved in a manner that is measurably better than conventional systems.
- If the project is successful, this could significantly reduce delivery costs.
- The item preventing a rating of “good” is an in-depth cost analysis showing exactly how this compressor, as presented, would be half the cost of current technologies. Further, additional cost analysis needs to be presented on simplification of design that would lead to reduced maintenance costs (as required by targets in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan [MYRDDP]). As shown, the compressor is still a compressor with common maintenance items.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- There is a good deal of engineering work to perform, so the project’s layout for this work is appropriate. What should be added are (1) temperature data on the coils of the actuator and (2) efforts to review how to have the product approved as a listed hazardous area electrical component. This is critical path work that must be performed for viability in hydrogen refueling stations.
- The future work seems to be fragmented into component development. In addition to that, the team is encouraged to evaluate the integrated system to determine whether certain design work must cross technology boundaries. Also, the team is encouraged to consider and set objectives for the life cycle of the system. A unit designed for a fifteen-year life may have different design features from one designed for three years of life. Uptime performance is another factor that deserves attention.

- This is a new start project. The proposed future work is short two critical components: a system energy balance and an energy transport analysis focused on the temperature time history for the drive piston.
- The PIs should work to quickly determine total energy consumption for the compressor system. Stage 1 should be built and tested to verify performance before any work is begun to construct the second and third stages.

Project strengths:

- Conceptually, this project would be a good way of reducing cost, footprint, noise, and eventually maintenance at hydrogen refueling stations.

Project weaknesses:

- As the project is currently presented, polymer seals are envisioned. In current technology, polymer seals do not have a very high seal life in reciprocating compressor refueling stations, and especially not at the potential surface speeds that have been presented. Sapphire-on-sapphire sealing would present an intriguing opportunity for big sealing technology advancement. The packing design at pressure and speed is concerning. A key omission is the lack of foresight regarding the need to consider that the linear actuator must be an explosion-proof piece of electrical equipment or, at a minimum, to be rated for Class 1 Division 2 Group B hazardous locations. With 600 amps going through the coils at 10 kg/hr and when scaled up to meet the MYRDDP target of 20 kg/hr, the surface temperatures, cooling requirements of the magnets, and power requirement could be enormous and must be considered as future work.
- There are serious concerns about the overall thermal behavior of this system. This project needs to perform a detailed energy balance with a focus on understanding the system's overall energy demand. Also, this team needs to understand the temperature of the drive piston as a function of time. There appear to be energy input terms but no output terms. This system could be configured for continuous operation, but the temperature time profile of the drive piston could be a showstopper.
- The project has a component development view, which is a weakness.

Recommendations for additions/deletions to project scope:

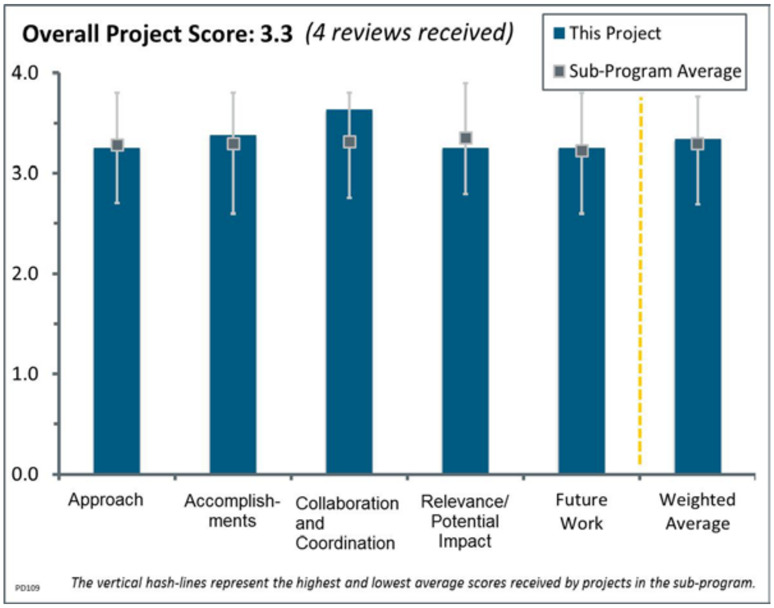
- The project team should (1) perform a detailed energy balance/budget for this system and identify and estimate the energy demand as a function of pressure and flow rate, and (2) perform a heat transfer analysis on the drive piston to understand the drive piston temperature time profile.
- The PIs should move quickly toward establishing an energy consumption estimate expressed as kWh/kg of hydrogen compressed.
- The project should have external mentors experienced in managing electric power and hydrogen compression systems.
- The project should add the hazardous location listing of the linear actuated coil.

Project # PD-109: Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage

Zhili Feng; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop a second-generation steel concrete composite vessel (SCCV) that will be more cost effective for forecourt hydrogen fueling station applications. Other objectives include (1) reducing the purchased capital cost of SCCV for forecourt hydrogen storage to $800/kg at 875 bar while meeting all other requirements, including a projected service life of at least 30 years and scalability to 1,000 kg of storage, and (2) fabricating a representative prototype mock-up that captures all the major features of SCCV technology.



Question 1: Approach to performing the work

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

- The project team has a good focus on cost reduction. There is a bottom-up analysis on materials. Estimates show a potential cost reduction of 60% compared to the first unit, but to be conservative, only 20% is targeted. Manufacturability is being considered, but it will likely be a larger fraction of the cost than the principal investigator (PI) suggests. It would be good to see some detailed attention given to the overall manufacturability of the system. Sensors will be deployed with the expectation that the manway can be removed. This will result in additional savings. There did not appear to be any attention given to maintenance. This could be a significant component of operating expenses.
- The project is building on an earlier project developing SCCVs. This current project, in particular, has a goal of moving the working pressure to 875 bar with an ultimate cost target of $800/kg hydrogen, which exceeds the U.S. Department of Energy (DOE) cost target of $1,000/kg hydrogen. The focus on advancing materials and sensor technologies to achieve significant cost savings is excellent.
- The project team is taking an already proven approach that builds on the results and learnings obtained from its previous project for the Generation 1 SCCV.
- This project builds on experience gained with earlier low-pressure projects.

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

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

- There has been excellent progress: milestones were completed for the first quarter, a go/no-go was passed in the second quarter, and the work for the last two quarters of the fiscal year is in progress. There has also been excellent progress in identifying a permeation barrier. The team completed the initial, level-one vessel design, identifying significant cost reductions. This is excellent, considering the footprint and installation issues in the cost reductions. The detailed cost reduction analysis is nice and thorough.
- This project was just initiated, but it has started to down-select steel materials and is making appropriate progress.

- Considering that this is a new project, the team presented good progress on this work. Identifying available materials for the vessel as well as conducting the preliminary identification for possible opportunities for cost reduction will direct this project in the right direction.
- This project is at an early stage, and progress to date is reasonable. It seems that despite the use of concrete, most of the load is being borne by steel rebar or wound steel wire. The advantages of concrete need to be clearly understood before the team proceeds with any construction activities.

Question 3: Collaboration and coordination with other institutions

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

- The collaborations and partnerships in this project are perfect for addressing all aspects of the project: material advancement, manufacturing, demonstration, cost modeling, and commercialization. Collaboration is a very strong aspect of this project.
- It is very clear that the current level collaboration is very broad and adequate to cover all the critical aspects, which will provide significant value to this project.
- The project has a good group of collaborators from industry, universities, and laboratories.
- The team for this work is appropriate.

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

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

- Developing technologies for underground storage of hydrogen is a very important aspect for enabling the introduction of hydrogen retail stations. Currently, it seems that one of the main issues with safety distances is related to large aboveground storage vessels, so this project is very relevant in advancing the hydrogen-for-mobility infrastructure.
- This project is expanding the work of another concrete overwrap project (PD-088)—this is a cost-reduction project. With respect to relevance, inexpensive forecourt high pressure is needed to facilitate the commercial deployment of hydrogen fueling stations. The potential impact is high.
- If successful in achieving the 60% cost savings, this technology could be highly impactful. The addition of some new partners, such as LightSail, could provide novel, low-cost vessel designs that might show lower manufacturing costs; a higher rate of manufacturing; and, almost most important, the ability to be easily repaired in the field.
- Existing commercial vessels already meet DOE targets.

Question 5: Proposed future work

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

- The focus on a lower-cost barrier layer, higher-strength steels, in situ inspection technology, and advanced reinforcement wires and wrapping techniques is very appropriate to meet the goals of the project.
- The proposed work for the next two years of this project looks complete.
- The project has a nicely detailed cost-reduction analysis. The overall plan to manufacture part of this in a factory and then move it to the site for the balance of the manufacturing is concerning. It is an interesting concept, but it might become bogged down during the execution.
- More analysis is needed before any construction is considered.

Project strengths:

- This project is largely well designed and well executed.
- The partner network is a project strength.
- The project builds on knowledge and experience from an earlier project.

Project weaknesses:

- There is strong competition from existing technology.
- There are significant concerns about the overall concept. These are the same concerns that apply to PD-088. If the concept was a direct burial tank, the tight contact with the surrounding ground would take up part of the load (if correctly designed and implemented). However, that is not the case; this is a stand-alone tank. This begs the following.
    - The concept is to use prestressed concrete. In this concept, the concrete is prestressed by steel wrappings. Concrete by itself has effectively no tensile strength; it is great in compression but not in tension. Prestressed concrete, however, can handle tensile loads as long as the tensile load does not exceed the prestressing from the steel wrappings. In other words, the steel takes the load of prestressing and the pressure load of the hydrogen inside the vessel. It seems that the concrete is not necessary; indeed, this system would be a lot simpler and less costly without the concrete, and presumably, the steel component can be reduced because of the lower tensile loads. This project has done a nice finite element method analysis, so presumably the case with and without concrete from a bill-of-materials and cost optimization standpoint has been performed.

Recommendations for additions/deletions to project scope:

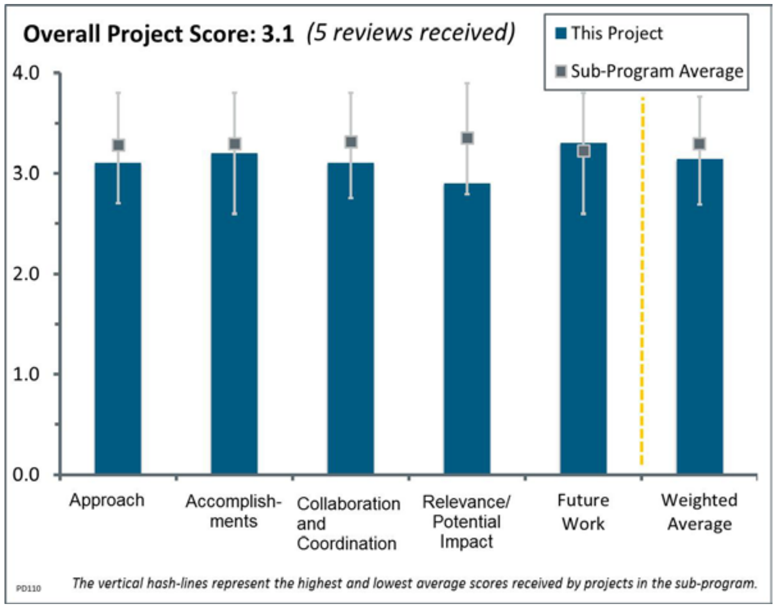
- The PI should justify to the reviewers and DOE that a prestressed concrete structure has enough merit over and above a tank that does not include concrete.
- It may be possible to achieve significant cost reductions by using a hydrogen permeation barrier approach with traditional Type II and Type III vessels. Cost estimates need to be examined to be sure that the increased costs associated with labor in vessel construction are included. Before any construction activities are authorized, the project should do an analysis of costs for competing vessels and be sure that costs of concrete-reinforced vessels show a significant advantage. DOE needs to fully understand the benefits of a concrete/steel-reinforced vessel versus a Type II or Type III vessel with steel reinforcement. The team should consider an independent review of these technologies.

Project # PD-110: Low-Cost Hydrogen Storage at 875 bar Using Steel Liner and Steel Wire Wrap

Amit Prakash; WireTough Cylinders

Brief Summary of Project:

The overall objective of this project is to develop a pressure vessel with a capacity of 765 L to safely store hydrogen at 875 bar that also meets the U.S. Department of Energy (DOE) storage tank cost target of <$1,000/kg hydrogen. The vessel must have a lifetime that exceeds 30 years/10,000 pressure cycles, have a safety factor of 3 on burst pressure to operating pressure, deliver hydrogen that meets SAE J2719 hydrogen purity requirements, and have design consistent with relevant American Society for Mechanical Engineers (ASME) codes.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This is a new project for this fiscal year; it started in October. Objectives are consistent with DOE goals. The project is to take Type I tanks nominally used for compressed natural gas and hydrogen storage and overwrap them with high-strength steep wires, approximately doubling the pressure capacity (2*55 = 110 MPa). The tank will also be subjected to “autofrettage pressure” to elastically deform the internal tank, locking in compressive stresses on the liner’s interior surface. The project will first demonstrate this on small 1.9-meter tanks, then move to 9.5-meter tanks. This is an intriguing project. Hydrogen-assisted fatigue crack growth is a concern, particularly at the slow frequencies to which these tanks will be subjected. However, this team has performed a literature search on the topic, and the relevant literature would suggest that this may not be an issue. The team is referencing the Sandia National Laboratory (SNL) work, which is appropriate.
- Designing a bulk storage tank from high-strength steels, reinforced with high-strength steel wires, is a simple approach that could show reasonable benefit. There is significant experience with fatigue and embrittlement of austenitic steels, and working with SNL to understand the fatigue and embrittlement is the right approach. The project should incorporate some cost modeling to truly understand the cost trade-offs for the various materials and design considerations.
- The approach is a variant of the Type III tank design. It is a sound, derivative approach.
- The team is doing a good job of modeling tank performance to guide production and design. Burst testing of the vessel is promising. There were no economic analyses to indicate how much these vessels are likely to cost.
- The project is addressing the relevant DOE targets. With the approach taken, however, a significant improvement compared to other storage concepts cannot be expected.

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

This project was rated **3.2** for its accomplishments and progress.

- For a project that is only seven or eight months old, the accomplishments are quite impressive. The team has developed a finite element method (FEM) model for optimization, procured three tanks, completed wire winding of one tank, initiated a burst test, initiated code approvals, and developed a fracture mechanics model. The burst test had to be terminated because of equipment failure and thus did not run to completion, so whether this technology will leak before burst is unknown. This concern was expressed during the review. Attention needs to be paid to ensure that this will indeed leak before burst. The progress is excellent for such a young project.

- The project started just recently. The team is off to a good start regarding addressing the realization and testing of the proposed concept.
- The accomplishments and progress to date are appropriate for this point in the project.
- The accomplishments thus far have been positive, although it is unclear whether the testing partner, Authorized Testing, will be able to test at the rated pressures. This will be key for future success.
- The project has made good progress in its initial phases. However, no technoeconomic analysis was given.

Question 3: Collaboration and coordination with other institutions

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

- The partners for this project are appropriate. The collaborators/collaborations are also very good.
- The project includes only a small team, but the relevant competencies are represented.
- The collaborations with Oak Ridge National Laboratory and SNL utilize the appropriate expertise. However, the project should also have a cost analysis and station design partner to provide an understanding of cost impacts at the station level.
- Reasonable collaboration appears to be occurring. WireTough is obviously working with ASME. This should be mentioned on the Collaboration slide.
- The collaboration and coordination do not seem to include any partners. The project is limited to national laboratories and a funding source. A station integrator with knowledge on end use and operating issues may be of assistance.

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

This project was rated **2.9** for its relevance/potential impact.

- The technology could be relatively easily manufactured using a supply chain created by the tire industry. The technology could be subject to embrittlement, which would render it ineffective at these pressures; however, if the principal investigators can understand and mitigate the material embrittlement, then this technology could show significant impact on hydrogen delivery and meet the 2020 cost targets.
- If successful, this project will produce an inexpensive, high-pressure tank suitable for forecourt applications. Modifying existing Type I tank technologies to make them suitable for the forecourt applications is a good approach as long as hydrogen-assisted crack growth does not become an issue.
- The relevance/potential impact of this project is interesting. The potential for cost reduction and market acceptance is high. Wire wrapping may be more tolerant of local damage (e.g., suspension bridge cable).
- The project addresses an important topic of the Hydrogen and Fuel Cells Program. If successful, it may offer a lower-cost solution compared to other storage types.
- There is strong competition from carbon-fiber-wrapped steel vessels, which already meet or come close to meeting DOE targets.

Question 5: Proposed future work

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

- The proposed future work is spot on. There is concern about hydrogen-assisted fatigue crack growth, so it is excellent to see that significant attention will be paid to this problem, and consulting with SNL is appropriate. The development of non-destructive evaluation (NDE) technology for this application is spot on. The NDE will prove to be a very valuable tool as this project continues.

- Given the success at 1.9 meters, moving to 9.5-meter tubes is a reasonable extension of the work if the economics are promising. The effect of pressure cycling on cylinder lifetime needs to be examined and described. For carbon-fiber-wrapped steel cylinders, the depth of cycling has a very significant impact on vessel lifetime.
- The proposed work involves scale-up and ASME acceptance per code case. Both tasks are appropriate.
- A cost analysis task is highly recommended to gauge the cost savings and overall cost of the technology as the project progresses. There is no mention of this task currently.

Project strengths:

- This is an intriguing project. It is well planned and, so far, well executed. For such a young project, the progress is excellent. There are technical issues that need to be overcome; however, this team recognizes them and will be addressing these issues as the project continues. This is excellent.
- The strength of this activity is that it is a derivative concept based on well-known technologies (e.g., cable from suspension bridges and Type III tank design).
- The project has made a good start with analysis and construction of cylinders.

Project weaknesses:

- There are no weaknesses at this stage of the project.
- The apparent weakness is the assumption of a quick and successful campaign for an ASME code case.

Recommendations for additions/deletions to project scope:

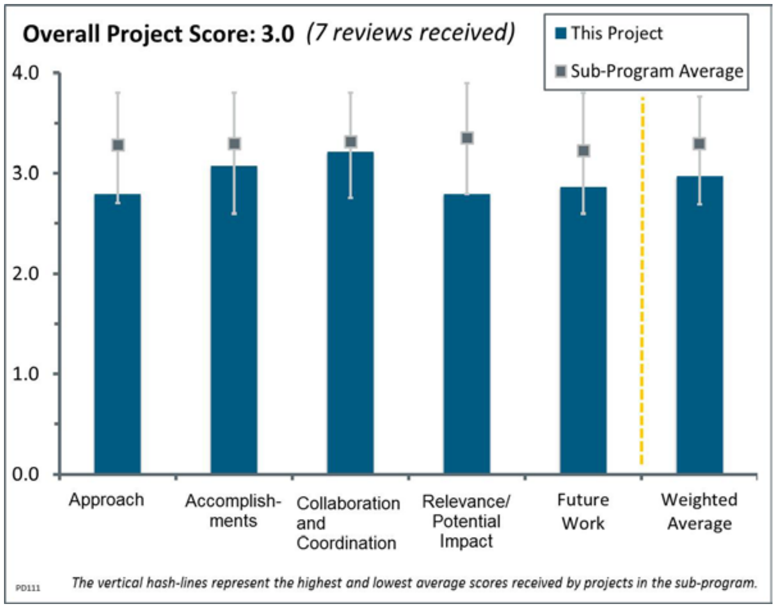
- Technoeconomic analysis should be added. DOE should carry out an independent economic assessment of this technology compared to carbon-fiber-wrapped Type II vessels. The effects of pressure cycling on vessel lifetimes should be added.
- The project should focus on the code case acceptance. This may be a time-consuming process.

Project # PD-111: Monolithic Piston-Type Reactor for Hydrogen Production through Rapid Swing of Reforming/Combustion Reactions

Wei Liu; Pacific Northwest National Laboratory

Brief Summary of Project:

This project is pursuing bio-oil reforming technology advancements. Pacific Northwest National Laboratory (PNNL) is working to (1) reduce the capital cost of plants by minimizing unit operations, decreasing pressure swing adsorption, and simplifying processes; (2) increase energy conversion through in situ CO_2 capture and in situ heat exchange between reaction and regeneration; and (3) increase durability by reducing operations and maintenance requirements.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The project started in fiscal year (FY) 2015 with a well-thought-out and feasible plan of approach. The concept is innovative and challenging, but the barriers have been identified, and a research and development plan is in place to address them. The project builds on other Office of Energy Efficiency and Renewable Energy (EERE)-funded efforts, including past efforts addressing catalysts for bio-oil reforming. Additional attention to the cost and composition variations of bio-oil may be needed to fully address all barriers.
- This project has an effective approach to reduce hydrogen production cost using a simplified rapid swing reformer-combustion process. The process utilizes in situ CO_2 capture and heat transfer for improved efficiency.
- The major technical hurdles have been identified. However, it appears these issues are being addressed independently at this point, under the assumption that the developments can be readily meshed later. Introduction of the new laboratory system into the workflow should help in this regard. The team should consider devoting more resources to addressing the technical challenges associated with the catalyst—especially poison and coking tolerance when running on bio-oil—and the translation of laboratory discovery to a successful monolith. Clearly, catalyst performance has a high showstopper potential for the project. It would also be good to see high priority given to assessing the relative kinetics of hydrogen production, CO_2 diffusion into the sorbent, and mass transfer through the monolith. Results may force operation into a small parameter-space box. The assumed timeline (e.g., catalyst/sorbent system identified in FY 2015) is extremely aggressive.
- This effort was generally focused, with several challenging milestones laid out very methodically. The messaging was the right tone, especially because this effort is addressing multiple challenges. However, there is an issue that is a specific concern—the principal investigator (PI) provided and compared catalysis selectivity results with unequal conversions (i.e., 5%, 8%, and 70% conversions). It is absolutely incorrect to compare, side by side, selectivity results for a chemical reaction at different conversion levels. A catalysis expert should be consulted to add some clarity on the data collected to date. There was also some concern about operating the differential chemical (catalysis) reactor at greater than 5% conversion. When such a reactor is operated at these levels of conversion, heat and mass transfer effects creep in. These can be checked and verified as not being significant; however, these verifications were not provided.
- The project is in a very early stage, and it is the high-risk type of project the government should be doing. However, there is concern that the potential issues involving the use of bio-oils have not been well-thought-

out. For example, the potential for catalyst poisoning from the bio-oil sulfur and nitrogen complexes and the lack of a reliable bio-oil producer with controlled specifications add to the complexity and risk profile of the project. The presentation did not include a credible backup plan to address these risks, which is especially important because the catalyst may or may not be zeolite-based.
- This novel reactor design has the capability to make hydrogen from a low-cost feedstock and capture CO_2. Catalyst poisons in bio-oil have not been addressed. These poisons may make this project a non-starter. The PIs need to begin work quickly on mass and energy balances.

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

This project was rated **3.1** for its accomplishments and progress.

- Good progress has been made in a short amount of time. Literature searches have been completed, and candidate materials for catalyst and sorbent components have been identified. An integrated testing system has been designed for demonstration at 2 kg/day and for scale-up to 1,500 kg/day. If successful, the technology will offer a viable option to natural gas reforming for distributed production of hydrogen by reducing or eliminating capital and process costs associated with the high-temperature furnace, air separation, and water-gas-shift (WGS) steps.
- The level of accomplishments is high. The team has accomplished a truly significant quantity of work.
- The project started about six months ago. The team has made good progress on CO_2 sorbent identification, building the laboratory test system, and the first-draft technoeconomic analysis. It is not obvious whether good progress has been made on the catalyst.
- Given the short time frame for the project, the work over the last six months has been adequate. The initial screening of the CO_2 sorbents seems to be progressing nicely. The key concern is with the catalyst work. So far, the experiments utilize chemical-grade phenol as a model compound for pyrolysis; it is not clear whether this is a good substrate substitute for the myriad of minor complexes in bio-oil.
- The project is in its early stages. Sorbent materials have been identified for evaluation. Future progress will rely on “rapid” reaction kinetics and heat transfer during reaction and regeneration cycles.
- The progress is adequate for a project in its early stages.
- The laboratory results seem reassuring, but it is difficult to assess the chances of overall success without estimates of the capital cost of this equipment. The researchers’ goal of achieving less than $4/kg depends on a 40% reduction in the cost of bio-oil. They need to describe the likelihood of reaching that bio-oil cost-reduction goal and what needs to happen in the bio-oil production process to achieve that cost reduction.

Question 3: Collaboration and coordination with other institutions

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

- PNNL is working with and leveraging staff and capabilities of the nearby Washington State University. Project partners include two small businesses that will lead the scale-up and commercialization of the technology if this project is successful. PNNL is continuing to reference and coordinate assumptions on bio-oil cost properties with other institutions (e.g., the National Renewable Energy Laboratory).
- The project seems to have a well-coordinated and aligned focus, with a good degree of collaboration. Further, this project aligns well with the Hydrogen and Fuel Cells Program and DOE objectives.
- There is good collaboration between the project members. Members are well versed in the fields of catalyst/sorbent material identification and reactor/process development.
- This appears to be a good team effort.
- There are four separate institutions participating in the project, each with specific relevant expertise.
- PNNL, as the central hub for the collaboration, seems to be doing a good job. It is not clear whether there are any direct interactions between other organizations; these should be encouraged, if they are not already happening.
- There is no apparent collaboration with experts on bio-oil properties and variability.

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

This project was rated **2.8** for its relevance/potential impact.

- This project addresses and supports the goal of reducing the cost of distributed production of hydrogen from biomass-derived renewable liquids. Preliminary Hydrogen Analysis (H2A) model analysis shows that an approximate 50% reduction in the assumed cost of bio-oil feedstock would be required to achieve cost goals. It would be useful to see more discussion of how this would be accomplished and what limitations or boundaries this would impose on deployment of this technology. For example, if cost reduction is achieved by minimizing or eliminating oil transportation costs, it is not clear how that would limit use of this technology. If cost reduction is achieved through economies of scale, it is not clear what scale of bio-oil production would be needed.
- Reducing the cost of hydrogen production aligns with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. However, it is not clear the capital cost reductions are actually achievable because there is a great deal of reliance on the right level of thermal generation and transfer from the swing reactions to effect efficient reaction/regeneration while producing a high concentration of hydrogen without WGS. In addition, the feedstock costs remain unknown because no pyrolysis plant actually exists.
- The primary connection to hydrogen production goals is the use of bio-oil. A thorough comparison of this approach to steam methane reforming (at the same 1.5-ton hydrogen/day scale) would be helpful in judging its relevance to hydrogen production goals. It is not clear whether there are net CO_2 benefits. In addition to aggressive assumptions about reductions in capital and operating costs, given the complexity of the process being proposed, H2A shows a 50% reduction in bio-oil cost is required to meet the cost-of-hydrogen-production target. The latter should be addressed in another project.
- The DOE target for hydrogen production is <$4/kg of hydrogen. Using this process, it is feasible to lower the cost of hydrogen production, but cost reductions may be limited by the cost of the biofuel used in the reaction.
- Most project aspects align with the Hydrogen and Fuel Cells Program and DOE research, development, and demonstration objectives. However, the impact could be greater with a better-planned approach.
- The relevance of small-scale, remote hydrogen production is questionable because of the large associated transportation costs for produced hydrogen.

Question 5: Proposed future work

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

- The project seems fairly well positioned to start integrating pieces. Execution will be key. Success of the process will require careful synchronization of multiple kinetics (e.g., reaction, diffusion, coking/decoking, and heat transfer). The team should develop a detailed process model to identify key bottlenecks and reasonable process operating points. It is not obvious when catalyst/sorbent system durability will be addressed (nor whether the replacement cycle has been included in H2A analysis).
- Reasonable project milestones were identified by project year. If it has not been submitted already, a schedule for down-selection of catalyst and sorbent materials for the integrated reactor system demonstration in Year 3 should be provided to DOE, as well as a risk mitigation strategy for this demonstration in case materials with needed performance properties are not found in Year 2.
- It would have been helpful to question Washington State University to get a better sense of the likelihood for success with its catalyst work. Coke completely deactivates the current Ni-based catalyst, so a plan is needed to develop an optimum reforming catalyst.
- The investigators should move quickly to work with real pyrolysis oils to assess factors such as coking, poisoning, coke burn-off, etc. Phenol is not a good model of pyoil.
- The project goals are to continue reducing capital cost, increasing energy conversion, and improving durability.

- The project is only 15% complete, and there were no slides explaining the future direction. The proposed plans to overcome some of the overarching challenges would have been good to see.
- There were no comments about determining the capital cost of this equipment (other than a bar chart with no details).

Project strengths:

- The project has an innovative design concept with the potential to significantly reduce the cost of distributed hydrogen from bio-derived liquids. The project partners include experienced researchers at PNNL as well as industry partners for development of components and reactor design. The latter also provide a possible pathway for further development and eventual commercialization.
- The sorbent part of the research is off to a good start. It appears the team has designed a system and purchased equipment.
- Strengths of the project include its novel approach to catalysis, separations, and process.
- The project features a well-defined cost analysis of the system economics.
- The project's novel design is a strength.
- The project features good laboratory testing experience and equipment.

Project weaknesses:

- There were no capital cost estimates to back up claims of achieving $4/kg cost. There was no assessment of the likelihood of achieving a 40% reduction in the cost of bio-oil. It would also be good to see an assessment of the well-to-wheels (WTW) GHG emissions and water consumption for this project.
- The team has not found materials that meet the performance requirements for an integrated reactor system. Baseline materials to be used in a third-year system demonstration should be identified as a fallback option in case optimum materials are not identified in time.
- The cost of biofuel may limit this process in reaching DOE's suggested hydrogen cost target of less than $4/kg of hydrogen.
- The project is tackling very significant technical challenges on all three fronts simultaneously. It has an overly optimistic timeline.
- No catalyst work has been done that demonstrates this part of the project will not be a showstopper.
- No clear future plans were elaborated.

Recommendations for additions/deletions to project scope:

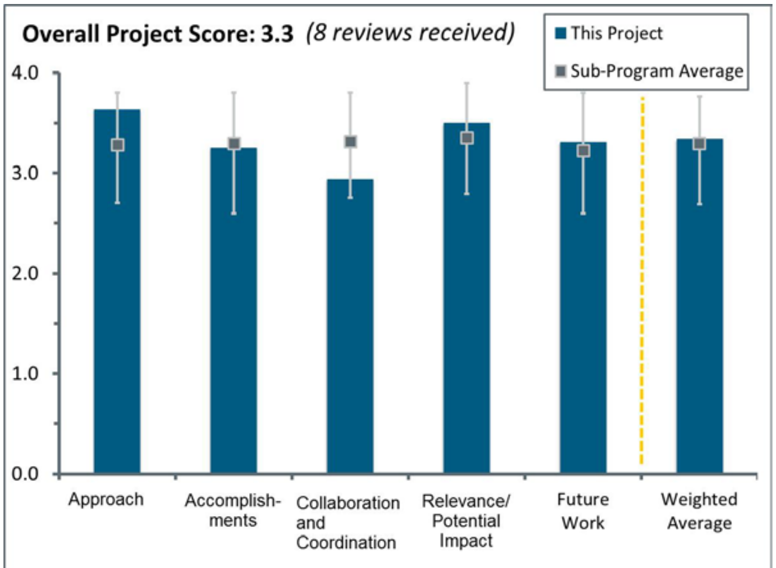
- No major changes are recommended. The project could add value by briefly addressing the following topics during analysis and presentations:
  - The effects of changes in bio-oil composition on the performance of the catalysts
  - Reactor design modifications to allow for carbon capture, utilization, and storage (CCUS)
  - The added costs and restrictions, if any, associated with forecourt safety and handling concerns for bio-derived liquids
  - Modular reactor unit designs for "ganging" to provide semi-central production
  - Coordination with the EERE Bioenergy Technologies Office (BETO) to estimate production requirements for bio-oil to meet goals for biofuels and hydrogen production
- The researchers should carry out technoeconomic analysis for using this process not as a source of hydrogen for vehicles, but as a source of hydrogen for stabilization of larger amounts of pyoil in the field. This may be more appropriate for work with BETO, but it is likely to have better economics than producing small amounts of hydrogen remotely and then transporting it to areas with hydrogen demand.
- The team should focus on a robust catalyst/sorbent system and process modeling over the three-year project timeline. It should leave the fully integrated demonstration unit for a later phase.
- The project team should add a task to assess the WTW GHG emissions and water consumption. It should also add a task to estimate the capital cost of this system.
- The team should put more resources into catalyst development.
- The team should conduct an investigation of lower-cost fuel sources that may be applicable to this process.

Project # PD-112: Reformer-Electrolyzer-Purifier for Production of Hydrogen

Fred Jahnke; FuelCell Energy, Inc.

Brief Summary of Project:

The objective of this project is to demonstrate reformer–electrolyzer–purifier (REP) technology based on FuelCell Energy's (FCE's) proven molten carbonate fuel cell (MCFC) technology as a cost-effective and efficient method for producing hydrogen from natural gas. Potential REP technology benefits include the low cost hydrogen production, significantly reduced CO_2 emissions compared to steam methane reforming, and scalability from home refueling to central production sizes. In addition to research and development (R&D), cost analysis will also be undertaken.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

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

- FCE has a solid track record of creating systems that meet multiple needs and are, by necessity, complex. This system has the potential to reduce the carbon footprint of hydrogen produced from natural gas. The project leverages FCE's proven MCFC technology, which is a plus. The complexity and novelty of the system may prove to be a detriment when the system is integrated into a commercial system. It would be good to see some reliability predictions and mitigations for a final commercial system.
- This project has the right focus on demonstrating long-term performance, given that it is essentially running existing hardware (in reverse), so there is no need to focus on materials and process development. The project should consider directly addressing the impact of upstream (sulfur removal) and downstream (compression) processes, even if they are "off-the-shelf." It is not insignificant that the feed must be sulfur-free (it would be good to know how many parts per million of sulfur can be tolerated), nor that the hydrogen produced is at atmospheric pressure (it would be good to know how compression to 700 bar would affect the economics).
- The project team's extensive commercial experience with designing, building, installing, and operating MCFCs gives it the in-depth understanding of the processes involved and the changes and developments required to convert the fuel cell technology to operate as an electrolyzer.
- Because this project modifies existing commercial fuel cell equipment to create the electrolyzer and already has a patent filed, it presents a lower-risk profile and appears to be quite feasible.
- The project has a defined approach to modeling, optimizing, and developing a combined reformer/electrolyzer for hydrogen production.
- This project was sharply focused and addressed the critical barriers; it would be difficult to improve the project significantly.
- The work scope is well defined with no major weaknesses. The project builds on successful MCFC technology.
- The project uses a novel approach to production using existing products with modifications.

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

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

- There has been excellent progress to date on single-cell testing. The focus to date has been on continuous operation at load. Results suggest that long-term durability does not look to be a critical issue at this time. Hydrogen purity of ~98% has been demonstrated. It would help if the milestone deliverable dates were defined. It is hard to determine which tasks have been started and completed and which milestones have yet to be started.
- The voltage stability of the cell over time is good. This testing needs to continue out to commercially relevant lifetimes. The funding opportunity announcement (FOA) under which this project was awarded, DE-FOA-0000826, Topic 1, has a target for greenhouse gas (GHG) emissions: 5,500 g CO_2e/gge H_2. The team needs to be explicit about where it stands relative to that goal. The team members state that REP can meet 5 kg CO_2/gge, yet they present no evidence of the system's ability to meet this number. A refined GHG analysis needs to be presented every year based on the available test data. The cost analysis states the system can meet \$1.4–\$2.2/kg H_2. This is based on a questionable assumption of free heat input. This project, like some others in the Hydrogen Production portfolio, makes the unfounded assumption that high-quality free heat will be available. Because high-quality heat has value to those who produce it, it is unlikely that free heat in the required quality will be available. The team needs to make realistic assumptions about the cost of the heat input and the effect of that on the cost of hydrogen.
- The accomplishments reveal the result of good collaboration. It is clear the partners participate and are well coordinated.
- The project has shown good progress on a subscale (single-cell) level. The completion of optimization studies related to heat transfer can further improve performance and cost. However, hydrogen purity and the effect on system economics require a more detailed investigation.
- The long-term operability testing and performance modeling efforts are appreciated. It is not clear whether the project is on track to finish the work plan in the next year or so, but the track record has been good.
- The resulting capital costs are not clear. The speaker was hesitant to provide numbers. However, the system does look to be scalable with low emissions, with a projected hydrogen production cost between \$1.38 and \$2.18 at 1,826 kg per day.
- There is good progress for this early stage project.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The degree to which the project interacts with other entities and projects is outstanding. There is close, appropriate collaboration with other institutions. The partners seem to be strong participants, and the efforts are well coordinated.
- To be honest, FCE does not need that much collaboration—it is the expert in this field—but the University of California, Irvine, (UCI) provides some analytical heft to the project.
- FCE has most of the expertise needed internally, so collaboration is not so important in this project.
- This project has only one collaborator that is focusing its efforts on modeling and cost studies. Further detail in the cost analysis needs to be completed to determine overall process feasibility. That being said, the principal investigator (PI) has developed systems for industrial use and is capable of completing the work on the reformer/electrolyzer technology.
- The FCE team appears closely integrated with UCI, which is handling the bulk of the analysis work. This partnership should be leveraged to address project weaknesses.
- It is not clear what level of support UCI is receiving. The work scope of the UCI National Fuel Cell Center is extremely broad and seems to be somewhat unfocused. As such, it is difficult to evaluate the expected benefit of all activities. For example, it is not clear what the expected outcome is of evaluating all of the external heat sources; i.e., whether this information will be beneficial in determining the most appropriate targeted markets for deploying this technology, or whether this information will be beneficial in accelerating deployment (or at least demonstration tests) in the most appropriate market(s).

- It is not obvious how the single partner, UCI, is integrated into the project, other than apparently helping with the Hydrogen Analysis (H2A) modeling work. UCI could help in a direct comparison to a steam methane reforming (SMR) case. Now is the time to identify a full-scale demonstration partner.
- The only partner is UCI. It would be good to have a potential customer already signed up to assist with third-party field testing (e.g., a member of the U.S. Drive Partnership's Hydrogen Production Technical Team or the California Energy Commission).

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

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

- This is the project with the highest chances of achieving the $2/kg DOE goal—and probably the only approach that can even suggest the possibility of home refueling.
- The system has great potential for alternate uses such as renewable energy storage, chemical conversion, or CO_2 capture. The simulation models provided promising results.
- This project is a unique and creative way to generate low-cost, low-carbon hydrogen. It is important that this project move forward to commercialization—but only to the extent it can meet cost, GHG, and reliability targets. Progress toward these targets must be clearly analyzed and updated every year.
- This project can significantly advance progress toward DOE cost targets for hydrogen production when low-cost heat sources are available.
- This project represents a strong near-term opportunity in the Hydrogen Production portfolio. It would benefit from comprehensive comparison to SMR, given that both make hydrogen from natural gas. The project should, on the same kg H_2/day basis, compare capital and operating costs, efficiency, CO_2 footprint, heat/electrical load, and other pros/cons.
- If successful, the project could potentially provide an economical and technological solution for home refueling.
- This could be a low-cost route to hydrogen and electricity.
- The identified markets span an extremely broad level of production, and it is not clear the technology will be competitive at all production scales that are being targeted.

Question 5: Proposed future work

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

- The future work for the project seems to be well thought-out and includes confirming system economics, large-scale modeling, waste heat identification for system optimization, fuel flexibility analysis, and commercialization.
- The project has a defined path forward and includes scale-up to a large multi-cell stack platform along with an updated hydrogen production cost analysis.
- The outlined proposed future work was sharply focused.
- The PIs have outlined a reasonable plan for moving forward.
- The proposed future work for FCE is well structured to meet overall project objectives, although it would be good to see some effort focused on performance under dynamic operating conditions. The future work for UCI needs to be better focused, with projected outcomes better defined.
- It is not clear whether upstream (sulfur removal) and downstream (compression) costs have been factored into the H2A analysis—if not, they should be. It would be good to see more thorough consideration of the opportunities to use the CO_2 in the waste stream. It would be good to see a case developed in which there is integration with electrochemical compression. The project team should consider identifying what would limit large-scale deployment (e.g., availability of materials, production capacity, and/or adequate quality waste heat).
- The parametric H2A analysis needs to address the cost of heat input. The future work plan is reasonable.

- It would be good to see a clear listing of capital expenditures (capex) for the proposed stand-alone hydrogen generator. The current description is confusing because the project is utilizing the equipment from the MCFC (de-sulfurizer, etc.).

Project strengths:

- The project builds on existing MCFC technology, which has accelerated this project's R&D progress. For example, a 3,000-hour durability test has already been completed on single-cell. Development of new technology is not required, thus accelerating the time to market. The projected long-term cost of hydrogen is less than $2/kg. The technology is projected to meet the DOE CO_2 emissions target of <5,000 g/gge, although it is not clear how this target is met.
- The system utilizes a combined reformer and electrolyzer stack that has the potential for low-cost hydrogen production and CO_2 capture.
- This is good lower-risk, near-term technology—it is effectively an advanced SMR process.
- It is a unique project with good potential to address cost and GHG goals.
- FCE has excellent commercial experience with MCFCs. This is an experienced scientific and engineering team.
- FCE has strong expertise in fuel cell manufacturing, which is transferable to development of the REP.
- The strong expertise at FCE is a real plus for this project.

Project weaknesses:

- The project targets production levels from 2 kg/day up to 16,000 kg/day. The PI should calculate the capex costs at the residential scale (2 kg/day), at the service station scale (1,500 kg/day), and at 16,000 kg/day and compare these costs against conventional SMR. Capex costs should consider all aspects of the cost, including balance of plant. For residential use, it is not clear what the payback period is or whether the payback time is reasonable such that there would be a market demand at this scale.
- Project execution needs to be strengthened to address the goals against which the project is measured.
- Economic analysis and quantified advantages over SMR are needed.
- FCE needs to close the deal with a third-party field tester in multiple climates.

Recommendations for additions/deletions to project scope:

- If increasing pressure were possible, this would be a very good addition. The standard H2A case for hydrogen production assumes hydrogen delivered from the system at about 300 psig. Costs of compression to this pressure need to be included in any technoeconomic analyses. The PIs should show technoeconomic analysis for stand-alone systems, along with similar analyses for locations with usable waste heat. The sources of waste heat need to be clearly identified and quantified. One specific analysis that would be useful would be for an early station with an ultimate capacity of 500–1,000 kg H_2/day, but the station could produce mostly electricity in early years with low demand and then swing production to more hydrogen as demand increases.
- The project should calculate capex cost at three production levels—residential, service station, and centralized production—and compare these costs against conventional SMR at these scales. Smaller-scale production rates will probably require that the system operate with frequent shutdowns and start-ups. Dynamic operation—including frequent shutdowns/start-ups—and its effect on long-term performance should be investigated. The project should define the appropriate scale for a demonstration and begin focusing R&D efforts toward preparing for demonstration. CO_2 emissions per kg H_2 produced should be quantified, including the CO_2 associated with external heat and electricity production.
- At every DOE Hydrogen and Fuel Cells Program Annual Merit Review, the team should present a single slide showing where the REP technology stands relative to GHG emissions (5,500 g CO_2e/gge target); cost using realistic assumptions, especially for heat input cost ($1–$2/gge target); and durability/reliability progress. This slide must be backed up by analysis, not merely a conclusory assertion that the goal is being met. It is insufficient to meet only one of these targets. As the FOA says, "Pathways to meet *both* the greenhouse gas reduction requirement and the production cost goal of $1–$2/gge must be clearly identified…" (emphasis added).

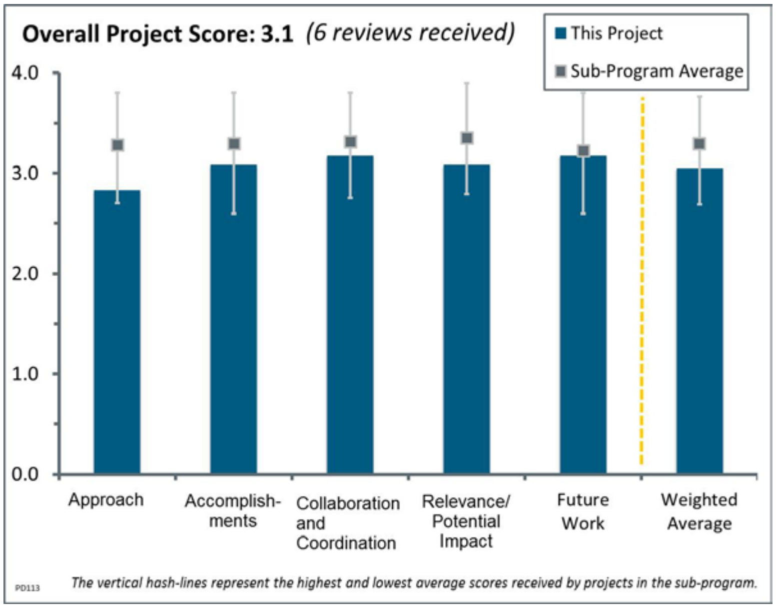
- A detailed economic analysis needs to be performed—specifically including the cost of external heat sources required in the reformer/electrolyzer technology. Hydrogen purity should also be considered in the analysis.
- The project should provide a detailed cost estimate of a stand-alone electrolyzer hydrogen generator system.
- Unfamiliar and undefined acronyms in the presentation (e.g., HMB, SOPO) took away from the message in some cases.

Project # PD-113: High-Efficiency Solar Thermochemical Reactor for Hydrogen Production

Tony McDaniel; Sandia National Laboratories

Brief Summary of Project:

The objective of this project is to develop and validate a particle bed reactor for producing hydrogen via a thermochemical water splitting cycle using a non-volatile metal oxide as the working fluid. Sandia National Laboratories (SNL) will demonstrate eight continuous hours of "on-sun" operation, producing more than 3 L of hydrogen.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach taken by this project is excellent to outstanding. It is not purely outstanding only because of the lack of any attention in the plan to materials durability analysis and testing. The reviewer-only slide on "Critical Assumptions and Issues" suggests establishing collaborations with a number of institutions with the capability to develop atomistic understanding of materials behavior in the extreme environments of this process. That is an important effort that should be given higher priority than the present plan. The project excuses this deficiency on the grounds that more fundamental research is needed than is possible to conduct in this project, but if this issue is a potential showstopper (and it might be), the project should engage it sooner rather than later. Apart from this single point, the planning and approach in this project are outstanding.
- The overall project objective is to develop and validate a particle bed reactor for producing hydrogen via a thermochemical water-splitting cycle using a non-volatile metal oxide (potentially CeO_2) redox material as the working "fluid." The project will demonstrate 8 continuous hours of on-sun operation, producing more than 3 L of hydrogen. The fiscal year (FY) 2015 effort is focused on identifying (discovering) suitable redox materials, designing a particle receiver-reactor for 3 kW operation, and conducting system modeling. An overall solar-to-thermal efficiency of >5% is targeted in the short term.
- Although the approach of coupling both new material discovery and efficient solarthermal reactor development is attractive, the probability of achieving both goals is very slim. There is a mismatch in terms of both development readiness and project timing needed to have any chance of success. The project objectives seem almost independent of each other because there is no milestone for material development, and reactor design goals are expected to be achieved with existing materials SPLM or CeO_2. In that respect, the project's goals, budget, duration, and skill sets do not seem well aligned.
- Stability and kinetics remain important but lesser-explored parts of this work. However, it was indicated that discovery of a new material with the desired redox and thermodynamic properties was a stretch goal, and so that material must be discovered prior to evaluation of the stability and kinetics.
- The keys to solar thermochemical (STCH) are sun-to-heat efficiency and heat-to-hydrogen efficiency. The project's attention to both material and reactor developments is laudable. The efforts on process modeling and technoeconomic analysis are also good. However, the technical challenges associated with the two key efficiency issues are so substantial that diluting the team's focus to design and build the solar simulator unit, on the stated timeline, may risk yielding only a hit-or-miss result. The principal investigator (PI) asserts the only way to know whether the chosen STCH approach will work is to build that unit. This is concerning. Some thought should be given to how to build more confidence in the likelihood of success.

- Barriers have been identified and addressed, and the technical approach to materials design and laboratory reactor testing is feasible, if challenging. The project partners have well-defined roles in contributing to the success of the project. However, the scope of the project does not seem appropriately scaled to the project duration and available funding.

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

This project was rated **3.1** for its accomplishments and progress.

- This project's accomplishments have been excellent. So far, material exceeding the expected performance of SLMA has not been found. Nevertheless, the advances in screening methodology have been significant, and the addition of entropy considerations in modifying potential candidates shows promise. The CPR2 remains an innovative and intriguing concept. The additional design work for managing material transport is interesting, although the proposed vibrational plates will likely add to the hostile environment for particle attrition. Even if the particles remain active, attrition could lead to performance degradation of the solar thermal interface windows if direct irradiation is implemented. System design options include direct or indirect particle irradiation and beam-up or beam-down configurations for solar thermal collection. Direct particle irradiation is likely more efficient, given the vacuum effects on heat transfer, but it is susceptible to particle attrition effects. Design options are partly driven by material durability in this environment. The improvements to the Hydrogen Analysis (H2A) v3 model are exemplary.
- Good progress has been made in qualifying the CPR2 for testing and in expanding the model of CPR2 and solar field performance. Materials discovery work is continuing, but it may take extended investigations beyond the scope of this project to find an optimal material of reaction with the thermochemical and performance parameter values desired to achieve solar-to-hydrogen (STH) efficiency of >20%. An innovation added this year has been to track and engineer materials system entropy as well as the onset reduction temperature and repeatable redox potential.
- Synthesis and screening of candidate redox materials is underway. Material selection will have a significant impact on capital cost and the levelized cost of hydrogen. Advanced analysis related to redox behavior (e.g., quantum theory and entropy considerations) is being used to guide discovery of high-performance redox materials. However, it is not clear from the presentation whether these analytical methods have actually led to discovery of any high-performance redox materials. Various perovskite doping strategies are also being evaluated. Other accomplishments include completion of a conceptual design of a 3 kW prototype reactor/receiver using simulated solar (lamp arrays). Technoeconomic analysis has been refined for a 100,000 kg/day plant. System analysis has been performed using Matlab. The exothermic nature of the oxidation step should be emphasized; it is not clear how the heat rejection is accomplished.
- The project has reported modest accomplishments, given that the STCH approach is extremely challenging and still at a very early stage of development, despite decades of research on this topic.
- The project's progress is difficult to judge. The presentation described mostly activities and "design criteria established"-type results, but it did not clearly translate those results to progress made on meeting technical targets. For example, it is not apparent how the current best redox material performs against the stated hydrogen/gram goal or the overall STCH efficiency goal, although it is noted that 0% progress has been made toward meeting the former. It would be good to see more concrete descriptions of accomplishments and progress.
- It is too early in the project to critically assess progress and the likelihood of success.

Question 3: Collaboration and coordination with other institutions

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

- The project team is excellent and leverages materials experience and reactor design capabilities at SNL – Livermore, and SNL – Albuquerque, respectively; academic materials discovery capabilities at several key universities; and access to DOE-Office of Science facilities. The status of work with the German Aerospace Center (DLR) needs to be resolved, and project plans and scope should be adjusted accordingly. In addition, this project offers the team an opportunity to provide leadership in coordinating across the community to establish conventions for analysis, best practices, and key measurements.

- The collaboration and coordination with other individuals and institutions is good to excellent. The collaboration in systems analysis is particularly interesting and represents a sort of one-of-a-kind activity. It is unusual for a technology team to turn its attention outside its boundaries of control for analysis. This project deserves commendation for its open nature in this regard. A missing ingredient is collaboration with an entity with existing capability for detailed atomistic-level characterization in an effort to understand the relationship between hydrogen production capacity and active particle durability. Such capability exists and is easily engaged, as shown effectively by the photoelectrochemical community. Collaboration and coordination would be improved if rapport could be established between SNL and the university STCH project. Both teams are pursuing very similar objectives using very similar general approaches and using materials derived from the same general class. Both teams appear to have chosen competitive—instead of cooperative and collaborative—postures. The program goals would be far better supported if these two institutions could work together to solve their common and challenging problems.
- Project collaboration is broad, including DLR (solar receiver), Arizona State University (technoeconomic analysis), Bucknell University (particle heat transfer), the Colorado School of Mines (materials), Northwestern University (quantum theory), Stanford University (entropy engineering), and CoorsTek (production of large batches of redox material).
- The project features an extensive set of collaborators that seem to be integrated into the team.
- Juggling this many collaborators is a challenge that seems to be going well. However, finalizing efforts with DLR has been a struggle.
- This project demands a wide range of skill sets—material synthesis, computation, reactor design, high-temperature (HT) material expertise, solar field design, economic analysis, etc. Therefore, effective collaboration is even more critical than in other hydrogen production projects. It is surprising the project team is not collaborating with the university STCH project. At the minimum, the project could benefit from reasonable knowledge sharing on the HT redox material screening and discovery effort.

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

This project was rated **3.1** for its relevance/potential impact.

- The relevance/potential impact of this project is excellent to outstanding. The magic material has yet to be found, and whether it can endure the harsh process environment remains to be determined. Nevertheless, the project has done an outstanding job in developing screening tools, general analysis of performance, and reactor concept development.
- The project supports the Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Office (FCTO) goal of reducing the cost of hydrogen production from renewable resources to <\$2/kg by 2020. It also supports the objective to verify the competitive potential for STCH cycles for hydrogen in the long term by 2015, and by 2020 to develop this technology to produce hydrogen. Meeting the cost goal will depend on the successful completion of this project, but also on technology development beyond the scope of the project and FCTO (e.g., lowering the cost of the heliostats to the DOE Solar Program SunShot target).
- Development of any efficient, cost-effective direct solar processes for water splitting has the potential to significantly expand the role of solar energy. This STCH technology represents one possible pathway for direct solar hydrogen. However, it is fraught with several extremely challenging technical issues, including the performance of the redox material, circulation of very HT solid particulates, selection of very HT reactor materials, radiative heating of solid particles, etc. Furthermore, the potential for high-efficiency performance is limited.
- Development of a successful STCH approach is well aligned with DOE hydrogen production goals. However, the likelihood of reaching the cost of production goal is extremely low without a breakthrough in redox material, and there has been no clear progress on that front.
- The project is relevant in reaching the ultimate DOE targets for STCH, whether the project goals are achieved or not.

- This project all hinges on a longshot for materials discovery. Leveraging the Materials Genome Initiative (MGI) is a clear advantage.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is excellent-to-outstanding. It is not purely outstanding only because of the lack of any attention in the plan to materials durability analysis and testing. The reviewer-only slide on “Critical Assumptions and Issues” suggests establishing collaborations with a number of institutions with the capability to develop atomistic understanding of materials behavior in the extreme environments of this process. That is an important effort that should be given higher priority than the present plan. The project excuses this deficiency on the grounds that more fundamental research is needed than is possible to conduct in this project, but if this issue is a potential showstopper (and it might be), the project should engage it sooner rather than later. Apart from this single point, the planning and approach in this project are outstanding.
- The project is short and aggressive, so there are a lot of high-risk milestones ahead, but the future work is appropriate for this short of a project period.
- The proposed work is reasonable within the context of the inherent thermodynamic and kinetic challenges.
- The remaining challenges were identified, and research and development (R&D) was outlined for the remainder of 2015 and fiscal year (FY) 2016 for the areas of materials discovery and optimization, CPR2 design and fabrication, and technoeconomic analysis. A reasonable mitigation strategy was presented for completing the project if an optimal redox material with the potential for >20% STH efficiency is not identified. The project is more than one-third over, and there appear to be continuing uncertainties regarding the DLR partnership. This issue should be resolved so the team can plan the remaining project work more effectively.
- The team should increase focus and resources in two areas critical to overall efficiency: (1) finding a material with much higher hydrogen production efficiency, and (2) engineering a way to significantly improve solar-to-particle heating efficiency. The team should sacrifice resources on design/build of an integrated unit to pursue those two areas. The team should develop a model to relate single-particle efficiency (i.e., grams of hydrogen/grams of metal oxide) to overall process efficiency (i.e., tons of hydrogen/day).
- For FY 2015, the team will continue the search for redox material and optimization. The reactor and solar field design will be finalized. For FY 2016, goals include production of 100 kg of redox material, on-sun testing of CPR2, and completion of a full technoeconomic analysis.

Project strengths:

- The project features an excellent project team that has the experience and available facilities to do the work. The project builds on experimental and modeling advances made in previous EERE-funded projects, including decades of reactor design experience at SNL.
- Project strengths include (1) addressing the need for integrated materials and reactor development and (2) taking a fundamental approach to discovery of a novel redox material.
- The facilities and skill sets in this project are outstanding. The project planning and execution are outstanding.
- The project supports some very interesting basic materials science. The collaborations are impressive.
- The team’s understanding of HT reactor systems is an area of strength.

Project weaknesses:

- The extreme technological challenges of this project demand consideration of alternatives. Even if consideration is restricted to purely solar-based hydrogen production technologies, it must be recognized that STH efficiencies of at least 18% can be achieved today with commercially available technology using state-of-the-art photovoltaics providing electrical power directly to conventional water electrolysis units. With HT steam electrolysis, which is at a relatively advanced stage of development (Technology Readiness

Level 5), an STH efficiency of at least 30% should be achievable using concentrated solar heat for the required HT heat addition (at 800°C instead of 1500°C) and state-of-the-art photovoltaics, even without system integration/optimization. This efficiency is three-times higher than the 2015 case associated with the metal oxide thermochemical cycle and higher than the ultimate efficiency predicted for this concept. While efficiency is not the only consideration (the bottom line is dollars/kilogram), it is hard to foresee a scenario in which this technology could be deployed as a practical, large-scale renewable hydrogen production platform. In terms of economics, as pointed out at the DOE Hydrogen and Fuel Cells Program Annual Merit Review by a reviewer, the cost of the HT solar receiver technologies alone may preclude achievement of low-cost hydrogen production using this technology.

- This would be an extremely large, amazingly complex plant. Fundamentally, it is a very challenging route to cost-effective hydrogen. Using commercial operation of cement manufacture and gas turbines to rationalize the feasibility only makes one question whether the challenges are sufficiently appreciated.
- The materials discovery work may be an ever-expanding universe of investigations, rather than one converging on a viable solution for CPR2 testing during the scope of the project. The primary focus for this project should be performing the reactor tests and demonstrating achievement of the project objective to produce 3 L of hydrogen in 8 hours.
- The level of collaboration in this project is good to excellent. The team needs to establish ties with an entity that has advanced characterization capability to explore the limits on active material durability. The project would benefit enormously from better coordination and collaboration between SNL and UC.
- Weaknesses include not fully recognizing the long-term nature of the concept and not tailoring the project scope accordingly.

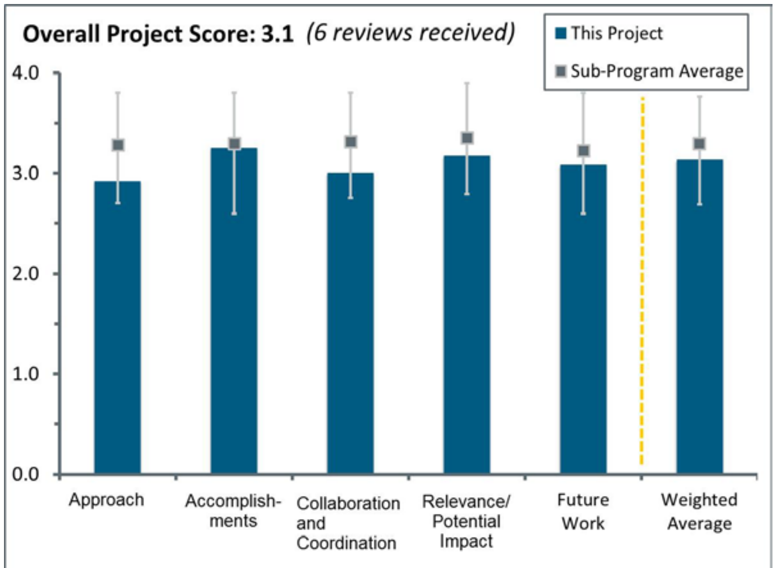
Recommendations for additions/deletions to project scope:

- The team should adjust the project scope as needed—in particular, the materials discovery activities—to match the time and resources available (including the absence of DLR contribution, if necessary) for this project. The team should also leverage past modeling and thermochemistry/kinetics testing to focus on a few key parameters/descriptors in order to meet project performance goals in 2016. If necessary, the researchers should rely on the mitigation plans presented to meet the project objective of 8 hours of continuous operation, under on-sun conditions, to produce more than 3 L of hydrogen. Materials discovery to identify optimal reaction material is important and exciting, but it can continue under future projects if an optimal material is not found in this project.
- Because this approach is in such an early stage of development, perhaps DOE should consider splitting the material discovery and the reactor teams into separate projects so the researchers can focus on their respective objectives without the unrealistic expectation of impacting each other’s effort in the duration of the project. However, the two teams should continue to interact and share results with longer-term DOE goals in mind.
- The team should be clearer in terms of its key technoeconomic assumptions—these will make or break the eventual commercial success of the approach and need significant effort to meet. It is unclear what the current status is, how far away the target is, and what the plan is to close the gap.
- It is absolutely critical that a fully functional, integrated, on-sun, long-duration demonstration of this technology is completed as soon as possible. Successful achievement of such a demonstration would go a long way toward justifying further investigation of this concept.
- Active materials R&D should include some detailed investigation of the effects of kinetics and oxygen vacancy levels on active material bond strength for better understanding of the relationship between production capacity and material durability.

Project # PD-114: Flowing Particle Bed Solarthermal Redox Process to Split Water

Al Weimer; University of Colorado

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

The overall objective of this project is to design and test the individual components of a novel flowing particle solarthermal water splitting system capable of producing 50,000 kg of hydrogen per day at a cost of <$2/kg of hydrogen. Further objectives include (1) identifying and developing high-performance active material formations; (2) synthesizing flowable, attrition-resistant, long-use spherical particles from low-cost precursors; (3) demonstrating high-temperature (HT)-tolerant, refractory, non-reactive containment materials; (4) constructing a flowing particle redox test system and testing components of the system; and (5) monitoring progress toward cost targets by incorporating experimental results into frequently updated detailed process models.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project is a follow-on effort to previous work funded through the Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Office (FCTO). The technology being developed in the current effort includes an innovative new reactor design for solar thermal water splitting. The project approach (including identification of materials of reaction, synthesis of reactive particles, design and demonstration of HT containment materials, iterative updating of an Aspen process model and the Hydrogen Analysis (H2A) model, and on-sun testing at the National Renewable Energy Laboratory [NREL]) is to test and validate the performance of components of the new design to move the technology concept from Technology Readiness Level (TRL) 2 to TRL 3. This approach is feasible and logical, and it includes integrating efforts from a U.S. Department of Energy (DOE)/National Science Foundation (NSF)-funded materials discovery project. Challenges and barriers were identified and will be addressed in future work. More information on the research and development (R&D) status and specific R&D plans for characterizing particle attrition resistance and high gas-gas heat recuperation would have been useful because these factors are critical to the success of the technology.
- The approach described in this project is good to excellent. The effort in materials development is outstanding, providing a high-throughput methodology for candidate active materials identification. At the same time, materials durability remains an unresolved issue. The barrier associated with chemical reactor development is addressed, but not comprehensively. Key issues such as the use of an inert gas sweep within the reactor have been addressed, but the use of a common cavity for both the oxidation and reduction reactions is problematic, unless the cavity is evacuated. Design and modeling are proposed, but absent a vacuum environment, it will be impossible to achieve anything like separately uniform temperature environments for the two reactions. Departures from uniformity mean some portion of the reactors will be at higher-than-required temperatures and some portions will be at lower-than-required temperatures. Process efficiency and the cost of active material reservoirs will suffer from a common chamber design. The approach provides for some integration with theoretical work that materially aids the identification of promising active materials, but key material characterization that could help assess the trade-off between production capacity and material durability is lacking. Material characterization capabilities are highly

specialized and require access to technology well beyond the scope of most institutions. This project would be improved by collaborating with existing characterization capability, with the aim of developing a basic understanding of the relationship between activity, reactant oxygen vacancy levels, and material durability. There is no guarantee that needed production capacity is compatible with material durability.

- The project features a good balance between fundamental understanding of materials, proof-of-principle laboratory testing, and process development. The project team might be taking the challenge of complex solar reactor design too lightly, given the importance of high efficiency for converting sunlight to very hot particles in the reduction zone. The team should maintain a heavy focus on finding redox materials with improved performance; the researchers should not let this focus slip.
- This project focuses on the development of innovative, HT solar thermochemical (STCH) water splitting processes based on a cobalt ferrite/hercynite redox cycle. The overall project objective is to design and test components of a flowing-particle solar-thermal water splitting process for 50,000 kg/day hydrogen production. The specific approach includes production and characterization of reactive materials and engineered particles, design of a particle flow reactor, development of thermal-shock-resistant containment materials, and demonstration of on-sun performance. Goals for this project include construction and operation of an HT (1500°C) particle flow redox system and demonstration for reduction/oxidation of >1 gm of active material. This project appears to be a direct continuation of PD-028, which ran from 2005 to 2014.
- Designing the reactor so that it is located in the receiver seems like an enormous technical challenge. The remainder of the proposed project seems logical, although the stability of the particle and reactor components must be addressed in more detail. Also, the precipitous drop in projected cost from the H2A model with moderate changes in parameters is shocking.
- H2A indicates the heat exchanger is key for the success of the system, but there does not seem to be a large emphasis on its development. The reactors and particle storage at the top of the tower will necessitate a very large tower that appears to be expensive. The proposed design has many obvious problems, such as heat transfer, material compatibility, challenges with HT valves, construction, etc., and should be reconsidered. The researchers are proposing to coat their large reactors with SiC for material compatibility with the redox environment. The use of a fluidized bed approach with SiC raises concerns. The fluidized bed will be similar to sandpaper wearing on the SiC, raising questions about durability and lifetime. Based on the design proposed and the H2A presented, the focus of the research should be on improved heat exchanger design and SiC material development. The improved heat exchanger design is not being done. Spray synthesis of the materials is more applicable to high-volume production than the atomic layer deposition (ALD) approach used in previous efforts.

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

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

- The project's accomplishments and progress toward its objectives have been excellent. Progress in achieving the DOE Hydrogen and Fuel Cell Program (the Program) target goals is good. The project plan is establishing specific materials performance testing at the expense of investments in particle durability and concept design. The plan is good but not outstanding. There are many materials but few reactor concept designs that will enable performance leading to meeting the Program's target metrics. Absent durability, active material performance is interesting but not pertinent to Program targets. Absent reactor concepts that can meet cost and performance targets, Program goals are not within reach. A more balanced project plan that identifies specific and quantitative go/no-go metrics is needed. The update of the Aspen Plus model to include process-specific functions and to include experimental results is an outstanding contribution to assess process performance.
- Good progress has been made to date in this new project, particularly in the areas of modeling and performance prediction, constructing and upgrading test reactor systems, and materials discovery (through the NSF/DOE project partnership).
- Good progress has been made regarding materials, preliminary reactor design, and process modeling. The technoeconomic analysis, with identification of key sensitivities, is also good. The very low sensitivity to redox material activity is surprising—a high-level explanation is warranted. The production of 0.00085 kg

hydrogen per kg of active material per reactor cycle (so even less on a particle basis) means there is a need to move a huge amount of solids around at a very high rate to generate nearly 2 kg hydrogen/sec (50 ton/day with production limited to 8 hours/day)—about 2,000 kg per second around the loop. Increasing that activity should be a big hammer on the overall economics, but the analysis says it is not. It would also be good to see an overall solar-to-hydrogen (STH) efficiency metric reported (current status and outline of path to target).

- The Aspen analysis is good. It is not clear that the reactor design concept is practical in a real-world, full-scale situation. The major cost savings, according to the H2A analysis, are in the heat exchanger, but it is not clear that work is being done on designing and improving the heat exchanger. The spray synthesis approach has some promising results. The sweep gas analysis was interesting, even if some of the other researchers disagreed.
- The reactor design has been updated to include an inert sweep gas, which yields improved overall performance by eliminating the low-efficiency vacuum pump. The reactor design has also been improved with a realistic receiver concept, although the details of radiative heat transfer to the particles still need to be worked out. An Aspen process model has been developed. An updated H2A model has been developed. Computational materials modeling (integrated computational, theory, and experimental approach MGI) has been performed to predict the hydrogen production capacity; the model has been validated with experimental results. Characterization of the engineered materials is underway. A particle flow reactor laboratory is being developed. SiC coating capability is being developed. Progress over the previous project has been modest to date.
- The project seems on task to date, but it is still early in the project, and many milestones are ahead.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- An excellent project team at University of Colorado (CU) and NREL has been assembled for this effort. In addition, leveraging CU interactions with the Australian National University (ANU) and the Saudi Basic Industries Corporation (SABIC) will provided added value to the project. The project team should take the opportunity this project offers to provide leadership in coordinating across the community to establish conventions for analysis, best practices, and key measurements.
- The project features good integration with the NSF "sister" project. It does a good job of leveraging outside funding sources (e.g., the NSF "sister project"), ANU, and SABIC. Collaboration with Sandia National Laboratories (SNL) would be good.
- Collaboration and coordination with other similar work is satisfactory to good. It would be better if rapport could be established between other similar STCH project being funded at a national laboratory and CU. Project teams are pursuing very similar objectives using very similar general approaches and using materials derived from the same general class. Both teams appear to have chosen competitive—instead of cooperative and collaborative—postures. The project goals would be far better supported if these two institutions could work together to solve their common and challenging problems. The project plan provides for some integration with theoretical work that materially aids the identification of promising active materials, but key material characterization that could help assess the trade-off between production capacity and material durability is lacking. Material characterization capabilities are highly specialized and require access to technology well beyond the scope of most institutions. This project would be improved by collaborating with an entity that has existing characterization capability to develop a basic understanding of the relationship between activity, reactant oxygen vacancy levels, and material durability. There is no guarantee that needed production capacity is compatible with material durability.
- The project features a good set of collaborators, particularly on the materials side, where the researchers are leveraging a "sister" MGI project. It is not clear whether or how the team is accessing the needed expertise on complex solar reactor design and the critical thermal recuperation step. If this collaboration is missing, the team should consider adding a partner in this area because high sun-to-hot-particles efficiency is critical.
- Collaborations have been established with NREL (high flux solar furnace user facility), ANU (solar simulator), and SABIC (materials characterization).

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

This project was rated **3.2** for its relevance/potential impact.

- The relevance of this project is excellent to outstanding. The potential impact is satisfactory to good. The potential impact assessment is based on the project's characterization of its detailed objectives. High-performance material formulation would have high hydrogen production capacity, meaning high numbers of oxygen vacancies per mole of active material, along with fast redox kinetics, meaning a significant energy difference between the initial and final states for the oxidation step. Both of these features would likely reduce active particle durability, making achievement of the cost target very difficult.
- The project supports the EERE FCTO goal of reducing the cost of hydrogen production from renewable resources to <$2/kg by 2020. In addition, it supports the objective to verify the competitive potential for STCH cycles for hydrogen in the long term by 2015, and by 2020 to develop this technology to produce hydrogen. Meeting the cost goal will depend on the successful completion of this project, but also on technology development beyond the scope of the project and FCTO (e.g., lowering the cost of the heliostats to the DOE Solar Program SunShot target).
- Leveraging the MGI is a clear advantage.
- STCH is very well aligned with DOE's long-term goals for centralized hydrogen production. However, it is an approach with a large number of substantial technical (particularly materials and engineering) challenges with no practical base off which to build. It is not obvious how it will gain a long-term advantage over the photovoltaic electrolysis approach.
- Development of an efficient, cost-effective direct solar process for water splitting has the potential to significantly expand the role of solar energy. This project claims to have a long-term potential for low cost hydrogen production. However, it is difficult to foresee a path to low-cost, large-scale hydrogen production using this technology that is achievable in a reasonable time frame.
- There is a need for low-cost renewable hydrogen.

Question 5: Proposed future work

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

- The project team has effectively outlined future work in reactive and containment materials development, reactor design, and modeling and prediction in a logical manner, with milestones and go/no-go decision points identified. In the future, more information on activities and plans in the following areas would be helpful:
    - Lifetime (durability) of reaction particles to reach production cost goals.
    - Demonstrated feasibility of achieving the gas-gas heat exchange levels needed to reach efficiency and cost goals.
    - Scale-up feasibility of ALD and other fabrication technologies to apply materials of containment coatings to full-size components.
    - Next steps for the 19% of perovskites screened that fell within the acceptable enthalpy range.
- The proposed future work is good to excellent. This element would be improved with greater attention to active particle durability and some investment in alternative receiver/reactor design.
- The focus and plan for laboratory-scale testing is good, as is the model-guided materials development. It would be good to see a plan to address heat exchange efficiency because this was identified as the primary technoeconomic sensitivity. Also, there should be analysis of the capital costs, including sensitivities (e.g., the assumption of how much 2.9 kT of redox material would cost is unclear).
- The researchers are focusing on the material development, which is most important at this stage. According to their H2A analysis, the single biggest need is low-cost heat exchangers, but there is nothing in the proposed work to deal with this challenge.
- Continued work will be performed on the development of reactive materials, HT reactor design and development, materials containment development, and improved system modeling (Aspen).
- More discussion of alternative pathways in case milestones fail would be helpful and beneficial.

Project strengths:

- The facilities and skill sets are excellent. This is one of the most experienced teams in thermochemical hydrogen production. The team has an outstanding history of changing directions when the focus of the work proves to be unfeasible.
- The researchers have "sister" funding through NSF. They have moved beyond the ALD synthesis to spray synthesis. Spray synthesis is inexpensive and amenable to high-volume fabrication. While this project is new, the researchers have been working in this area for a very long time.
- The project strengths include an innovative reactor design and materials approach, an excellent project team, and leveraged interactions with other researchers.
- Progress has been made on redox material synthesis. The project will support HT reduction and oxidation operations at the laboratory scale this year.
- Project strengths include the integration of modeling and experimental research approaches.

Project weaknesses:

- There are no serious weaknesses, but the future work should focus on critical points—namely, demonstration of particle attrition resistance, sufficient gas-gas heat exchange and heat transfer in the reactor during operation, and the feasibility of application of coating materials of containment to full-scale components.
- This project faces many of the same extreme technological and economic challenges as other HT STCH processes. These challenges include identification of an appropriate redox material that will enable long-duration, high-efficiency, low-cost operation; selection and demonstration of reactor materials for very HT operation; and management of solid particulate circulation and radiative heat transfer. The magnitude of these challenges should not be underestimated. Furthermore, this technology must be shown to be competitive (at least in the long term) with other hydrogen production technologies, in general, and with other solar water splitting technologies, in particular. Solar water splitting can be accomplished today with commercially available technology using state-of-the-art photovoltaics (PVs), providing electrical power directly to conventional water electrolysis units, with a demonstrated efficiency of 18% or higher. HT steam electrolysis, at TRL 5, could also be operated as a solar water splitting technology using concentrated solar heat for the required HT heat addition (at 800°C instead of 1500°C) and state-of-the-art PVs. STH efficiencies of at least 30% should be achievable with current technology. In terms of economics, the cost of the HT solar receiver technologies alone may preclude achievement of low-cost hydrogen production using the HT thermochemical processes.
- There are significant questions on the reactor/receiver design. The researchers propose to coat the reactor with SiC to improve the material compatibility. It is likely that the fluidized bed approach will wear off the SiC. This needs to be addressed.
- The level of collaboration in this project is satisfactory. The team needs to establish ties with an entity with advanced characterization capability to explore the limits on active material durability. The DOE Hydrogen Production sub-program would benefit enormously from better coordination and collaboration between SNL and CU.
- Weaknesses include the heavy academic weighting and the lack of collaborators with practical, large-scale engineering experience with complex reactors and processes.

Recommendations for additions/deletions to project scope:

- Reactive materials R&D should include some detailed investigation of the effects of kinetics and oxygen vacancy levels on active material bond strength for better understanding of the relationship between production capacity and material durability. In reactor design, the common chamber redox concept should be examined for temperature profiles assuming something close to the planned solar flux profile to qualify/quantify temperature distributions and non-uniformity effects in both reactors. It is possible the common chamber concept is not workable. Some preliminary design of separate reactor chambers might be warranted.

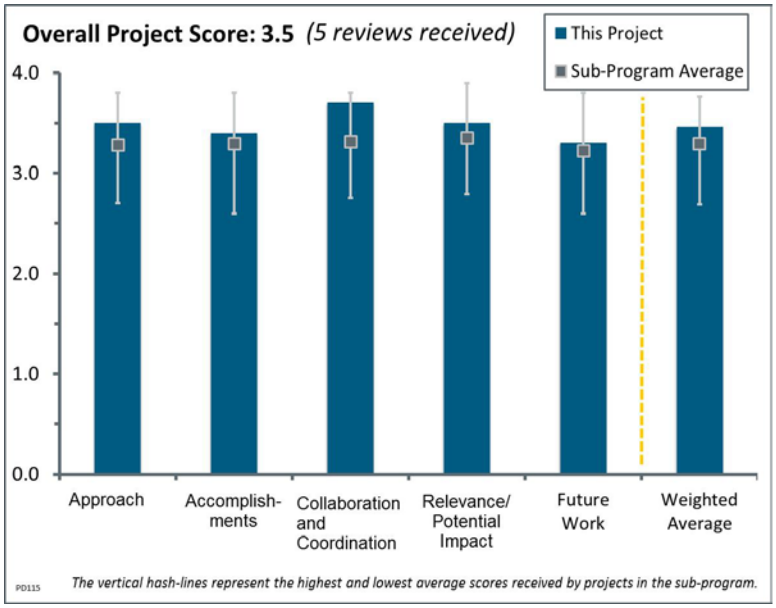
- It is absolutely critical that a fully functional, integrated, on-sun, long-duration demonstration of this technology is completed as soon as possible. Successful achievement of such a demonstration would go a long way toward justifying further investigation in this concept.
- The comparison studies between inert gas sweep and vacuum pumping appear to be a recently added task. It may be helpful to conduct a more extensive literature search on the relative merits of the two approaches before initiating R&D on this topic.
- The project team should add input from a consultant with experience in cost estimates for large circulating-bed type reactors to shore up the economics.
- The researchers need to redesign their main reactor/receiver concept.

Project # PD-115: High-Efficiency Tandem Absorbers for Economical Solar Hydrogen Production

Todd Deutsch; National Renewable Energy Laboratory

Brief Summary of Project:

The long-term objective of this project is to develop a durable, semiconductor-based, solar-driven water-splitting device with greater than 20% solar-to-hydrogen (STH) efficiency that can operate under 10–15 times (or higher) solar concentration and generate renewable hydrogen for <$2/kg. Current year objectives include (1) pushing boundaries on achievable semiconductor photoelectrochemical (PEC) solar-to-hydrogen efficiencies through development of new materials and structures, and (2) continuing development of stabilizing surface modifications viable at high current densities.



Question 1: Approach to performing the work

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

- The objective of this project is to develop a highly efficient, durable material for PEC water splitting using concentrated solar energy. For this technology, efficiency was identified as the most significant driver for reducing hydrogen cost. Therefore, the primary focus of the work is on increased STH efficiency through the use of tandem absorbers. Durability can be improved through the use of surface modifications (e.g., ion implantation, flash sputtering, atomic layer deposition, and moly disulfide [MoS_2] coatings). New materials are sought for ultra-high efficiency. The materials discovery search incorporates theory, modeling, and experimentation. STH efficiencies of 20% are stated to be feasible. Ultimately, low-cost cell synthesis will be required. The approach includes theory, modeling, and experimentation.
- The project team has responded to U.S. Department of Energy (DOE) targets for PEC efficiency, durability, and cost barriers.
- The team's approach of focusing on III–V semiconductors is consistent with the Office of Energy Efficiency and Renewable Energy STH efficiency targets of 20%–25% because there are very few materials combinations outside of III–V materials that are capable of reaching these efficiencies. The National Renewable Energy Laboratory is well positioned to do this research, given the expertise of its III–V synthesis team and the team's history of using these materials for PEC water splitting. One potential weakness of the approach is the reliance on high optical concentration for favorable economics with III–V-based absorbers. While low concentration (e.g., approximately 10x) has been demonstrated in a large-volume laboratory test cell, there are significant constraints for a real-world reactor.
- The approach of this project addresses durability and fabrication costs of III–V materials to advance device performance levels of this record-achieving material. This is one of three proposed approaches to meeting DOE targets for PEC performance. This plan is strategic and derived from PEC community consensus that affords alternative or backup lines of investigation should any one or two of the alternative lines of research prove to be unfeasible. The general strategic plan is excellent, building on successful materials while seeking new, improved materials and device configurations in collaboration and coordination with the PEC technical community. Regarding materials durability, the presentation indicates that materials durability can be met through engineering, but theoretical studies and advanced characterization work is also warranted to understand how interface treatments are effective (or not) in improving durability while

retaining performance. It would appear that III–V material durability will not be achieved by engineering alone. In that case, the project timelines are probably unrealistic. Regarding integrated device configurations, the presenter stated that the current device design is unsuitable for solar concentration levels or the reduced electrolyte optical depth proposed for meeting efficiency targets. Design options were not presented or discussed.

- This design of the approach is sound and well thought out. It leverages years of research in the field to focus on the central issues and barriers to the success of PEC hydrogen production. The Surface Validation Team should include consideration of the kinetics of surface decomposition because the branching ratio of the rate of decomposition to the rate of all reactions determines durability. The present approach contains only examination of the static aspects of durability.

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

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

- The team has demonstrated the use of an “inverted metamorphic multijunction” for increased utilization of the solar spectrum. Durability of >400 hours was achieved. Some fouling occurred; cleaning of the cell surface using methanol and nitric acid restored photocurrent to the original value. Surface modification with N_2+PtRu was achieved and characterized. Nitrogen decreases the bandgap and stabilizes the cells. A new reactor design reduces the optical path length through the electrolyte, thereby increasing cell efficiency.
- Initial results with the inverted metamorphic multi-junction (IMM) cells are very encouraging (especially considering the processing mistake limiting the current density). It seems inevitable the team will demonstrate 15%–20% STH in the near future, which will be a world record for this sort of tandem device. The design is shown for a new test cell that will minimize the distance between the electrode and the window, but no clear plans for a realistic reactor design that would operate under 10–100x concentration with minimal solution IR loss were provided. Developing a more concrete design and experiments using the fabricated reactor should be important goals. A 50–100x concentration is unrealistic. At 50x and with 20% STH, this is approximately 800 mA/cm^2. It may be possible to deliver reactants to the surface and prevent bubble build-up with a flow cell at these higher concentrations, but avoiding significant IR drop, even in 3 M H_2SO_4, would require a very small gap between counter electrode and photoelectrode. A/cm^2 current densities are achieved in polymer electrolyte membrane (PEM) electrolysis with only a 100–300 mV IR drop, but that is because the researchers are using 50–90 μ thick Nafion solid electrolyte.
- Durability testing showed good-to-excellent progress by reaching the 400-hour durability milestone, but the testing methodology is unsatisfactory because of electrode fouling. The project should establish the cause and remediate fouling to achieve a satisfactory durability testing protocol. Additionally, the project must establish the reason for degradation of photocurrent onset potential. It is possible that the durability treatment affects catalyst activity lifetime or leads to catalyst loss. Either phenomenon would reduce durability progress. Additionally, the poor performance of the “new standard” ion gun and PtRu sputtering setup suggests continued ignorance regarding earlier success with the “magic” sample. It is possible that some unknown contaminant derived from the original setup is essential to reliable durability treatment. Investigation of IMM fabrication is an excellent initiative that promises improved junction morphology while affording potential cost reduction in both material component assembly and device production. In addition, the IMM process enables buried junction fabrication that allows effective use of the solar spectrum while maintaining adequate current density. Progress on the reactor design is good to excellent. Recognition of the electrolyte optical depth effects on STH performance is important, and implementation of design changes is underway. However, system thermal management and gas transport issues become more important and difficult to resolve. It is unclear whether the original general concept can be retained.
- Although it is still early in the project, investigators have completed several characterization studies on catalyst distribution and the effect of surface modifications. A reactor design to improve optical concentration has also been developed. A 400-hour durability milestone was completed, but some work remains to determine performance degradation mechanisms.

- The team has made commendable progress; the work was competently done and featured good technical support. It appears that “fouling” of the electrode has a greater impact on durability than any electrode/catalyst decomposition. A better grasp of this problem is needed at a chemical level.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration and coordination with other institutions and related technical work is excellent to outstanding. The PEC Working Group is inherently a broad collaborative enterprise, and improved coordination with photovoltaic (PV)-based III–V activities is an important addition to the project.
- One of the strengths of this project is its large number of collaborators in the field of PEC research and development.
- The project includes 10 university partners, plus Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory.
- The coordination with other institutions is very good. If the kinetics and chemistry aspects of the problems cannot be addressed within this group, more outside help should be sought.
- There is good collaboration with the surface science group (Heske/University of Nevada, Las Vegas); the researchers have used this collaboration to understand stability. No aspects of the theory collaboration (Ogitsu/LLNL) were discussed.

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

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

- The relevance and potential impact of the project are excellent to outstanding. The PEC Working Group investment in performance metrics and testing protocols has significantly improved the reporting basis for the entire PEC community. At the same time, identification of the role of upper and lower bandgaps in optimizing STH performance of simple integrated devices has provided excellent guidance to the selection of promising materials and doping/alloying strategies for development and testing. Optimal performance of 25% STH is challenging but possible, and 20% STH appears to be achievable. The identification of component fabrication and integration processes is leading to the development of pathways to reduced device cost, which, in tandem with increased STH performance, promises the possibility of meeting DOE Hydrogen and Fuel Cells Program (the Program) goals for PEC hydrogen production.
- The project is highly relevant to renewable hydrogen production and consistent with DOE’s goals/mission. As illustrated by the Hydrogen Analysis (H2A) model’s technoeconomic analysis and discussed in the presentation, the potential impact of this technology is highly dependent on the ability to bring down III–V synthesis/fabrication costs with alternative, scalable manufacturing methods.
- This work supports the development of direct STH PEC cells. PECs operate at low temperature and are potentially more efficient and less expensive than PV/electrolysis for solar water splitting. Successful development of this technology would expand the role of solar energy to include distributed hydrogen production for the transportation sector.
- PEC water splitting is a long-term technology in DOE’s portfolio. The objectives are in line with DOE targets to develop cost-effective and efficient PEC materials.
- Given the technoeconomic analysis upon which this project is based, this is the logical approach to the problem of hydrogen production.

Question 5: Proposed future work

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

- The principal investigator (PI) is pressing toward the right endpoint—getting something that works and pushing it to the prototype stage. That is when the next round of challenges becomes apparent.

- The project has a defined path to improve PEC cost, efficiency, and durability.
- The STH and durability next-step targets are good to excellent, although the presentation did not describe the future work to understand the treatment processes for durability enhancement. Use of lower bandgap configurations to achieve higher current density is not accompanied by adequate description of means of retention of water splitting capability, so it is not clear what value should be given to this future work task. The statement in the presentation that "Multi-physics" modeling will be used to evaluate limits on achievable concentration is unclear. It is also unclear whether there is concern about photoactivity saturation effects or about thermal management issues. The latter seems more likely to be the controlling factor but requires significant concept design detail for evaluation. The photoreactor prototyping task seems to precede significant effort in concept design and performance simulation. The proposed order seems backwards. Whereas the presenter stated that work is already proceeding in new photoreactor concept development, the task of simulating performance under operational environments is significant and should precede prototype development. The presentation showed little concept design beyond the original general concept, so it seems that significant concept design work remains before performance simulation can proceed.
- It is apparent that long-term stability tests are a challenge for the small photoelectrode sizes, which necessitate the use of surfactant to avoid bubbles but create fouling of the counterelectrode. If at all possible, larger electrodes should be made and/or different sealing methods should be employed to avoid this issue and unambiguously demonstrate stability targets. For some of the same reasons that the team is presently having issues with its long-term stability measurements, a real PEC reactor would not likely operate with surfactant present. Previous results of MoS_2-coated p-n Si photocathodes show that linear sweep voltammetry (LSV) curves are shifted to significantly more negative potentials (100–200 mV) compared to using Pt. It is unclear whether it is feasible to achieve efficiency targets with MoS_2-protected photocathodes. On the topic of light concentration, it is not clear how sensitive the H2A analysis is to light concentration. Although Pinaud's *Energy and Environmental Science* article compares Type 3 reactor @ 1 sun and Type 4 reactor @ 10 suns, this reviewer has not seen an H2A analysis (i.e., Tornado plot) showing how sensitive the Type 4 hydrogen cost is to light concentration. This would be valuable to know.
- The team will attempt to demonstrate increased efficiency (i.e., >15% STH) with lower bandgap configurations. The researchers plan to demonstrate 875-hour durability under 1 sun in outdoor conditions. Photoreactors will be designed and built with low optical concentration and low electrolyte penetration depth.

Project strengths:

- Important strengths are the project team's quality, in-house facilities, and open teaming and collaboration approach to satisfying other facilities and expertise requirements. Another strength is that its relationship with the Advanced Materials Manufacturing (AMM)/Materials Genome Initiative (MGI) efforts helps to populate the third approach to meeting the Program goals by identifying promising third-generation materials.
- The DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR) presentation was excellent. The work is very promising, but challenges remain in the areas of cost, durability, and materials. Overall, this technology appears to have great promise.
- The project's strengths include its good approach and the team's expertise. The team has a great likelihood of meeting world-record efficiency targets.
- Strengths of this project include the collaboration among team members with experienced backgrounds in PEC synthesis and characterization.
- The project features an excellent technical staff and facilities, as well as an experienced group of collaborators.

Project weaknesses:

- There was no mention of plans to scale up to larger electrode areas. A detailed plan for reactor design is missing from the presentation. Even if the reactor design is not demonstrated in this project, it would be great to include this plan to illustrate the vision of what a commercially viable product/reactor would look like. A complete, explicit list of milestones was not provided. It would be useful to include this for the next AMR.

- A large cost may be incurred in the fabrication of a complete PEC system (i.e., integration of liquid/gas plumbing and electrical connections), and it may be difficult to achieve DOE's 2020 future cost targets. Although it is early in the project, a discussion of scale-up challenges should be presented.
- The technology as presented uses sputtered-on PtRu (with N) as a catalyst durability layer. This approach may have significant cost implications. The team is also evaluating non-platinum group metal (e.g., MoS_2 and atomic layer deposition TiO_2) surface treatments.
- The projected need of electronic-grade materials requires guidance from a physicist/device physicist, which leaves the research group open to being blind-sided by chemical problems. The PI needs to compose a chemical "think tank" from among collaborators to cover this condition.
- The project is complex, and the team must overcome many obstacles to meet the project objectives and/or the Program goals.

Recommendations for additions/deletions to project scope:

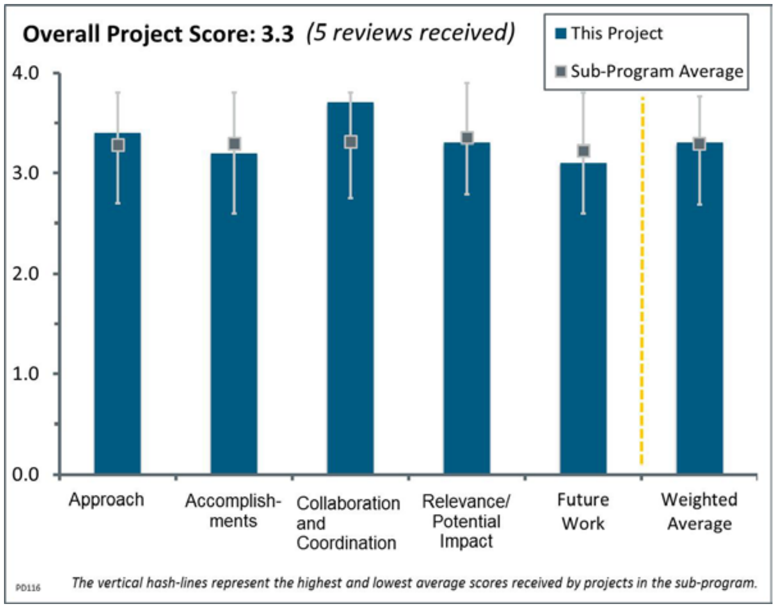
- The project scope is mostly appropriate.
- Having a significant solar concentration level is a central ingredient of this project. In this regard, thermal management is likely to be a limiting feature for photoreactor design options. The project might be improved significantly by including design and engineering work to evaluate thermal management issues.
- The team should add additional details regarding the cost analysis related to scale-up.

Project # PD-116: Wide Bandgap Chalcopyrite Photoelectrodes for Direct Solar Water Splitting

Nicolas Gaillard; University of Hawaii

Brief Summary of Project:

The long-term objective of this project is to identify efficient and durable chalcopyrite-based materials that are capable of generating hydrogen via photoelectrochemical (PEC) water splitting at a cost of $2/kg or less. Leading efforts involving theoretical modeling, synthesis, and advanced characterization, the Hawaii Natural Energy Institute (HNEI) will (1) develop new wide bandgap (>1.7 eV) chalcopyrites compatible with the hybrid photoelectrode design, (2) demonstrate at least 15% solar-to-hydrogen (STH) efficiency, and (3) generate 3 L of hydrogen under 10 times concentration in 8 hours.



Question 1: Approach to performing the work

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

- HNEI is exploring potentially low-cost chalcopyrite photoabsorbers with tunable bandgaps, which represent a very promising class of materials to achieve high STH conversion efficiencies with a tandem device. The materials development approach includes systematic evaluation of the solid-state properties of the chalcopyrite absorber layers separate from the electrochemical environment. This is a useful means of deconvoluting catalysis and corrosion effects from the performance of the chalcopyrite absorber. The researchers are spending early efforts exploring new emitter layers for the new chalcopyrite absorber layers, which is a well warranted and important task if they are to achieve the performance milestones. The project milestones are clearly presented.
- The project features a well-defined approach that focuses on accelerating material development through modeling, synthesis, and characterization of chalopyrite materials. The approach addresses barriers of efficiency to final synthesis and manufacturing.
- This project aims to identify and develop new wide-bandwidth (>1.7 eV) copper chalcopyrites ($CuInGaSe_2$) for PEC water splitting using an integrated experimental, computational, and theoretical approach. The cells under consideration are “hybrid photoelectrode” (HPE) cells. These cells include high-current-density photovoltaic (PV) “drivers” with wide-bandwidth PEC cells.
- This work is one of three general approaches to PEC performance achievement. It seeks new materials with characteristics that hold promise for meeting the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) goals in 2025 and complements the second approach of seeking to stabilize and improve on existing materials with high STH efficiency. The general approach of this project is excellent. It builds effectively on earlier work and is sharply focused on barriers to achieving the Program goals. The selection of copper chalcopyrite alloys for bandgap management has proven effective in identifying potentially satisfactory candidates for meeting STH goals. The project suffers most from requiring PV-grade materials and device fabrication and integration. The cost of materials and device fabrication will likely prove seriously challenging. Integration, coordination, and collaboration with other work (e.g., device testing, materials characterization, process execution, and evaluation) are outstanding.
- The project is well conceived, given the goals. The development of new absorbers is commendable, yet risky, because one must learn new surface chemistry with each new compound. Given the use of S and Se

compounds, the principal investigator (PI) should consider assembling the data on the stability of these compound solids as a class and not analyze each electrode's stability as an individual case.

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

This project was rated **3.2** for its accomplishments and progress.

- The progress is good to excellent, as exemplified by the conclusion that alternative copper chalcopyrite alloys are necessary to meet project goals. The identification of three potentially successful wide bandgap candidates is outstanding. Evaluation of sulfurized conventional chalcopyrites and their photoactivity is an important step that allows follow-up investigation of improved alloys with appropriate tandem band levels for water splitting. The role of sulfides in both interface durability and buffer performance in conventional copper chalcopyrites is an important advancement. It is important to follow up with identified alloys to demonstrate that these conclusions are not contradicted by alloyed characteristics. Exploration of new material surface energetic performance (such as ZnO) is crucial to continuation of progress. Interface stabilization with moly-sulfide demonstration is good but insufficient to meet the Program durability goals.
- Three promising high-bandgap, PV-grade absorber compositions (i.e., $CuIn_{0.4}Ga_{0.6}S_2$, $CuGaSe_{0.7}S_{0.3}$, and $CuIn_{0.2}Al_{0.8}Se_2$) have been identified. PV-grade absorbers have been demonstrated at 1.55 eV. The crucial role of surface Cd doping has been demonstrated. Chalcopyrite photocorrosion has been quantified, and advanced characterization methods have been developed to identify mechanisms. The HPE system has been simulated to identify solid-state requirements. The team also investigated a PEC reactor with a 10x solar concentrator.
- Overall, the team has made good progress toward project and DOE goals. The early work has demonstrated the team's ability to precisely tune the bandgap of the chalcopyrite materials of interest and reported promising solid-state and PEC performance (current density and photovoltage) for some of these alloys.
- The team is on track to complete milestones for 2015. The performance of chalcopyrite photoelectrodes that can generate 12 mA/cm^2 will be a key go/no-go decision in the near future.
- The progress has been extremely good—not so much regarding the number of compounds created, but in terms of the establishment of an integrated approach to theory, modeling, and synthesis to create new absorbers.

Question 3: Collaboration and coordination with other institutions

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

- This project is inherently outstanding in collaboration and coordination, partly due to its strong presence within the PEC Working Group and partly due to its incorporation of testing and evaluation collaborations with material experts in related but different lines of research. These are shown in the presentation element "Project-specific collaborations."
- The project features excellent collaborations, including theoretical and surface science support in addition to tie-ins with the Materials Genome Initiative.
- The project features a well-established team capable of addressing DOE's cost and performance barriers for PEC water splitting.
- Collaborations have been established with The Swiss Federal Laboratories for Materials Science and Technology, Columbia University; the University of Los Andes (Colombia); the National Institute of Advanced Industrial Science and Technology (AIST, Japan); the University of Bordeaux (France); and the University of California, Irvine.
- It is disappointing to hear the PI has had no input from the Stanford group at this stage of the project execution.

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

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

- The relevance of the project to the Program objectives is excellent to outstanding. The potential impact is outstanding, largely because of the incorporation of this work in the PEC Working Group, arguably the best example of expert team collaborations in response to huge technical and cost performance challenges. The PEC Working Group investment in performance metrics and testing protocols has significantly improved the reporting basis for the entire PEC community.
- Overall, the project is relevant because it involves the development of efficient, direct STH PECs. This project aims to create the first all-chalcopyrite HPE device to achieve PV-grade performance with thin-film materials to meet DOE goals.
- The discovery of new semiconductors for PEC work is always impactful, especially those that can be synthesized differently from the standard electronic-grade solids. These semiconductors provide opportunities for future device development.
- The objectives of the project are in line with DOE’s targets regarding the development and fabrication of cost-effective and efficient PEC materials.
- The project is relevant to DOE goals and has a high potential impact if a tandem chalcopyrite-based device can be demonstrated with STH >15%. The viability of a mechanical tandem for a commercial device and the challenges of manufacturing a high-performance monolithic device could limit the potential impact.

Question 5: Proposed future work

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

- The future work is well defined. A critical junction in this project will be whether the team can demonstrate chalcopyrite photoelectrodes capable of 10–12 mA/cm^2 with bandgap greater than 1.7 eV. It may be early in the project, but it would be good to see additional discussion on the cost of a full-scale system.
- The proposed future work is good. The future work plan is abbreviated, although the intense focus on quantitative targets is outstanding. The plan does not include investment in a general design for supporting the long-term DOE Program goal.
- A device design of a monolithic tandem is illustrated on slide 8, but it would also be useful for the team to show a schematic that illustrates the team’s vision for what the complete, integrated device for real-world application might look like. For example, it is not clear how ion transport between the front and the back of the device would be achieved. This is not shown in the current side-view schematic. In situ x-ray emission spectroscopy (XES) measurements of $CuGaSe_2$ are proposed (or were already performed). From slide 13, it is implied these are to be done for direct exposure of the chalcopyrite to the electrolyte; however, it seems obvious from electrochemical measurements (and common sense) that the photocathode will require a protection layer. The team might consider doing the in situ measurements on the photoelectrodes containing protection layers instead. For the development of new buffer layers for p-n junctions, it would be great to see some more direct experimental measurements of energetics/band alignment across the emitter/absorber interface (perhaps using techniques at the University of Nevada, Las Vegas).
- The proposed future work includes a continued search for PV-grade wide bandgap absorbers, evaluation of surface passivation treatments, the use of MoS_2 for corrosion resistance, and device certification.

Project strengths:

- The project is focused on a very promising class of materials for water splitting, and the team is very well qualified to carry out the upcoming tasks, although hitting the ultimate milestones (e.g., 15% STH efficiency) will be very challenging. There are nice collaborations between team members and outside collaborators.

- Important strengths are the project team's quality, in-house facilities, and an open teaming and collaboration approach to satisfying other facilities and expertise requirements. The team has a record of identifying no-go metrics and implementing transitions to more promising lines of effort.
- The new solids this project is creating for PEC use are very important in their own right, not just in this application.
- The project features strong team members who are well versed in PEC material development and characterization.
- This work represents an interesting alternative approach to PEC solar hydrogen production.

Project weaknesses:

- No transmittance data for the wide bandgap energy top cells was provided, which is very important for device design (current matching) and thus the ultimate STH of the tandem devices. It is not clear how the optimal bandgap combination changes as the average transmittance of the top cell is varied. Based on the best performance of world-record chalcopyrite PV cells, there will be very little photovoltage to spare if the STH targets are to be met (especially 15%). For this reason, it is unlikely that MoS_2 can be used as a catalyst coating for high-efficiency devices based on chalcopyrites. Still, the MoS_2 coatings might be useful for other materials and/or if one of the chalcopyrite layers is combined with a higher open circuit voltage cell. The researchers will focus on mechanical tandems, which is reasonable, given their limited resources. Monolithic tandems would have a big advantage from the standpoint of manufacturing and the achievable capital cost, but it was noted that significant processing challenges exist for processing both absorber layers on the same substrate.
- The project is complex, and the project team must overcome many obstacles to meet the project objectives and/or the Program goals. The design of an operational photoreactor concept is unclear.
- This technology does not appear to be less mature than the National Renewable Energy Laboratory metal oxide semiconductor approach.

Recommendations for additions/deletions to project scope:

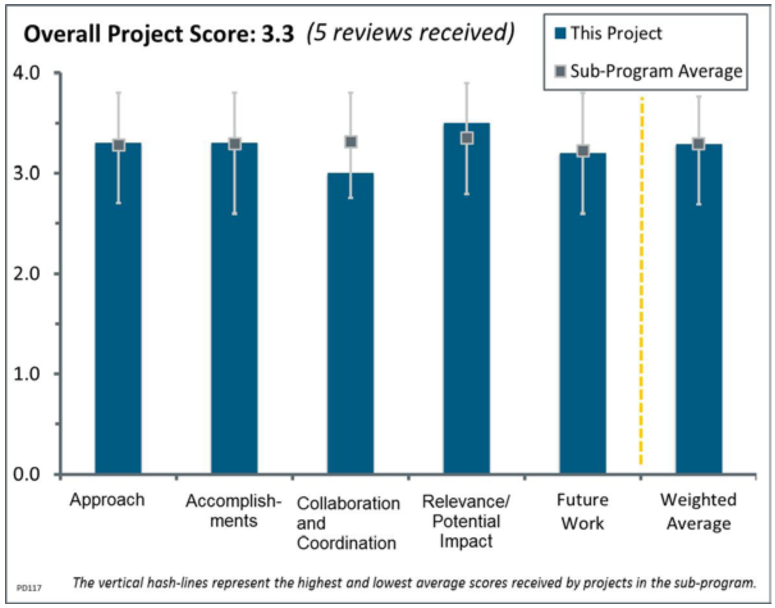
- Complementing the planned work with some initial evaluation of Al alloyed selenides would be interesting. Whereas some efficiency reduction might be expected, that could possibly be offset by likely reduced fabrication cost, which is one of the outstanding barriers to this hydrogen production method.
- Analysis of scale-up and the associated cost would be an interesting focus in PEC development programs.
- On-sun technology demonstration should be performed as soon as possible.
- The scope is suitable.

Project # PD-117: High-Temperature, High-Pressure Electrolysis

Cortney Mittelsteadt; Giner, Inc.

Brief Summary of Project:

The overall objective of this project is to reduce the cost of polymer electrolyte membrane (PEM) electrolysis by developing membranes capable of operating at a higher temperature and pressure with improved efficiency and durability. High-pressure delivery will simplify the systems and reduce the overall capital expenses. High-temperature (HT) operation will increase efficiency, reduce operating expenses, and reduce the balance of plant (BOP). Long-term durability will reduce maintenance and capital expenses.



Question 1: Approach to performing the work

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

- The overall project objective is to reduce the cost of PEM electrolysis for energy storage by improving membranes for high-pressure operation, high efficiency, and durability. High-pressure hydrogen is produced using electrochemical compression, so there is a large pressure difference across the membranes. This will require development of special membrane materials (e.g., hydrocarbons [HCs]). The cells are also operated at relatively HT (95°C demonstrated) for more favorable thermodynamics and to improve kinetics. High temperature operation will challenge chemical durability; additives will be required. The conductivity to permeability (C/P) ratio must be increased for high efficiency.
- Increasing the C/P ratio is key for achieving high efficiency and operating pressure over a large operating range, which is important for integration with renewables.
- The approach is effective and contributes to overcoming most barriers.
- The project’s relevance is strongly explained and justified. Selection of the four types of membranes and the corresponding theory of how they were selected (and how they work) is not well explained. While the C/P ratio is good for screening, it is also desired to simultaneously have high conductivity. Thus, screening for conductivity might be an important adjunct to the C/P metric.

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

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

- The testing station for the new types of membranes has been built, and four different types of perfluorosulfonic acid (PFSA) and HC membranes have been developed. Three membranes demonstrated a C/P ratio of greater than 2. Membranes showed long lifetimes (i.e., 30,000 hours), and catalysts were stable.
- A 5000 psi test stand (not funded by this project) is ready. This test stand has been modified for detailed diagnostics. Four PFSA membrane types were tested with additives to minimize crossover and degradation. Several HC (sulfonated aromatic HC polymers) membranes have also been developed. C/P ratio was identified as an important metric and was measured for many membranes, with two HC membranes exhibiting a ratio >2. Testing was completed at 95°C and 1000 psi.

- The project has made good progress in screening candidate membranes for the ratio of conductivity to permeability.
- The accomplishments were generally effective but could be improved. This project contributes to overcoming some barriers.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- There is good collaboration; partners participate and are well coordinated.
- Giner, Inc. is working with Virginia Tech (alternative membranes) and 3M (ionomer).
- The coordination between partners seems adequate, but there is little basis for assessment. Further reviews could more fully explain the collaboration.
- The project collaborates with only one partner.

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

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

- The project aligns well with the DOE Hydrogen and Fuel Cells 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 project is perfectly relevant to increasing the potential of integrating a PEM electrolyzer with renewable energy sources, while at the same time increasing efficiency and operating pressure.
- Direct electrolytic production of hydrogen at high pressure using electrochemical compression reduces downstream compression energy costs. Efficiency is enhanced with high temperature because of the lower thermodynamic voltage requirement and better kinetics (similar arguments can be made for HT steam electrolysis). Cost is reduced because of the lower precious metal catalyst requirement.
- The project's relevance, in terms of various parameter trade-offs, was very nicely explained. However, the potential impact could be better quantified in cost terms for the specific project goals. For instance, the cost curve shown is unclear and does not indicate the expected cost reduction if the project is successful.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work will be performed to mitigate crossover seen with some alternative PEM materials. Testing will be completed at 1000 psi and 95°C, followed eventually by testing at 5000 psi and 95°C. Catalyst formulations will be developed for lower platinum group metal (PGM) loading. Tests will be performed on HC-based membranes. Short stack tests will be performed. Long-duration tests will be completed up to 5,000 hours.
- The future work is well planned out. It would be useful to show how the efficiency of the electrolyzer varies with temperature because variable operation will lead to temperatures lower than the nominal 95°C.
- Additional testing of the alternative membranes is both necessary and planned. Actual validation at 5000 psi (with comparison to the baseline membrane) is critical.
- The project is generally effective, but it could be improved; it contributes to overcoming some barriers.

Project strengths:

- This work has great potential for direct high-pressure hydrogen production using PEM technology. Delivery of high-pressure hydrogen reduces BOP costs because most applications require high-pressure hydrogen. Higher-temperature operation increases overall efficiency. The membrane development work is innovative.

- The approach was very well laid out. The completion of Tasks 1 and 2 in the short time since project initiation should be commended.
- The industrial partner has the expertise to understand the project and to implement improvements in its product line.

Project weaknesses:

- It is not clear whether the proposed process to directly generate high-pressure hydrogen is more economically valuable than the existing techniques, which generate hydrogen at low pressures and then use compression.

Recommendations for additions/deletions to project scope:

- It would be interesting to see measurements of efficiency at temperatures lower than the nominal 95°C.
- The team should add an actual conductivity metric (in addition to using a C/P goal).

2015 — Hydrogen Storage
Summary of Annual Merit Review of the Hydrogen Storage Sub-Program

Summary of Reviewer Comments on the Hydrogen Storage Sub-Program:

In fiscal year (FY) 2015, the Hydrogen Storage sub-program portfolio continued its focus on onboard automotive applications as well as increased its emphasis on new materials and novel concepts to meet performance requirements. Reviewers commented that the sub-program is well managed and has effectively engaged partners in industry, academia, and national laboratories. The reviewers also commented positively on the use of results from the Hydrogen Storage Engineering Center of Excellence (HSECoE) to help direct and focus materials development efforts. Because FY 2015 marked the final year of the HSECoE, the researchers were encouraged to disseminate the lessons learned from this multiyear effort to the hydrogen storage community. The U.S. Department of Energy (DOE) Materials-based Hydrogen Storage Summit was cited as a good example of bringing the research and development (R&D) community together to disseminate results and exchange ideas. Reviewers remarked that the sub-program has evolved to include a more balanced portfolio of near- and long-term approaches than it did in previous years. Overall, reviewers recommended increasing the focus on longer-term, “higher payoff” technologies that could provide breakthroughs in performance. They noted, however, that these activities should include both basic and applied R&D efforts—ideally through a well-coordinated, collaborative approach.

Hydrogen Storage Funding:

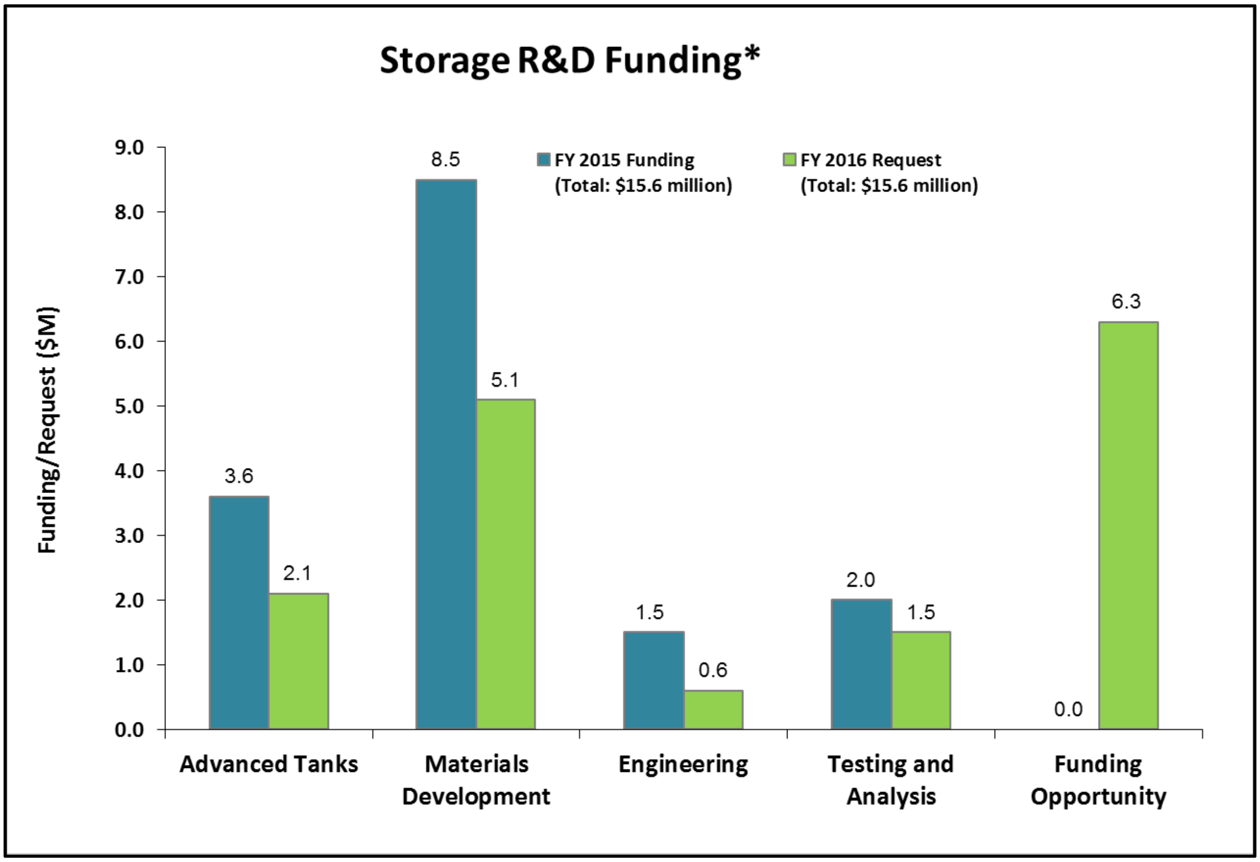
The chart on the following page illustrates the appropriated funding planned in FY 2015 and the FY 2016 request for each major activity. The sub-program received $15.6 million in funding in FY 2015, and it has a budget request of $15.6 million for FY 2016. In FY 2015, the HSECoE entered the final phase of its multiyear effort, which focused on validating systems models previously developed in earlier phases. HSECoE models are now posted online and available for use by the scientific community. Additional efforts aimed at advancing conformable compressed hydrogen storage systems were initiated in FY 2015. Work on hydrogen storage materials development remains an important part of the portfolio, with four new projects initiated in FY 2015. New efforts in materials-based storage technologies are planned in FY 2016.

Majority of Reviewer Comments and Recommendations:

The Hydrogen Storage portfolio was represented by 21 oral and 12 poster presentations in FY 2015. A total of 19 projects—via oral presentations—were reviewed. In general, the reviewers’ scores for the storage projects were good, with scores of 3.5, 2.7, and 3.2 for the highest, lowest, and average scores, respectively.

Advanced Tanks: Six projects on advanced tanks were reviewed, with a high score of 3.3, a low score of 2.9, and an average score of 3.1. Reviewers considered the work to identify lower-cost precursors for high-strength carbon fiber manufacturing and efforts to demonstrate pathways to lower-cost advanced tanks to be highly relevant efforts that may have a significant impact. For the tank cost reduction projects, reviewers commented favorably on current efforts aimed to validate modeled predictions on cost-reduction pathways through fabrication and testing of real systems that include alternative fiber and resin as well as low-cost balance-of-plant components. Reviewers also noted the potential increase in hydrogen capacity offered by cold/cryo-compressed technologies, but they also emphasized the need for continued temperature/pressure cycling as well as additional emphasis on the vacuum jacket insulation and related hydrogen dormancy. In general, reviewers recommended more detailed and validated technoeconomic assessments. Overall, the reviewers thought the efforts could have a significant impact on the industry.

Materials Development: Four materials-based hydrogen storage projects were reviewed, with a high score of 3.0, a low score of 2.7, and an average score of 2.9. Generally, reviewers commented on the high quality of the scientific work and capabilities of the research teams. However, they also commented that many of the materials currently under investigation would not be able to meet the full set of DOE targets for automotive onboard storage of hydrogen. However, for nonautomotive applications, which are the focus of several of the projects, they noted that significant impacts may be realized. Materials projects will continue in FY 2015, subject to appropriations, and new projects will be initiated. These projects will emphasize a stronger link and feedback route between the



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

experimental and theoretical efforts, as well as place more emphasis on meeting projected material-level property requirements to meet the system-level targets.

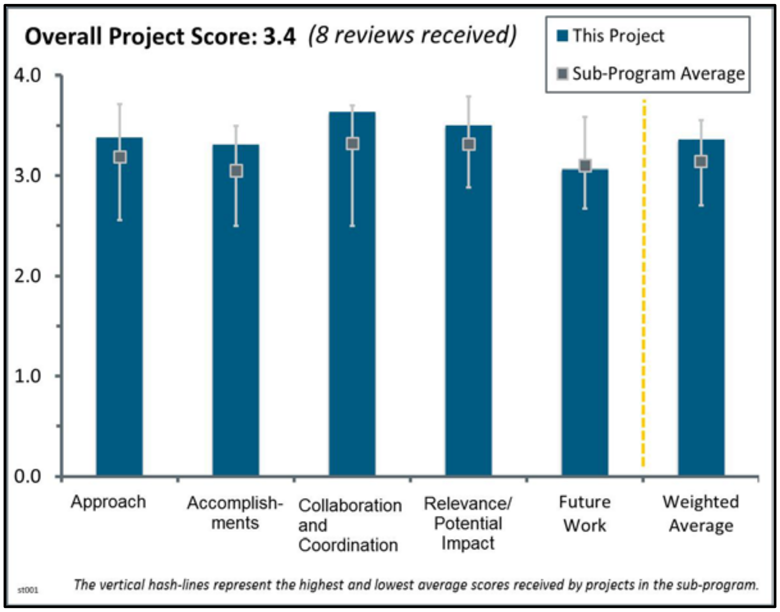
Engineering: Seven projects were reviewed on hydrogen storage engineering, with a high score of 3.5, a low score of 3.1, and an average score of 3.3. Reviewers stated that the HSECoE has made significant progress in the past year and features strong management, providing for good coordination and clear collaboration among the partners. The reviewers commented favorably on the development and use of integrated models on projecting system performance, especially for the relevant and important role in determining the material-level properties required to achieve the DOE storage targets. In general, the reviewers considered the individual HSECoE partner projects to be well thought-out and well executed. The reviewers commended the HSECoE for its use of detailed milestones for tracking progress. The reviewers also appreciated the HSECoE providing the lessons learned for use by future collaborative efforts. The reviewers recommended that the researchers place more emphasis on improving the system performance for targets furthest from being met. Overall, reviewers thought the HSECoE and its partners are making good progress in evaluating materials-based storage systems and making decisions to meet DOE performance targets.

Testing and Analysis: Two projects related to testing and analysis were reviewed, and both received a score of 3.4. Reviewers stated that these projects are very relevant in assisting DOE's R&D portfolio evaluation. Reviewers commended the project team's strong expertise in modeling thermodynamic, kinetic, and heat transfer phenomena, as well as its development of a comprehensive and rigorous set of tools and methodologies that enable detailed predictions of materials and system performance. Reviewers also commended the project team for developing an understanding of data from a multiplicity of R&D efforts and integrating that data into cogent analyses from a wide spectrum of technical areas. Reviewers recommended the continued use of experimental data, whenever available, to test and benchmark models. Reviewers also commended the project's strong and close collaboration with national laboratories, original equipment manufacturers, and tank manufacturers. Reviewers noted that the projects have done a good job in identifying major contributors to overall costs and pathways for cost reduction. However, reviewers noted the need to provide cost uncertainties in general, as well as to include a range of possible costs for systems analyzed. Overall, reviewers praised the thorough analyses performed by a strong team and emphasized the importance of these projects in improving the quality of research in the Hydrogen Storage sub-program and providing clear insight to guide future research.

Project # ST-001: System-Level Analysis of Hydrogen Storage Options

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:



The main objective of this project is to develop and use models to analyze the onboard and off-board performance of physical and material-based automotive hydrogen storage systems. Specific goals include (1) conducting independent systems analysis for the U.S. Department of Energy (DOE) to gauge the performance of hydrogen storage systems, (2) providing results to materials developers for assessment against system performance targets and goals and to help them focus on areas requiring improvement, (3) providing inputs for independent analysis of costs of onboard systems, (4) identifying interface issues and opportunities and data needs for technology development, and (5) performing reverse engineering to define the material properties needed to meet the system-level targets.

Question 1: Approach to performing the work

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

- The approach in 2015 follows from the efforts in previous years to use thermodynamic and kinetic models to assess the performance of materials-based storage approaches and to explore system-level issues. In addition, finite element analysis approaches were used to identify and quantify the relationship between liner properties and liner failures in cryo/cold hydrogen storage tanks. The approaches are providing useful information needed to understand performance limits and to guide the evolution of improved system designs. The approaches complement those adopted in the Hydrogen Storage Engineering Center of Excellence (HSECoE), and the project directly supports activities being conducted in the HSECoE and in independent studies of compressed tank designs and performance.
- The presenter discussed progress on the development of models to analyze onboard and off-board performance of physical and material-based automotive hydrogen storage systems using a reverse engineering approach to provide the material property needs to meet the system-level targets. This approach and insight is extremely valuable for materials developers.
- The plan aligned with DOE Hydrogen and Fuel Cells Program (the Program) goals. The value of this project is in informing research and development (R&D) work, helping researchers determine which materials and systems to pursue and which to stop. This project provided valuable support to the Centers of Excellence, but as those efforts wind down, what is next is not clear. Reverse engineering has provided useful input, but it is clear that new materials are required to meet targets. Additional system-level analysis or reverse engineering may be overkill at this stage.
- The approach for ST-001 was very good. This project is trying to address onboard and off-board targets, which is appreciated.
- This team consistently performs at a very high level and collaborates across the Program very well. The team members are always open to suggestions. There is one area in which there could be improvement: they could provide more concrete guidance to the materials development communities.
- Overall, the approach is very sound. Historically, this team has strong expertise in modeling thermodynamic, kinetic, and heat transfer phenomena. Extension of the effort to mechanical properties

modeling is being pursued for Type IV liners. It is unclear whether the team has the necessary expertise to conduct this work.

- It was good to document some of the specific results, but it appears that the overall results from the cold gas storage options were fairly obvious. The approach for off-board chemicals took into account only the thermodynamics of some of the materials. While this approach did provide a general range for acceptable material properties, it is not specific enough for actual materials, especially those that are kinetically limited.

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

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

- Important new results concerning the relationships between high-density polyethylene (HDPE) liner properties and liner failure in Type IV tanks at cryo temperatures were obtained. Specifically, predicting the internal pressures needed to prevent or mitigate liner separation at low temperatures and understanding stresses at critical interfaces in the tanks will be critical to the design of safe, high-performance cold gas tanks.
    - A careful analysis of cold tank performance characteristics, including well-to-tank (WTT) efficiency, fuel cost penalty, and overall system cost, provides DOE and the hydrogen storage community with solid benchmarks for deployment of cryo/cold tank storage systems.
    - A system analysis, based on a reverse engineering approach, and sensitivity analyses of a chemical hydrogen storage system provided a useful set of metrics for a high-efficiency–high-capacity chemical storage system compatible with current fuel cell operating parameters.
- There has been nice progress in modeling liner behavior at low temperature with preliminary validation from Hexagon Lincoln tanks. However, it is not clear where to go from here—perhaps making recommendations for redesign. There is nice progress with the cold gas storage analysis, which clearly shows challenges associated with meeting the volumetric target. Regarding chemical hydrogen storage, much of this seems similar to what was presented in previous years; it is not clear what was done in 2014. Conclusions are not revealing anything that is not already known (enthalpy change, ΔH = 20–40 kJ/mol and decomposition temperature, T_d = 60°C–80°C). The materials community is already actively looking in this area.
- Progress and results in the area of the tank liner interactions are very well communicated, as in all the areas in which the team is asked to provide in-depth energy and efficiency analyses to provide guidance to ongoing programs and to inform DOE program managers. This project is crucial to achieving the overall DOE goals in the area of hydrogen storage. One area that could be improved is the presentation of off-board regeneration issues; because the prior work in that area for all types of off-board materials was laser-focused not on energy efficiency but rather on proof of principle, the analysis of off-board WTT efficiency and the resulting message about the lower efficiency of off-board materials may discourage future R&D idea generation in this area. In other words, there may not be enough, or any, reliable data on what the real potential of off-board regeneration is, and so the analysis effort appears to paint perhaps too dismal a picture.
- The project showed progress toward estimating both onboard and off-board efficiency for different materials. It would be useful to see a side-by-side materials comparison with three columns: (i) onboard efficiency; (ii) off-board efficiency; (iii) off-board X onboard. The last column provides an overall view, assuming that off-board and onboard efficiency are equally weighted. Fuel cost is approximately 5% higher than the baseline, but onboard system cost is approximately 20% lower. It is not clear what the best way is to compare this trade-off. For example, perhaps the onboard system cost is a one-time cost, whereas the fuel cost is paid for each fill. Obviously, there are initial savings, but it is not clear whether the 5% added fuel costs “catch up” with those savings.
- This project has made a lot of progress since fiscal year 2014. The activities in reverse engineering to determine chemical storage properties will be very valuable.
- The energy efficiency calculations are based on the thermodynamic properties of the material, which seems narrow and does not take into account other losses; i.e., the regeneration of materials is highly specific and

dependent on the recycling process. In the future, it would be advisable to account for this to offer appropriate guidance in materials selection and design.

- There has been good progress, but the results—especially with respect to the chemical hydride work—are very general and may not apply to specific materials.

Question 3: Collaboration and coordination with other institutions

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

- Excellent collaborations with numerous organizations are in place, and they serve to support the overall goals of the project. Collaboration with Pacific Northwest National Laboratory (PNNL) on cryo-tank properties and validation of model predictions was especially fruitful in 2014/2015. The work directly supports multiple efforts within the HSECoE; solid cooperation and good coordination among those activities is apparent.
- There is excellent-to-outstanding collaboration with national laboratory researchers and the HSECoE, among others who rely on the analytical guidance from this effort to focus their own R&D efforts. This team works diligently to develop an understanding of the data that are derived from a multiplicity of R&D efforts and integrates them into cogent analyses from a wide spectrum of technical areas.
- The project has close, timely, and appropriate collaboration with other institutions; partners are full participants and well coordinated.
- It appeared that the collaboration with all of the partners was very close and well-coordinated.
- The team appears to be maintaining good collaborations with other groups within the Program.
- There are a number of collaborations with national laboratories and Strategic Analysis, Inc. Other than PNNL, it was not clear how close these collaborations are. Close collaborations, in which there are regular discussions with the tank or materials developers, are crucial.
- Collaboration exists between other stakeholders.
- Work is published and reviewed with the Storage Systems Analysis Working Group and others.

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

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

- The independent systems analyses performed in this project directly support the goals of the Program by providing relevant and timely information concerning the performance of onboard and off-board hydrogen storage and regeneration approaches. Likewise, the models and predictive capabilities developed on this project are key enabling elements for future storage technology development.
- The project's relevance to and impact on the overall Hydrogen Storage sub-program are excellent to outstanding. One area of improvement would be to communicate more explicitly the clear guidance that the analyses provide to the materials development communities. Often, this guidance is not heard well by the materials developers, and so the community continues to flounder with materials that have little or no chance of achieving technical success.
- The analysis for onboard and off-board will be very valuable for materials developers and system integrators.
- There is excellent independent analysis support.
- The project strives to offer guidance in the selection of materials, which is helpful in future materials selection and design efforts.
- Clear issues were identified with the liner at low temperature, but it is not clear what impact this work is having on tank design. Regarding cold gas storage, there has been no progress toward meeting the volumetric target, and there are similar problems with the cost target. It is not clear what the plan is. Continuing this has little value without a plan to meet these other targets. Regarding chemical hydrides, the project has identified a narrow band of free energy change and decomposition temperatures that should be pursued. These values are similar to back-of-the-envelope calculations that have been around for many years. Other than confirming what is already known, it is not clear how much value there is here.

- The work on reverse engineering of chemical storage materials was perhaps too general to have a substantial impact on current programs.

Question 5: Proposed future work

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

- The proposed future work is a straightforward and sensible extension of the prior work on this project. Emphasis is placed on both physical storage and materials-based storage. It will be important for the principal investigator (PI) and his team to consult with the DOE program manager to determine the levels of effort that should be allocated to different tasks and sub-tasks in the future. For example, given the current emphasis of the overall Hydrogen Storage sub-program on adsorbents and physical storage systems, it is not clear whether much additional work on chemical storage materials (e.g., AlH_3 and Ammonia Borane [AB] slurries) and metal hydrides is needed. These are important decisions and priorities that should be made in consultation with the Fuel Cell Technologies Office (FCTO).
- Plans build on past progress and generally address overcoming barriers. It is great that there are plans to provide system-level support to new projects.
- The proposed work for physical storage seems reasonable: working with partners to validate models and providing guidance for next-generation design. However, with the HSECoE winding down, it is not clear how much of this type of support is needed. Materials-based storage work seems less impactful. It is not clear what more analysis of decomposition behavior provides. It is not clear what is meant by "determine favorable properties of unstable room-temperature metal hydrides." In general, what these properties should be is known. There is little value in confirming what is already known. A key challenge here is regeneration. Guidelines for regeneration would be useful.
- Realizing that most of the future work in this area is dependent on FCTO guidance, there is one area that seems to have not yet been analyzed in detail, and that is the area of the complex metal hydrides. This appears to be an area of need because much of the ongoing materials R&D work in storage is focused on complex metal hydrides.
- The effort to reduce the cost of carbon-fiber-wound tanks will be valuable; however, it is uncertain how much value there is in validating AlH_3.
- Validating models from other national laboratories and the HSECoE is good, but more emphasis should be placed on developing new system models.
- For the future planned analysis on the tanks, it is necessary that created models are thorough and not oversimplified (e.g., for the AlH_3 slurry).

Project strengths:

- Overall, the project shows nice progress in evaluating tank design and the energy cost associated with cold fill. Previous results on metal and chemical hydrides have provided useful insights into WTT efficiencies and the energy cost associated with regeneration.
- This project provides important and valuable information to DOE concerning the performance characteristics and limits of physical and materials-based storage systems. The PI and his colleagues are acknowledged experts in systems analysis relevant to assessment of hydrogen storage systems. They have developed a comprehensive and rigorous set of tools and methodologies that enable detailed predictions of materials and system performance.
- Strengths include the team members' high technical competence and ability to effectively collaborate with the various R&D activities across the spectrum of storage activities.
- The project gets formal feedback at least two times a year, once from the technical team and once from the DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR), and the project team is very responsive to constructive suggestions. The timely feedback from a variety of experts in the community helps the team members stay focused and provide a more complete analysis. Each time they present their work, they get constructive feedback from reviewers. The AMR probably provides the best opportunity because the reviewers have time to read through the presentation prior to the AMR meeting.

- Overall, this project was very strong and well presented. No major weaknesses were seen. It will be good to see the progress through this year.
- The physical storage work using ABAQUS is a project strength.

Project weaknesses:

- No major weaknesses are apparent in this project.
- It is unlikely that important new information will be derived from further studies of chemical and metal hydride storage systems. Additional tweaking of existing assessments is probably not cost effective. It seems that additional work in those areas should be conducted only after materials discovery projects have identified more compelling candidates capable of meeting (or at least approaching) DOE targets. Experimental validation of the analyses conducted in this project is an important area that needs more emphasis.
- Work on chemical hydrides provides little new insight. Clearly more work needs to be done on the materials side. Additional analysis of hydrogen release rates from AB or alane is missing the point—cost/regeneration is the critical target for these materials, and all the focus should be on identifying energy-efficient regeneration strategies and working with the chemical hydride community to implement them. Similarly, additional work on cold gas storage seems unnecessary unless the volumetric limitations can be addressed.
- The energy efficiency calculations are very useful in down-selecting materials and tank designs; however, the reliance of the Gibbs function is useful only for qualitative, non-comparative-type analyses.
- The reverse engineering approach appears to be too general.

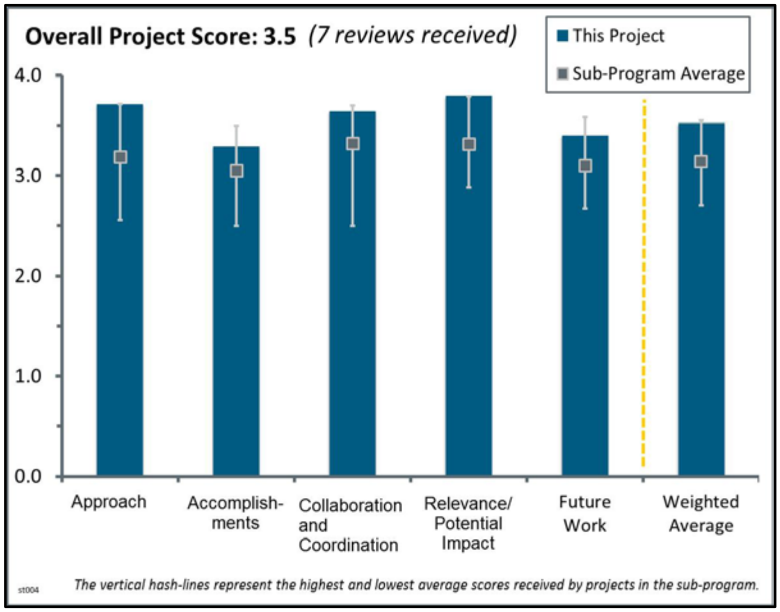
Recommendations for additions/deletions to project scope:

- The project should do the following:
  - Keep publishing results in a timely manner in appropriate peer-reviewed journals.
  - Continue to use experimental data whenever available to test and benchmark models.
  - Provide references (in backup slides) for experimental values used (e.g., changes in enthalpy and entropy for reverse engineering analysis).
- From this team's deep experience and technical excellence, a broader, more comprehensive examination of the bounding conditions for materials R&D would be very valuable. This team has developed important conclusions; some of its conclusions have an impact on *all* materials, not just the one material class this project examines. This appears to be lost on much of the materials development community.
- Physical storage and methods to reduce carbon fiber material and cost should be emphasized over validating HSECoE models that most likely will not be implemented.
- It is not clear whether this project will continue indefinitely or whether the project will be completed in the near future. Apparently, DOE makes decisions annually about continuation of the project (slide 2 in presentation). It would be helpful to understand what drives those decisions and how priorities for research directions are established.
- It is necessary that the assumptions included in these models are stated and that the models created are thorough and are not oversimplified.
- The project should probably be scaled back. The best hope of meeting targets lies with new materials discoveries. This work has provided significant benefit to the materials and engineering efforts, but there is little value in continuing at this level until new materials or engineering designs are developed.

Project # ST-004: Hydrogen Storage Engineering Center of Excellence

Don Anton; Savannah River National Laboratory

Brief Summary of Project:



Using systems engineering concepts, this project's goal is to design innovative materials-based hydrogen storage system architectures with the potential to meet U.S. Department of Energy (DOE) performance and cost targets. Savannah River National Laboratory (SRNL) will develop and validate system, engineering, and design models that lend insight into overall fuel cycle efficiency. All relevant materials data for candidate storage media will be compiled and required materials properties defined to meet the technical targets. SRNL will also design, build, and evaluate subscale prototype systems to assess the innovative storage devices and subsystem design concepts, validate models, and improve both component design and predictive capability.

Question 1: Approach to performing the work

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

- The overall approach taken by the Hydrogen Storage Engineering Center of Excellence (HSECoE) is excellent, combining material exploration with practical engineering solutions for onboard materials-based hydrogen storage systems. Although ammonia borane (AB) is not considered a viable candidate material, the engineering work carried out by the HSECoE is applicable to a future, yet-to-be-identified chemical hydrogen storage material. Likewise, while metal-organic framework 5 (MOF-5) is not the sorbent material that will meet DOE targets, the tremendous amount of work invested in developing, analyzing, building, and testing prototypes is most valuable for a future sorbent system. Material property guidelines were developed for the overall system to meet the DOE performance targets.
- The project is progressing according to the plan and will likely fulfill the goals of developing and testing prototype storage tanks. Overall, this is an extremely productive and successful research project. A huge number of materials have been considered previously for hydrogen storage, but evaluation of the available physical and chemical data for practical applications is far from straightforward, and modification toward relevant technological system targets is even more challenging. This task has been conducted extremely successfully within the HSECoE.
- A well-formulated, phased approach to identifying system needs, design and development of engineering concepts, and prototype development and testing has been adopted. Timely go/no-go decisions were implemented. This allowed the team to converge on the most reasonable prototype systems based on the best materials candidates available to date. The time sequencing of the tasks and subtasks on this complex project is logical, and the highly collaborative nature of the project ensures that problems are addressed in a rigorous and effective way. By carefully addressing the "white spaces" in the spider charts, the team was able to focus on the critical issues that ultimately affect achievement of DOE targets.
- The project has a good-to-excellent organizational/engineering approach to delegating tasks and marrying engineering with research efforts to address the "white space" issues of the various materials classes and resulting storage systems. Toward the end of the HSECoE's efforts, the team demonstrated the substantial benefits of the "Center Approach" to a technically and organizationally complex area of research and

development (R&D) to drive the field forward at a higher pace than could be done by a collection of individual efforts.
- The overall approach to looking at completely different systems—applying a rigorous down-selection process and touching all the most important factors for future automobile applications—is highly commendable for other projects. In a very good functioning team of several partners, a very interdisciplinary approach—from basic research to technology development, from experimental to computational exploration of those systems—has been applied. Different alternatives were/are evaluated and compared in an extraordinarily professional way. In the case of those alternatives that are currently not competitive, the basic needs and demands were determined and clearly stated.
- This project's approach is excellent. It serves as the coordinating effort of the HSECoE, the most thorough and important Center of Excellence thus far in the DOE storage effort. It is an operational over-structure that is well planned and executed. The approach covers all the important system barriers, candidate materials data compilations, and a prototype demonstration.
- The approach was very good, and the HSECoE has provided a lot of beneficial work.

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

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

- A large amount of progress has been made during the nearly six years the HSECoE has been in place. This includes models, reactor design, heat transfer enhancement, risk analysis, practical data collection, information dissemination, and many other engineering areas. Both adsorbent and chemical hydrogen material model systems have been studied in major detail, and many practical innovations have been made. There have been some technical difficulties encountered with the final prototype. Given the large number of experts involved in this project, it may be argued that the problem (polymeric cryogenic seals) could have been anticipated better, or at least solved more quickly. Although a temporary flanged system has been applied to complete the prototype testing, this part of the project is incomplete as the project approaches its end this month. It is disappointingly clear that no current solid-state material is capable of reaching DOE goals, by far, but of course this was not the HSECoE's aim. The web/share sites have nicely disseminated results and models to the public. There have been a number of publications and conference participations.
- Through extensive analysis and modeling efforts, the project team developed an easily communicated set of spider charts that clearly indicated where various materials systems had advantageous properties, as well as where these systems were challenged to meet the current targets. The HSECoE overall was able to then focus on and communicate potential solutions to some of these "white space" issues. This is an important contribution to future materials development efforts. The use of failure mode and effects analysis helped the team establish a catalogue of issues and rank them in priority such that the issues that were most likely to be important were addressed first.
- The down-selection process has been applied strictly and in the right and correct way. The storage alternatives that are currently most promising have been identified. For all the others, it has been clearly stated what has to be done or achieved to fulfill the DOE goals. For the most promising alternatives, subscale prototypes have been assembled and several technical problems have been solved.
- The progress is outstanding.
- Testing for both Modular Adsorption Tank Insert (MATI) and hexagonal honeycomb heat exchanger (hexcell) systems was behind schedule. Testing of the pressure vessel was delayed because of leakage in the cryogenic seal of the pressure vessel and a funding transfer delay. A six-month extension is requested to complete the tests. The milestone for demonstrating dormancy and refueling time in a full-scale, 5.6 kg hydrogen tank appears to be in jeopardy. The HSECoE continues to make great progress in system modeling, having added more models to the website and making them available to end users. The models are extremely useful to system analysts for evaluating candidate hydrogen storage materials. The HSECoE can add significant value to the website if key experimental data are also included.
- Less progress was made in this final year of the project compared to prior years. Considerable effort and time were devoted to addressing problems with leaks in the cryogenic tank system(s). This detracted significantly from the overall technical progress. It is surprising (or perhaps unfortunate) that so many

problems associated with cryo-tank leakage became evident at this late stage in the project, given the close involvement of a partner with extensive tank expertise (Hexagon Lincoln) in the overall project. Likewise, internal bureaucratic problems associated with directing funds in a timely way to the University of Quebec severely limited the important work on adsorbent performance analysis by that partner.

- The delays, such as shipping the system from Oregon State University and the sealing issues of the tank from Hexagon Lincoln, were a little disappointing. Also, it would have been good to see lessons learned for all material classes.

Question 3: Collaboration and coordination with other institutions

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

- According to the presentations given by Don Anton and the other subproject leaders of the HSECoE, as well as further knowledge about the work of the HSECoE, it seems the project partners had excellent knowledge about what was done by the other partners. They seem to have worked together in an outstanding and intense manner.
- Overall, this is a very innovative and productive research center led by a very experienced and professional director, D. L. Anton. It is very likely that prototanks will be fully constructed and tested, which is a huge step forward for hydrogen storage for mobile applications. All partners are very well integrated in the project.
- Apart from the problems with transferring funds to the University of Quebec, collaboration and cooperation among partners was excellent. Over the years, this has been a hallmark of this project. This is a complex project comprising multiple interactive tasks and subtasks. The principal investigator and all team members have done a fine job to ensure that the technical efforts are coordinated and that information concerning results, progress, and future work is communicated effectively among all participants.
- There was top-notch collaboration among all team members. Don Anton has done an outstanding job coordinating the myriad activities in the HSECoE.
- The many partners within the HSECoE have cooperated very well together. There seems to be good synergy. There have been many communications and face-to-face meetings among the participants.
- In the end, the HSECoE developed into a fairly tight set of collaborators. It is unclear whether this was driven by the HSECoE director or was simply the force of will of the collected researchers and engineers from across the various institutions that participated in the HSECoE.
- Some of the delays were unnecessary and could have been managed better (e.g., the damage to the system from improper shipping).

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

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

- This project is directly relevant to the objectives and needs of the DOE Hydrogen and Fuel Cells Program (the Program). The project was burdened with the problem that no single material had hydrogen sorption performance characteristics that even approached DOE system targets. Nonetheless, the project provided system solutions that will undoubtedly be relevant when (or if) an adequate material or combination of materials is ultimately identified.
- Several alternatives for hydrogen storage in mobile applications have been evaluated. A subscale prototype has been developed for the most promising alternatives. Through this, a real alternative to (only) compressed gas tanks has been demonstrated that has a real chance to become competitive with compressed gas tanks.
- The work carried out by the HSECoE is directly relevant to the Program goals for onboard hydrogen storage. The HSECoE employs two surrogate materials (AB and MOF-5) to address the onboard engineering issues and develop sets of material requirements to meet the DOE targets.
- The project has had high relevance to and potential impact on the Program goals. The project is an example of a successful DOE Center of Excellence. Unfortunately, the overall results suggest considerable doubt

that DOE system targets can be met in the foreseeable future with either adsorption or chemical hydrogen storage materials. Compressed hydrogen storage seems to be the only practical solution for some time.
- The “Center Approach” to this highly complex area of developing the guiding engineering principles for storage systems and storage materials is critical and highly relevant to Program goals.
- The HSECoE is very relevant and the work that has been completed is good.

Question 5: Proposed future work

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

- Subscale prototype tests should be completed as planned. Outcomes should be put online as planned. The overall outcome of the work should be summarized in a book written by/with contributions from the core partners. The HSECoE should be continued in a network of the core partners that monitors scientific discoveries and technological achievements that could change the competitiveness of the different alternatives.
- The remaining tasks are consistent with the program plan and revised schedule.
- “Proposed future work” is not applicable, because the project is ending. A focus on providing detailed documentation of the approach, results, and conclusions is imperative.
- “Proposed future work” is not applicable, other than to figure out how to maintain the legacy of the HSECoE’s output using enduring National Renewable Energy Laboratory support.
- This project has ended. It would have been preferable for the models that were completed to be useful externally instead of focused on SRNL only.
- The project officially ends this month.

Project strengths:

- This is a very well-organized and productive project. The project’s aim is highly relevant. There is a strong network and strong collaboration between the partners in the project. The team members have developed completely new types of hydrogen storage tanks based on physisorption of hydrogen, as well as implemented Internet-based systems for the exchange of information and modeling of storage systems. Overall, this is a very innovative and productive research center led by a very experienced and professional director, D. L. Anton. It is very likely that prototanks will be fully constructed and tested, which is a huge step forward for hydrogen storage for mobile applications.
- A well-coordinated project team with expertise in all areas relevant to hydrogen storage system development has been assembled to conduct this project. In many ways, this project should serve as a model for DOE to use in the future to address complex and challenging system issues. The project is well managed and focused, as well as highly interactive and collaborative.
- The HSECoE was highly focused on the defined goals. It was managed extraordinarily well and in an organized manner. Collaboration was exceptionally good. The scientific/technological excellence of partners was extremely good.
- The project has great leadership and strong management. The HSECoE is successful thanks to its highly qualified and experienced researchers.
- The strength of the HSECoE was collaborating with the necessary teams in the industry to accomplish many tasks that will continue to be useful in the industry.
- This is an excellent and well-executed Center of Excellence.
- It took a while, but the HSECoE eventually gelled and became a highly functional team.

Project weaknesses:

- There are no weaknesses.
- The final year of the project has been plagued with both bureaucratic (fund transfer) and technical (cryo-tank leak) problems. This clearly inhibited the overall momentum of the project as it nears its conclusion. Although it is not the fault of this project, since its inception, the most noteworthy weakness of the overall effort continues to be the lack of a material that meets DOE requirements. It is unfortunate that so much

time, effort, and funds have been expended without the realization of a prototype system that meets DOE targets.

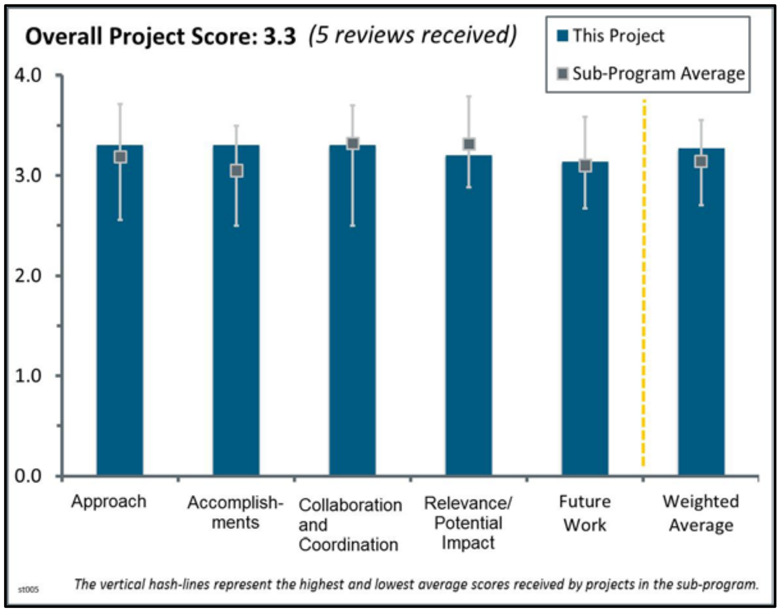
- The weaknesses were the lack of lessons learned for all material classes, the delays from shipping and sealing issues, and the models' not being for external use.
- Weaknesses are the difficult targets and very limited choices of adequately promising storage materials.
- It is not clear what is coming after the HSECoE. It has to be made sure that the gained knowledge is not lost.
- Test data may be hard to find years down the road if they are not documented, organized, and kept systematically on the website (similar to the efforts devoted to system models).

Recommendations for additions/deletions to project scope:

- It is important to maintain the gained knowledge. Because the HSECoE members are the best experts in their field, they should summarize the gained knowledge as completely as possible in a book. After the end of the HSECoE, a network of the most important partners/core partners should be established or maintained to monitor further developments and discoveries and to update/alter the outcome of this evaluation.
- Careful documentation of all aspects of the approach, results, and conclusions reached in this project is essential! Unacceptable loss of "institutional knowledge" is at stake here. Ensuring a positive impact of the project on the development of future systems depends on this.
- The results from this project are very promising and call for further R&D in this field. Allocation of resources to keep the software and databases up to date and to make the extreme amount of useful data generated within the project available for future projects in this field would be very valuable.
- It is hoped that the prototype can be finished and fully tested. It is also hoped that the models/designs/data can be continued via the HSECoE website for many years to come for future generations to use if and when a materials breakthrough is made. (The project leader indicated this will very likely be the case.)
- The project should consider adding experimental data to the Internet access.

Project # ST-005: Systems Engineering of Chemical Hydrogen, Pressure Vessel, and Balance of Plant for Onboard Hydrogen Storage

Kriston Brooks; Pacific Northwest National Laboratory



Brief Summary of Project:

The objectives of this project are to develop hydrogen storage systems that meet U.S. Department of Energy (DOE) 2020 targets for light-duty vehicles based on adsorbents and chemical hydrogen storage materials; develop engineering solutions to overcome deficiencies of materials from the Materials Centers of Excellence; identify, develop, and validate critical components for performance, mass, volume, or cost; and develop models and simulation tools to predict the performance of materials that would be acceptable in engineered hydrogen storage systems for light-duty vehicles.

Question 1: Approach to performing the work

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

- The project has taken a very effective approach, on which it thoroughly performed, which includes the following:
  - Developing and validating a liquid-nitrogen (LN_2)-cooled wall tank.
  - Conducting cost estimations.
  - Validating a balance-of-plant (BOP) redesign.
  - Reporting on findings and progress.
  - Producing a chemical hydrogen storage system model.

  Combined usage of experimental and computational experiments has been extremely well done. Strategic Analysis, Inc. (SA) and the Hydrogen Storage Engineering Center of Excellence (HSECoE) conducted independent cost analyses, which were very useful for verifying the results.
- The overall project appears to be well executed and logical in its design. The project is mostly wrapping up, so the work presented here is in its final stages and refers to specific tasks for cryo-absorbents and chemical hydrogen storage systems.
- There is a logical progression of tasks throughout the lifetime of the HSECoE to develop feasibility and/or cost assessments across several systems platforms. Crucial proof-of-principle validations should be provided when appropriate. The strength of the approach was the attempt to provide experimental validation of sub-models being developed in parallel with other members of the HSECoE.
- The project has a solid engineering approach.
- The project is reasonably well focused on relevant barriers: charging rate, BOP, cost (adsorption), and reducing the loss of hydrogen on the fill (replacing with LN_2). It is not clear what is being done to address the dormancy, which is another critical issue resulting in loss of hydrogen. New engineering solutions to help mitigate materials issues would be great, but it is difficult to see how the proposed tank designs will ameliorate these issues in any significant way.

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

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

- A very detailed and thoroughly analysis and improvement of the BOP has been performed. Test of fatigue at these low temperatures is extremely important and was successful. Prototype design and testing with different thermocouples is very important (although there seemed to be no simulation results). Correct conclusions were drawn (directing LN_2 flow). Consolidation of the valve block with extraordinary reduction of mass and volume, number of fittings, and cost is a special accomplishment to be praised. The evaluation of different polymer materials for seals, pistons, seats, and tanks/pipes was a very necessary part of the work and has been done very thoroughly. Tests performed are showing that the mechanical properties of these materials should be not affected by the hydrogen.
- Results from the LN_2-cooled tank show nice promise. This work addresses one of the key issues with these tanks: the loss of usable hydrogen.
    - Predictions on material fatigue are also very useful. Although it is likely beyond the scope of this project, it would be nice to have more experimental data in this area to develop life estimates for these tanks. Tank costs should be normalized by life for a true comparison.
    - It is not really clear what state the chemical hydrogen system model is in at this point. Perhaps this is a simple user-friendly toolkit.
    - The analysis of metal-organic framework tanks (Modular Adsorption Tank Insert [MATI] and Hexagonal heat exchanger [hexcell]) seems a little redundant with SA's work.
- Regarding the LN_2-cooled wall tank tests, some type of experimental demonstration was needed. The accomplishments appear to be a broad exercise to explore and predict the cooling within the tank and to validate the model predictions via 2 L tank tests. Scaling up projections to a 120 L tank is a good idea and shows the kilograms of LN_2 necessary for cooling. However, there were limited other "lessons learned" from the testing. Cost validation with outside sources is a good idea. The project cost analysis is sound and comprehensive. The consolidated valve block is a good idea in theory, but it is quite complex. Further consideration of the thermal losses associated with the valve should be considered. The degree of industry input into the feasibility of the integrated valve is not clear. Polymer compatibility testing was worthwhile and useful despite not leading to significant variance from expectations. Posting the chemical hydrogen storage model to the Internet is a significant step toward analysis transparency and dissemination.
- Progress has been good to excellent on providing proof-of-principle demonstrations for specific components or approaches, such as cooling of the tank walls and others identified as crucial for the further development of systems models and for model integration, often in collaboration with other HSECoE members. The project collaborated well with SA on MATI/hexcell system cost estimations. Finishing off the chemical hydrogen storage systems model and having it posted on the HSECoE's model page is a good-to-excellent accomplishment. Improvements in BOP componentry (e.g., the consolidated valve block) may result in cost and volume/mass savings.
- All objectives for the prototype LN_2-cooled wall tank have been met.

Question 3: Collaboration and coordination with other institutions

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

- The approach taken to— independently perform cost analysis and afterward compare the results—is very good and persuasive. The collaborations as listed on slide 23 is persuasive.
- Collaborations across the HSECoE and with SA are good to excellent.
- There are active collaborations internal and external to the HSECoE.
- There continues to be good coordination within the HSECoE and Storage Systems Analysis Working Group, and good outside collaboration with SA. That is good. However, there does not appear to be much other outside/non-laboratory collaboration. Discussion with BOP component manufacturers or seal vendors might be useful.
- There is excellent collaboration within the HSECoE but little beyond this group.

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

This project was rated **3.2** for its relevance/potential impact.

- The Pacific Northwest National Laboratory (PNNL) team worked on disparate areas in which engineering demonstrations at the proof-of-principle level were required to provide feedback to model development. This is a highly impactful and relevant area to the HSECoE's efforts in support of the broader goals of the DOE Hydrogen and Fuel Cells Program (the Program). Development of models accessible by the public is absolutely an element critical to the HSECoE's success, and PNNL's team had a substantial impact on that program element.
- This project of the HSECoE is an important part of the Center. The demonstration of potential cost savings due to the consolidated valve block shows one way costs could be reduced.
- Comprehensive analyses such as this significantly contribute to the overall achievement of Program goals by conducting a deep dive in component technologies and issues.
- This project addressed a potentially significant engineering challenge for absorbent-based hydrogen storage for automotive applications.
- Work on LN_2-cooled tanks has clearly led to an increase in the fill rate. However, it is unclear what the impact is on the "loss of usable hydrogen." In the spider charts presented by other HSECoE members, this metric is one of the furthest from being met. Replacing liquid hydrogen (LH_2) with LN_2 will certainly reduce wasted hydrogen, but there is still a cost associated with LN_2. Overall, the challenge remains that significant cryogens are required to fill the tank. These costs should be worked out. The metric "loss of usable hydrogen" may need to be made more general, or a second metric may need to be added—"fill cost" or "cryogen cost."

Question 5: Proposed future work

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

- Completing the analysis and scale results of the LN_2-cooled wall tank prototype, finalizing the PNNL contribution report, improving the chemical hydrogen storage model, supporting material developers in using the framework, and documenting the results in reports and journal articles are very important tasks. Nevertheless, the results of the HSECoE should also be summarized in a book, and the results of this work should be summarized in one chapter of that book as well.
- The project is wrapping up, so future tasks are appropriately centered on documentation and ease of project information dissemination to the public.
- It is not clear that there are any plans to deal with the loss of hydrogen associated with dormancy. Mechanical testing at low temperature would be useful to better understand fatigue and tank life. It is probably beyond the scope of this project, but tank cost should really be normalized by life. A user-friendly toolkit for the chemical hydrogen storage system model (as proposed) would be useful. It may be valuable to consult with the chemical hydrogen storage materials community to get the right parameters.
- "Proposed future work" is not applicable, because the project is ending.

Project strengths:

- There is extensive collaboration with industrial and scientific partners within the HSECoE. The project is combining both evaluation of system components and modification/redesign to improve system costs. This is very good, systematic, and successful work. Congratulations to the project team.
- There are clear improvements in fill rate. Use of LN_2 will likely reduce cost (although this is still a little unclear because both LH_2 and LN_2 could be captured and reused). A user-friendly chemical hydrogen storage system model would be useful to help guide the materials work. Component integration (e.g., consolidated valve block) seems to be paying off.
- Strengths include the comprehensive analysis of engineering and cost aspects of adsorbent and chemical hydrogen storage systems.

- Project strengths include experimental validation at the proof-of-principle level in support of model development.
- PNNL has outstanding engineering capabilities.

Project weaknesses:

- No weaknesses were detected.
- Cost models for the hexcell and MATI prototype tanks are useful, but the overlap with SA work seems unnecessary. Certainly there is some value in comparing the two analyses and resolving discrepancies, but the limited funds may have been better spent targeting other key issues. The cost of cryogens is still unclear. Replacing LH_2 with LN_2 may be a good start, but it would be useful to get a comparison (perhaps "loss of hydrogen equivalent"). It is not clear how much LN_2 is needed and what the estimated cost is for a single fill (the best-case scenario would be capturing all LN_2).

Recommendations for additions/deletions to project scope:

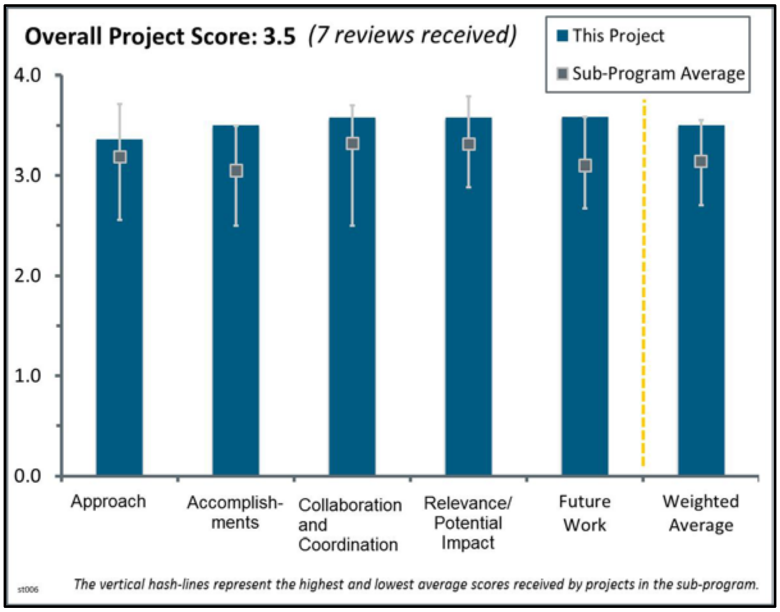
- The project should contribute to a book about the results of the HSECoE.

Project # ST-006: Advancement of Systems Designs and Key Engineering Technologies for Materials-Based Hydrogen Storage

Bart van Hassel; United Technologies Research Center

Brief Summary of Project:

The goal of this project, as part of the Hydrogen Storage Engineering Center of Excellence, is to design materials-based vehicular hydrogen storage systems that will allow for fast refueling and a driving range of greater than 300 miles. The major objectives of this project in fiscal year 2015 are to (1) develop Integrated Power Plant Storage System Modeling to compare hydrogen storage systems on a common basis, support storage system model integration, and develop a graphical user interface (GUI) for models on the Internet (www.hsecoe.org); (2) ensure hydrogen quality through particulate filter right-sizing; and (3) share results through publication.



Question 1: Approach to performing the work

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

- United Technologies Research Center (UTRC) clearly identified what had to be done in the relevant tasks of the Hydrogen Storage Engineering Center of Excellence (HSECoE) (e.g., the influence of compaction on the materials and the overall system's behavior). UTRC played an important role within the HSECoE without the early constriction of too narrow a focus on special details. In the end, this is very beneficial for the overall HSECoE initiative because UTRC could identify and react to various materials or system problems that were discovered in the progress of the HSECoE projects.
- This is a logical engineering approach to addressing the assigned tasks in collaboration with the HSECoE's partners. Experimental validation at the proof-of-principle level in support of sub-model development contributes significantly to the HSECoE's goals.
- The project is well focused on critical barriers and technologies necessary to contribute to the HSECoE. The project's contribution dovetails very well.
- The work is very thorough and well done.
- The overall approach was good; however, the cost analysis for the filter was lacking. The cost seemed very high and more work could have been done on that analysis.
- How barriers are being addressed needs to be better outlined in the work approach.

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

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

- Excellent progress has been made in modeling and in developing a GUI (Simulink). Models and appropriate data selections have been put on the HSECoE website. Progress has been made toward the modeling of various candidate systems: physical storage (compressed gas), metal hydride, chemical hydrogen storage, and adsorbents. Physical storage has apparently been included for comparison purposes relative to the HSECoE's material-based storage systems. The key contribution is the development of a common base for comparing various competing systems. There has been useful feedback from the public.

A side effort on the filtration of adsorbents (metal-organic framework 5 [MOF-5]) was completed. Especially useful was the generation of filter pressure drops at service flow rates. These important data suggest this potential problem can be adequately handled. A good spectrum of publications and presentations has been authored.

- UTRC accomplished many small-to-large achievements, rather than one very large achievement, within the time frame of the project. These achievements included using pellets to improve material properties, finding the right and proper method to guarantee high-purity hydrogen, and implementing software tools to describe whole systems. The models were made available on the Internet and can help both materials developers and systems engineers to evaluate new materials and technology achievements. UTRC's work, accomplishments, and progress are very important and necessary parts of the HSECoE.
- The system modeling and system integration work that has resulted in what may be a user-friendly Internet-based application for public access supports a key set of goals within the HSECoE. Demonstration of an effective particulate filter to validate the feasibility of the approach was good to excellent as well.
- The GUI and beta tests were good, and the storage model integration for the public was very strong. The requirements for the hydrogen filter can be used throughout the industry.
- The presentation was excellent and clearly highlighted progress toward project goals.
- The modeling effort is useful for technology development and selection, thereby addressing barriers. The specific technology development efforts need clearer ties to barrier reduction outcomes.

Question 3: Collaboration and coordination with other institutions

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

- UTRC demonstrates that it has collaborated effectively and intensively with the other HSECoE partners. On top of that, UTRC has communicated the results internationally via conferences and the International Energy Agency.
- Collaboration within and beyond the HSECoE has been excellent. Such collaborations are important in developing a broadly meaningful model. A good spectrum of publications and presentations has been authored.
- The project encompasses academia, laboratories, and industry, with reasonable participation across the project members.
- Collaboration is good to excellent with all HSECoE partners. Participation in Task 32 is good.
- There was no great need for collaboration on this project, but it seemed that UTRC was able to get all of the necessary information from the project partners.

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

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

- In the years from 2009 to 2015, UTRC has made many important contributions (both experimental and computational) to the HSECoE in different fields: (1) metal hydrides, (2) chemical hydrogen storage, (3) adsorption, and (4) the Simulink framework. From 2014 to 2015, the main focuses were hydrogen quality (looking for efficient adsorbent particulate filtration), the general comparison of hydrogen storage systems on a common basis, the integration of storage system models in a framework, and GUI development for the Simulink framework. All of these are important tasks for the HSECoE, and thus they are highly relevant.
- The development of publicly available models of storage system interactions is a highly relevant and impactful contribution from this team. Sub-model validation via experiment also has a high impact in demonstrating model fidelity.
- Clearly, the work is important to sorbent storage systems. The most challenging aspect of the sorbents, besides their low capacity, is the liquid nitrogen cooling.
- The project clearly supports the HSECoE and thus contributes to progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- The project is very relevant, and there will be a strong benefit to the industry from this project.
- The modeling effort has clear utility. It is not as clear that the contribution toward reaching targets is attributable to filter work.

Question 5: Proposed future work

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

- The project is about to be completed very successfully through development of an Internet-based GUI for programs. Furthermore, experimental studies of particle-free release of hydrogen were conducted very successfully. The aim and outcome of this project is highly relevant.
- The project ends this month, along with the HSECoE. The only remaining work is the final report and publication preparations and submissions.
- The project is nearly complete, and the remaining work is reasonably defined.
- The project is scheduled to be completed in June, so other than submitting final reports, there is no future work.
- Future work comprises the remaining tasks necessary for the project.
- This question is not really relevant to this work because the project ends in June.
- This is not applicable, because the project is wrapping up.

Project strengths:

- The project contributes to the design of materials-based vehicular hydrogen storage systems that will allow for fast refueling and long driving range—in particular, development of approaches to compare hydrogen storage systems on a common basis (i.e., by Internet-based GUI programs for modeling and a very user-friendly Internet-based simulating [Simulink] framework). The results from the project are very valuable for future research and development (R&D) in the field. Furthermore, experimental R&D is conducted with a focus on hydrogen quality and gas filtration regarding particle-free release of gas, which is also highly relevant. Thus, the project combines experimental work, both within this project and using results from other partners, with modeling. This project is well integrated in a larger research consortium. In conclusion, this is a very well-organized and productive project led by a very experienced and professional principal investigator (PI). The project is highly relevant, well organized, and integrated in a larger consortium. The project has progressed according to the plan and will likely fulfill the goals and soon be finalized very successfully.
- Overall, this project was very strong. The focus of the project remained on enabling customers to fill their vehicles quickly and provide a range greater than 300 miles.
- The project strength, and indeed the strength of UTRC’s contribution, seems to be the in-house experience in various engineering disciplines. In accordance with that expertise, the UTRC project has yielded many important contributions in various fields.
- The team members provided high-quality work throughout the project. Their openness and generosity in sharing what they were doing and learning is appreciated by the hydrogen storage community. They did not appear to withhold information that might help out someone outside of their project.
- Model integration and sub-model experimental validation are strengths.
- Modeling and container engineering contributions were the main strengths.
- The model development is a valuable tool.

Project weaknesses:

- No weaknesses are observed.
- No weaknesses are detected.
- No weaknesses can be seen in the 2015 work. In the 2014 work, the carbon used in the filtration materials studied for ammonia scrubbing was custom-made, and the procedure for making it is not something that an average laboratory can do. In work that is supposed to be for commercialization, the PIs should stick to materials that are available to the public at reasonable cost.

- The only weakness was the cost of the filter. The cost seemed high, and there could have been more focus on understanding why it was so high.
- Better relationships need to be identified between DOE goals and specific technology development efforts.

Recommendations for additions/deletions to project scope:

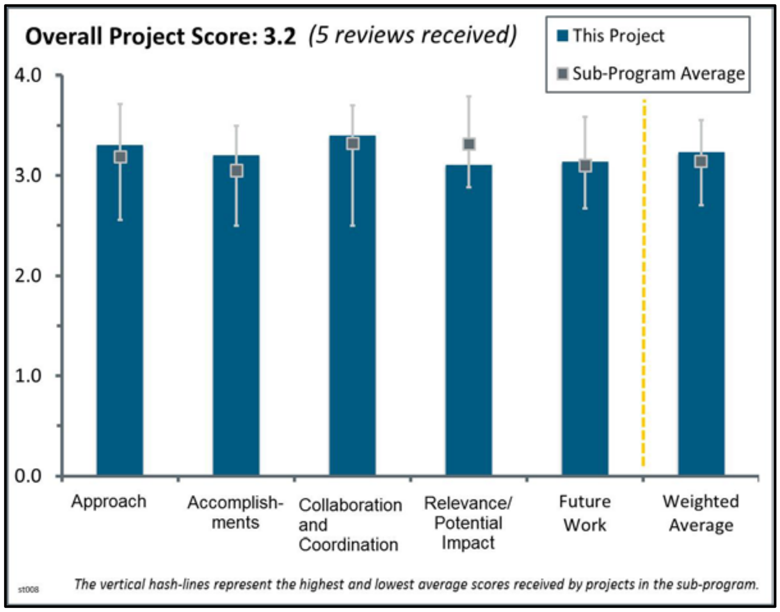
- The results from this project are very promising and call for further R&D in this field. Allocation of resources to keep the software and databases up to date is very useful for future projects in this field.
- It would be useful if low-level, online model support could be continued in the future.

Project # ST-008: System Design, Analysis, and Modeling for Hydrogen Storage Systems

Matthew Thornton; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to manage Hydrogen Storage Engineering Center of Excellence (HSECoE) vehicle performance, cost, and energy analysis technology areas; lead an effort to make models developed by the HSECoE available to other researchers via an Internet-based portal; and develop and apply the model for evaluating hydrogen storage requirements, operation, and performance trade-offs at the vehicle system level.



Question 1: Approach to performing the work

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

- System-level modeling and correlation of vehicle performance with hydrogen storage requirements and characteristics are useful for the design and development of optimized storage systems. The approach adopted in this project for model development and creation of an improved graphical user interface (GUI) is logical and straightforward. Development of a user-friendly operating environment is a valuable feature embodied in the overall approach. The principal investigator (PI) and his team should be commended on their efforts to incorporate reviewer suggestions (especially the need for a more robust model validation effort) into the approach for the 2015 work.
- The approach to getting the finalized models onto the Internet in a publicly available, documented, user-friendly format is without flaw. The approach to collaborating with other HSECoE partners in developing the integrated storage, fuel cell, and vehicle performance model is very solid.
- The project is highly relevant, and the National Renewable Energy Laboratory (NREL) is very well suited to integrate the vehicle, fuel cell, and storage models.
- The approach is appropriate and well defined. The user-friendly modeling framework is very useful for system analysts to evaluate a candidate storage system.

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

This project was rated **3.2** for its accomplishments and progress.

- The coordination and migration of the modeling framework and Internet posting of system models developed in the project were important and valuable accomplishments in 2015. In addition, solid progress was achieved regarding developing protocols for conducting simulation performance checks (e.g., power failure caused by storage system or speed trace misses). Also, for a project of this kind, extensive model documentation is critical. The PI and his team have done an excellent job to ensure the documentation is available and updated.
- Dealing with the multiplicity of issues surrounding the Internet publication of models that have come from a variety of sources on a variety of platforms and are being used by the public on a variety of platforms is a great accomplishment. It is hoped that this accomplishment will endure to maintain the usability of the models, which is the key legacy of the HSECoE.

- The vehicle system-level model of hydrogen storage systems that was created, which is also available to the public, is very useful for researchers developing hydrogen storage materials.
- The researchers have achieved modest improvements/upgrades to the modeling framework that lead to significant enhancement in usability. Incorporation of system diagrams is a big help and greatly enhances clarity. System-level modeling performance checks are a very good addition to the project, given the complexity and integrated operation of the models. There appears to be a significant (+25%) over-estimation of fuel consumption between the model and U.S. Environmental Protection Agency data on the city drive cycle. This needs to be explored further.
- Not much progress was made in this past year because the HSECoE is winding down in its final year. The page views per session and average session duration declined by about one third compared to last year's report.

Question 3: Collaboration and coordination with other institutions

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

- The solid collaborations with multiple HSECoE partners have been important and valuable features of this project since the inception of the HSECoE. The project features especially noteworthy collaborations with Pacific Northwest National Laboratory and Savannah River National Laboratory on model development, with the United Technologies Research Center on GUI development and model integration, and with multiple HSECoE partners on model documentation.
- The project leveraged excellent-to-outstanding collaboration to publish the integrated models on the Internet. It also collaborated highly effectively with the other key HSECoE partners involved in each of the models in developing the integrated models and in providing documentation for the public domain.
- The team appears to be working well and in a collaborative fashion with the many groups within the HSECoE.
- The PI interacts well with all members of the HSECoE to coordinate the model posting.
- Collaboration seems to exist with other institutes.

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

This project was rated **3.1** for its relevance/potential impact.

- The HSECoE's efforts address many aspects of the storage system. This task integrates the design and expected performance into an integrated model to assess overall performance. Such a holistic view is essential to both understanding and achieving DOE's goals and objectives.
- This project is relevant to the Hydrogen and Fuel Cells Program (the Program) and supports critical Program goals. System-level modeling and correlation of storage characteristics and requirements with vehicle performance provide a valuable framework for quantifying system trade-offs and optimizing system design.
- Getting the integrated system—fuel cell—vehicle models onto the Internet and in working condition is a highly significant and visible milestone for the HSECoE. This is also an area of high impact because this effort provides for the enduring legacy of the HSECoE and is available to the public.
- This project is essential in keeping all of the developed models in one place and making them available to end users. The benefits go beyond the end of the lifetime of the HSECoE. It is to be hoped that DOE will continue to fund some minimum effort for maintaining the website. The potential impact can be enhanced if the HSECoE will consider including test data on the website in support of the models.
- The models are indeed useful to get a "feel" of how the materials may perform onboard a vehicle; however, they are likely not representative of a real system.

Question 5: Proposed future work

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

- The project is ending soon; one anticipates the remaining work on the adsorbent model will be just as good as the work on the other system technologies.
- This question is not applicable—the project is ending. A focus on model validation and completion of system documentation are important tasks to be conducted prior to project completion.
- The remaining tasks are consistent with the project plan.
- The future work is limited but appropriate for a project that is winding down.
- The project is almost complete.

Project strengths:

- This project is being conducted by a well-qualified team that leverages extensive and valuable collaborations with other HSECoE partners. The project provides a vital link between vehicle performance and hydrogen storage and fuel cell system operating characteristics and requirements.
- The ability to use the models generated by the HSECoE and integrate them into a vehicle system-level model helps the researchers get a good idea of how the materials would perform in a fully integrated system.
- A strength of the project is the collaboration to achieve an Internet-friendly documented set of integrated models for public access.
- NREL has done a nice job of integrating many aspects into an overall system assessment.

Project weaknesses:

- No weaknesses were detected.
- The main weakness in the project in prior years has been an insufficient emphasis on model validation. The PI and his team have recognized this issue, and they made significant progress on this important area in 2015.
- The main weakness of this project is that the vehicle system models do not allow for flexibility in integrating other tank models beyond those generated by the HSECoE. These may not be representative of the tank systems onboard a vehicle, and therefore the performance obtained is not representative.
- Model validation continues to be an area with opportunity for improvement.

Recommendations for additions/deletions to project scope:

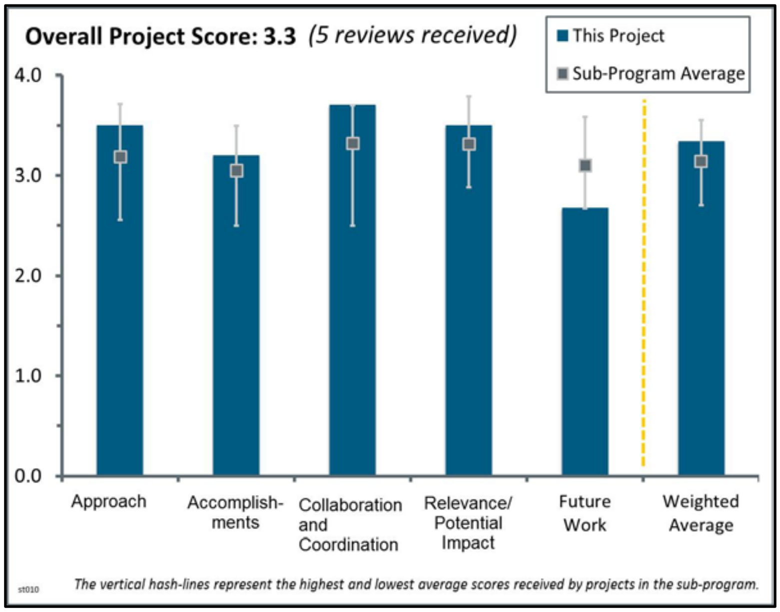
- There are no recommendations to make—the project is ending. Completion of model validation work and updating documentation are important focus areas as the project draws to a close.
- The research team should consider adding experimental data to the Internet portal.
- This question is not applicable.

Project # ST-010: Ford/BASF-SE/UM Activities in Support of the Hydrogen Storage Engineering Center of Excellence

Mike Veenstra; Ford Motor Company

Brief Summary of Project:

This project, led by Ford, is focused on material-based hydrogen storage systems that offer potential advantages, such as volumetric efficiency, over conventional physical-based hydrogen storage systems. This project has three goals that contribute to the overall Hydrogen Storage Engineering Center of Excellence mission: (1) to develop a dynamic vehicle parameter model that interfaces with diverse material-based hydrogen storage system concepts, (2) to develop robust cost projections for these storage system concepts, and (3) to devise and develop system-focused strategies for processing and packing framework-based sorbent hydrogen storage media.



Question 1: Approach to performing the work

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

- The project has clear goals and provides extensible inputs for modeling to account for variations in potential adsorbent materials such as metal–organic frameworks (MOFs), should they become available. The team has overcome barriers and challenges and made progress beyond the specific, measurable, attainable, realistic, and timely (SMART) goals in ways that help other partners in the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- This project focuses sharply on practical properties and adsorbent barriers from the very important point of view of an original equipment manufacturer (OEM) (automobile and adsorbent manufacturers). This view is critically integrated with the overall HSECoE. Cost analysis is an important component. The project is responsible for the very important determination of gaseous impurity effects on the potential deactivation of adsorbents (particularly MOF-5). It serves as the major manufacturing entity for HSECoE adsorbents and cost studies.
- The approach in 2015 focused on evaluating MOF-5 performance characteristics, including potential degradation modes, failure mode and effects analysis (FMEA) for MOF-5 in both Hexcell and modular adsorbent tank insert (MATI) operating environments, and continued work on development of a robust cryo-adsorbent system model. The approach addressed important issues related to the use of MOF-5 (and related adsorbents) in a high-performance cryo-adsorbent system. Especially important was the focus on evaluating impurity effects, identifying and mitigating potential system failures, and maximizing MOF-5 properties by compaction and enhancement in thermal conductivity.
- The overall efforts of the HSECoE were excellent. It would have been good to see a summary of how the researchers purified the MOF-5 sample. MOF-5 performance is very dependent on the amount of residual solvent remaining in the sample. Also, with both tetrahedral and octahedral Zn sites for adsorption, the manner in which one degases can significantly affect the results. As the project moves forward, a summary in the final report for the HSECoE would be helpful. Also, the description of the effect of pellet processing and compaction on slide 20 was interesting. However, a more complete explanation of the extent of solvent remaining and how a better "sweet spot" could be found would have been helpful.
- The approach is good, but it can be improved.

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

This project was rated **3.2** for its accomplishments and progress.

- The project team has made a significant amount of very useful progress. The comparisons among two MOF-5 systems and state-of-the-art compressed gas systems (slide 7) are especially useful. The cost, volumetric, and gravimetric calculations show potential competitive possibilities of MOFs relative to compressed hydrogen. The main disadvantage of an adsorbent approach, relative to compressed hydrogen, is the need for a more complex cryogenic system. Contractors have made impressive progress in understanding MOF manufacture, impurity effects, failure modes, compaction, thermal conductivity, and modeling. All of these are encouraging and are of immediate practical value to the HSECoE. The selection of the optimum tank design from the OEM point of view (i.e., Hexcell versus MATI) cannot be made at this time. The presenter indicated a little more testing is needed.
- The project team achieved all of the SMART milestones and additional goals. MOF-5 cycling is complete, and robustness has been illustrated. The FMEA is robust. Exploring the robustness of puck formation and particle size was reasonable. The new layered puck and aluminum pins seem like positive advancements.
- This question earns a “Satisfactory” rating. The cost comparison should be corrected by estimating the cost per 1% of gas storage. In such a case, the high-pressure system is more cost-effective than those developed during the project. There is no evidence that the graphene used is really graphene and not a nano-graphite; a Raman spectrum could provide such evidence. The role of the residual solvent requires clarification because it is removed during cycling (if there is no role, the team should explain that).
- While it would have been helpful to have a more in-depth study on some aspects of the thermal conductivity properties of various sorbent materials, it is understood that the scope, as defined by DOE, did limit some other initial studies on “new” sorbent-based materials.
- Progress in 2015 was less significant than in prior years (especially 2014). It is not apparent that noteworthy new results were obtained in 2015 on maximization of MOF-5 material properties. Likewise, only minor advancements to prior work (2014) on MOF-5 robustness to hydrogen impurities and FMEA analyses were made during this reporting period.

Question 3: Collaboration and coordination with other institutions

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

- Excellent collaborations and coordination with other HSECoE partners are readily apparent. The OEM perspective provided by this project is a critical component of the overall HSECoE effort.
- The HSECoE, by design, was an excellent illustration of a successful collaboration between industry, academia, and national laboratories.
- Subcontractors BASF and the University of Michigan provide outstanding expertise and contributions. This project has integrated very well into the HSECoE.
- The interactions seem to be strong, well handled, and proactive.
- The project features good collaborations.

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

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

- The project is well designed, integrated with the HSECoE, and well implemented. Moving forward in parameterizing the laboratory-to-OEM production and implementation of a chemisorption-based solution seems possible from this contribution to the HSECoE. It is clear that many of the obstacles and solutions generated in this project will have an impact on any storage solution.

- This project provides an essential OEM perspective to the HSECoE on important issues and problems relevant to achieving DOE storage system targets. The project is directly relevant to DOE research, development, and demonstration (RD&D) goals.
- This project is particularly relevant to the Program because it provides practical OEM input to the HSECoE. Its impact has been measurably valuable toward meeting goals and targets.
- The project is aligned with the Program's and DOE's RD&D objectives.
- As next-generation materials are developed, the groundwork laid by the completion of this project within the HSECoE will be important. It would have been good for an OEM to take a stance on which tank design is most relevant to its current thoughts on hydrogen storage systems.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The team should prove that the obtained results are transferable onto other absorbents—for example, activated carbon.
- The project formally ends this month with the overarching HSECoE. There are some work completions and reporting planned to follow. The end story will be very useful to the future of adsorbent research and development (R&D).
- This question is not applicable—the project is ending this year. Comprehensive documentation of project results and conclusions is essential.
- There is not much left to do, and time is running out. The future plans might be seen as excessive, given the short remaining time.
- The project ends in June 2015. Therefore, the future work is limited to a final report.

Project strengths:

- Since the start of the HSECoE, this project has been an essential element of the overall technical effort in the Center. Involvement of a principal investigator with deep knowledge of OEM needs and requirements is a great benefit. The project team is well organized and highly coordinated, and it has consistently maintained a keen focus on the critical issues that need to be addressed in this project.
- The interaction between the partners is a strength of this project. The extent of the questions that were answered over the previous years is another strength. This HSECoE was unique in the level of accomplishments achieved.
- The project is meeting goals, demonstrating positive aspects of absorbents, and contributing to the HSECoE's use of MATI pucks. In addition, it had enough time to do extra analysis and measurements.
- Collaborations and interactions within the HSECoE are an area of strength.
- The project features excellent practical OEM perspectives and R&D approaches.

Project weaknesses:

- There are no real weaknesses other than the inherent challenges with adsorbents, especially the need for cryogenic containment.
- Weaknesses include MOF-5 as being a model system only, lack of sufficient cost estimates, and that some materials characterization issues are possible (the nature of graphene additives).
- Weaknesses include the limitation of the work scope and the inability to look at some newer materials at the end of the project. However, it is recognized that the logistics of such were almost impossible.
- This has been a consistently strong project, and it has no major or notable deficiencies. However, the progress in 2015 was less significant/noteworthy than in prior years.

Recommendations for additions/deletions to project scope:

- There is a critical need for the HSECoE to develop a comprehensive final report that includes the results and conclusions from this project as essential elements. The need for a detailed report of this work cannot

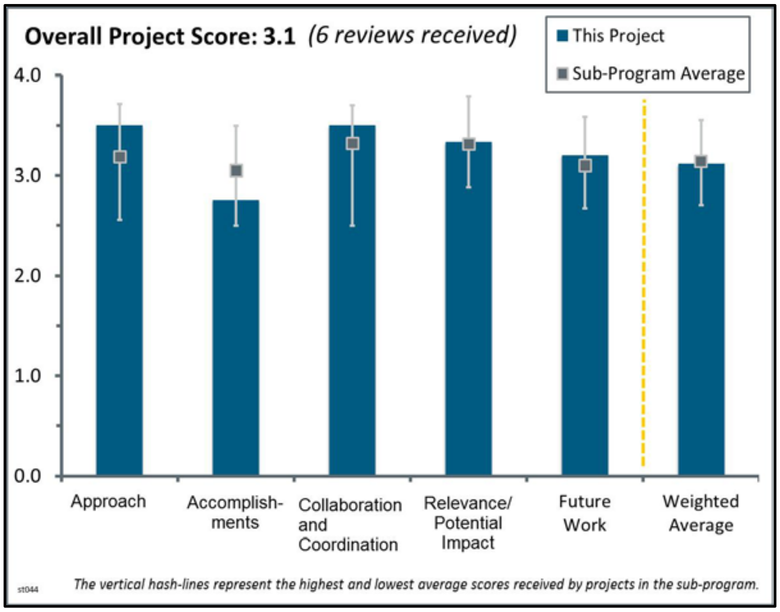
be overstated. Future work on advanced system development employing new/improved materials will build on the findings from this work. Unless the results are clearly and comprehensively presented, unnecessary and costly duplications in the technical effort will result.
- The project should add spot-testing of selected results on the system with a different hydrogen absorbent(s)—for example, using activated carbon or a different MOF.
- The project should finish its work as planned.
- This question is not applicable.

Project # ST-044: Savannah River National Laboratory Technical Work Scope for the Hydrogen Storage Engineering Center of Excellence: Design and Testing of Adsorbent Storage

Bruce Hardy; Savannah River National Laboratory

Brief Summary of Project:

Objectives of the current phase of this project include (1) designing, fabricating, testing, and decommissioning the subscale prototype systems for adsorbent storage materials; (2) validating the detailed system model predictions against the subscale prototype system to improve model accuracy and predictive capabilities; and (3) developing and demonstrating the acceptability envelope for adsorbents.



Question 1: Approach to performing the work

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

- The focus in 2015 was to develop a subscale prototype for adsorbent storage materials and to validate model predictions with experimental results in order to assess the predictive capability of the models. The team employed a straightforward and reasonable approach based on (1) demonstration and evaluation of the modular adsorbent tank insert (MATI) type and hexcell type of heat exchangers and (2) use of the results to update the cryo-system performance models. The approach enabled useful information about heat exchanger properties and performance to be acquired in a timely way. Additionally, a well-formulated approach was used to identify and quantify the coupled adsorbent and storage system properties needed to meet performance goals.
- The design and fabrication of prototype systems with validation of modeling to contribute toward the predictive capabilities is well executed. Progress has been made in completing the test facility. Modeling and system properties are strongly integrated and well aligned across the Hydrogen Storage Engineering Center of Excellence (HSECoE).
- The project appears to be well aligned with key barriers. It seeks to design, fabricate, and test adsorbent systems; compare the results with predictions; and provide acceptability envelopes.
- The overall approach is logical and reasonable. Small-scale prototypes of the MATI and hexcell are built and tested to gather data for model (kinetics and thermal) validation.
- The approach is sharply focused and difficult to improve significantly. The same approach can be used to evaluate/analyze similar systems. However, it is not quite obvious that the results of this work are directly transferable to other gas storage systems. This should be experimentally proven before the project is completed.
- The project features a well-defined approach for comparison of tank construction. However, it was surprising to see alumina utilized for the system tests. It would have been better to use a standard that consisted of a composite of a material with a thermal conductivity similar to metal–organic framework (MOF)-5 and the same amount of expanded natural graphite or graphene added.

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

This project was rated **2.8** for its accomplishments and progress.

- The team obtained important new information concerning MATI and hexcell heat exchanger performance characteristics. Unfortunately, progress was limited by the need to address persistent leak problems in the cryo-systems. While this inhibited overall progress on the technical effort, the leaks occurred in a fully instrumented testing apparatus, so this issue should be less problematic in a final, fully welded system that does not require feed-throughs and ancillary connections for system testing. Useful information was obtained on adsorbent acceptability envelopes that determine whether current adsorbents can meet targets and provide the coupled range of required properties for new adsorbents. It would be helpful if a trade-off analysis of the hexcell and MATI heat exchanger approaches could be made available to the research and development community. A considerable amount of development and engineering work has been conducted on these systems. A comparison of these two different heat exchange approaches is needed to assist original equipment manufacturers (OEMs) in selecting the optimum system embodiment for a specific application. Testing and validation data are needed.
- The team has made nice progress with the development and testing of MOF tanks (hexcell and MATI). The models show good agreement with tank evaluations. Progress on the adsorbent acceptability envelope has identified some concerns:
    - Meeting the 700 bar tank target will require a substantial increase in the number of adsorption sites.
    - The inverse correlation between gravimetric and volumetric adsorbent acceptability is a concern (but not too surprising). Predicted capacities are below compressed gas (700 bar) under most scenarios.
- The results will help to solve multiple issues; however, it is unfortunate that the project is not going to conclude in a system that can be used in real applications. Therefore, this question deserves a “Good” rating.
- The lack of multiple cycle testing overshadows the other significant accomplishments.
- The team made relatively little progress this year, with the major items being the implementation of the test system and hexcell manufacturing and implementation. Simple calculations to describe the characteristics of the ideal adsorbate were performed.
- Progress was slow this past year. The project was listed as 95% complete (as of 4/10/15), but there remains quite a bit of testing to be done with both the MATI and the hexcell. Model validation will then follow after testing is complete.

Question 3: Collaboration and coordination with other institutions

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

- Close collaboration is needed and well executed with partners in this project. Significant progress is made through the combination of design, testing, and modeling in the different institutions with added perspective coming from external collaborations.
- The collaboration between Savannah River National Laboratory (SRNL) and other HSECoE members, especially Oregon State University (OSU) and Université du Québec à Trois-Rivières (UQTR), was strong and fruitful.
- Solid and valuable collaborations among partners are evident and have continued to contribute to the overall success of the project.
- The project features very good collaborations; partners participate and are well coordinated.
- It was good to see Richard Chahine included in the HSECoE.
- Overall, the HSECoE partners appear to be working together very well. It was difficult to differentiate the level of effort from each institution for any one task. The icons at the bottom of the slide are helpful, but they do not really describe the level of effort. External collaborations were less clear.

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

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

- The hexcell manufacture is useful, along with the limited theory for adsorbate. The testing facility should be the most useful element of the project and deliver meaningful results to direct the future of the Hydrogen and Fuel Cells Program (the Program).
- The project is important to the overall success of the HSECoE effort and, by extension, to meeting the overall Program goals.
- Testing of MOF-5 in both the MATI and hexcell provides crucial data for model validation. The test data covers a wide array of engineering issues—such as heat management and balance-of-plant requirements—that must be integrated in an onboard system so that the system can meet the DOE targets in weight, volume, and refueling time simultaneously.
- This project has made nice progress, and the results are clearly having an impact on the community. At this stage, there appear to be a couple of key outstanding issues related to MOF tanks (e.g., loss of usable hydrogen and gravimetric/volumetric capacity trade-off) that must be addressed by the materials community.
- The project supports advances toward the Program's goals and DOE research, development, and demonstration objectives. However, there is little chance to meet those goals, owing to the limitations of the adsorbents (MOF-5).
- A decision and/or recommendation needs to be made about which tank design is most applicable to which types of hydrogen storage materials.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Determining low-temperature mechanical properties and life cycling would be useful. It is unclear how much damage occurs to the pucks after 1 cycle and 10 cycles, whether cracked pucks matter, and whether there is a buildup of impurities. Results indicate that system targets require a material with at least 160 adsorption sites; this suggests future work should focus on materials development rather than on tank design and analysis.
- The proposed future work is reasonable. The team may want to add another task (e.g., experimental validation of the project's results using other types of adsorbents, such as activated carbon).
- This question is not applicable—the project is ending. It is essential that the approach, results, and conclusions are carefully documented.
- The project is ending, and the remaining tasks are needed to complete the testing program and model validation.
- The team is so close to getting this done. It is not clear whether there will be time to actually analyze any data that comes from the testing.
- The project is ending.

Project strengths:

- A well-thought-out approach comprising modeling, experimental development, testing, and evaluation elements has been adopted. A highly coordinated team with expertise in all relevant project areas is conducting a highly focused technical effort. The results from the project are key enablers to development of a prototype test system.
- Strengths include the integration across the HSECoE, smart choices taken in deciding the path forward, and step-wise monitoring of tank properties, etc.
- The results provide useful feedback to the materials community.
- Project strengths include the approach and collaborations.
- The collaborators are a strength of this project.

Project weaknesses:

- Determining low-temperature mechanical properties and effects of thermal cycling would be useful. Tank life is probably outside the scope of this project, but it needs to be considered. There are no clear plans to deal with the "loss of useable hydrogen." Using liquid nitrogen to cool the tank may help, but this scenario will still require considerable cryogens. The cost estimate per fill is unclear. It is also unclear whether there are any plans to deal with dormancy issues.
- Progress was limited by the need to address persistent leak problems in the heat exchanger systems. It is surprising these problems only became apparent near the end of the project. It is unfortunate that the partner(s) responsible for the tank development (possibly Hexagon-Lincoln/SRNL) was unable to address the problems in a more timely and effective way.
- There is little chance the project will meet DOE goals, owing to the limitations of the adsorbents (MOF-5).
- The project has been quite expensive, and progress seems to be particularly slow.
- The lack of multiple cycle testing is a weakness.

Recommendations for additions/deletions to project scope:

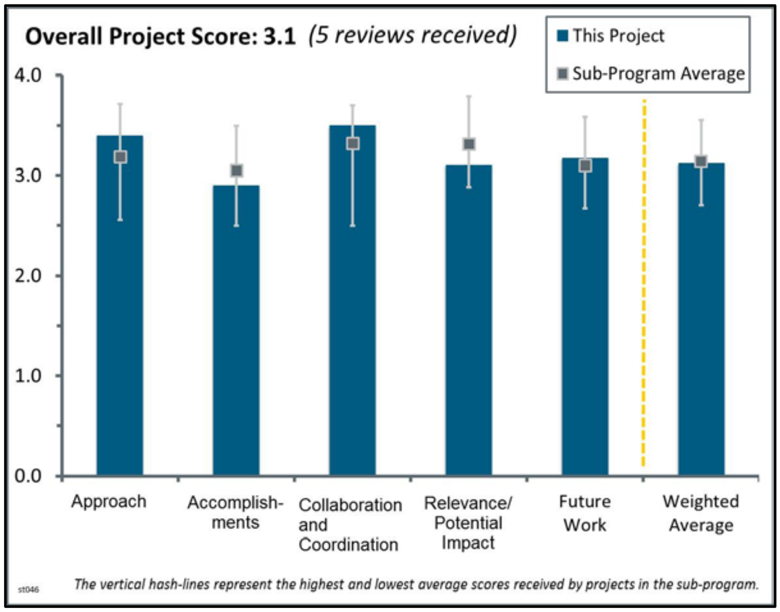
- A comprehensive final report is needed. Future efforts on system development should not be forced to "reinvent the wheel." The report should include a trade-off analysis of hexcell and MATI heat exchanger approaches for specific OEM applications.
- This project has made nice progress and identified clear challenges for the materials community. Given the limited resources, it is probably best to refocus on addressing the materials challenges.
- The team should add another task (e.g., experimental validation of the project's results using other types of adsorbents, such as activated carbon).
- This question is not applicable.

Project # ST-046: Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

Kevin Drost; Oregon State University

Brief Summary of Project:

As part of the Hydrogen Storage Engineering Center of Excellence, the objective of this project is to use the enhanced heat and mass transfer available from arrayed microchannel processing technology to design, fabricate, and test a modular adsorption tank insert (MATI) prototype to address the weight, volume, and charge/discharge rate challenges commonly associated with adsorbent-based hydrogen storage systems. The specific objectives of this project for Phase III are to demonstrate fundamental technical feasibility and validate simulations through subscale system evaluations.



Question 1: Approach to performing the work

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

- A MATI utilizing enhanced thermal and mass transfer is the centerpiece of one of the two principal heat exchanger concepts adopted by the Hydrogen Storage Engineering Center of Excellence (HSECoE) for a prototype cryo-adsorption storage system. A solid approach based on results obtained previously by the project team has been formulated and adopted in 2015 for assembly and testing of the device and validation of a thermal model that simulates the device performance. The novel concept and approach address important storage system needs.
- The design and fabrication of prototype systems with validation of modeling to contribute toward the predictive capabilities is well executed. Step-wise approaches to the scale-up of the MATI system have been taken. Modeling and cooling plate development have been performed.
- This project nicely addresses the barriers associated with heat and mass transfer of a practical adsorption-based system (i.e., size, weight, and charge/discharge rates). It is nicely integrated into the HSECoE.
- The approach is well designed for the remaining work scope.
- It is surprising that with all of the efforts at Ford, the thermal conductivity and hydrogen permeability data were missing. Even the mechanical stability of a puck should have been a straightforward evaluation within any engineering department. A before-and-after evaluation of the pucks after multiple cycles would have added to the long-term properties of the metal–organic framework (MOF)-5 samples. The engineering issues the principal investigator (PI) discussed (i.e., thermocouple leak-through at elevated pressures and cryogenic temperatures) should have been self-evident. Slide 20 appears to show there is still considerable heterogeneity in thermal distribution within the pucks; this will not be solved with the pins.

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

This project was rated **2.9** for its accomplishments and progress.

- Good progress was achieved on assembly and testing of three MATI prototypes, enhanced puck design and fabrication, and first steps toward model validation. A fully instrumented test system was developed to experimentally characterize the thermal performance of the device. Unfortunately, persistent leaks at various locations in the MATI assembly during cryo-temperature cycling precluded complete and timely testing of the device. Important new results were obtained related to improvements in MOF thermal conductivity in the MATI assembly (e.g., Al pins and expanded natural graphite enhancement in MATI pucks) and development of a modeling protocol for simulating gas fluid flow and heat transfer.

- The project's MATI adsorption system design has been largely developed, built, modeled, and tested. The pressed pucks have been tested for mass flow and heat transfer using a highly instrumented testbed. There have been some serious problems with cryogenic leaks that put the project well behind schedule. The project formally ends this month and is only 95% complete. A temporary (stopgap) flanged container was developed to at least complete the prototype system. It is not completely clear that this project's MATI design is superior to the alternate hexcell design.
- Project objectives are being met, but it is not clear how these objectives relate to DOE goals.
- The team has made limited progress since last year. There is an almost one-year slip in the specific, measurable, assignable, realistic, time-related (SMART) goals for Phase III because issues developed during cooling. Some aspects have moved forward, and pressure testing has begun on the larger test system. Modeling has been extended, and new pucks with pins have been designed. It is not clear the team can finish the project in time.
- Accomplishments were limited by engineering issues.

Question 3: Collaboration and coordination with other institutions

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

- Valuable collaborations with HSECoE partners are evident. The interactions with the University of Michigan/Ford on puck design and with SRNL on prototype development and device simulation are especially noteworthy.
- The collaboration and coordination within the HSECoE seem excellent.
- The project worked well with SRNL.
- Collaborators are involved in project planning and execution.
- This project has to connect with several other groups in the HSECoE to be successful. It does this in several ways—relying on partners for MOF pucks, delivering prototype systems to SRNL for testing, and providing data for simulations. However, the year's efforts seem to be less collaborative and more divided, with little effort by some partners.

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

This project was rated **3.1** for its relevance/potential impact.

- The heat exchange technology developed in this project is an important element of the approach adopted by the HSECoE for a cryo-adsorbent storage system. The approach is innovative and addresses issues of cryo-system weight and size and charging time. The project is relevant to the goals and objectives of the Hydrogen and Fuel Cells Program (the Program), and the level of effort is appropriate to meet those goals.
- Except for some degree of incompleteness, the project has made clear advances toward the Program's goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan in terms of its participation in the HSECoE.
- The system focus of the project is geared toward DOE goals and will have some impact if the design and modeling are all extensible.
- With the end of the project near, the impact of the work is muted and incomplete. Significant progress was made, but more answers should have been forthcoming.
- It could be made clearer how improvements in volumetric density and heat transfer contribute to better meeting DOE targets. Additionally, improvements do not come without cost, and the impact is not well presented.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- This question is not applicable—the project is ending. Careful and comprehensive documentation of the Oregon State University (OSU) work in the final report is essential. If possible, the work to validate the heat and fluid flow model should be completed.
- The project formally ends this month. The proposed future work is fine, but it is not clear how it will be accomplished after the end of the contract.
- The future work is clearly defined. With most of the funding spent, it appears there is more work to complete than funds available.
- This should be the end of the project, but it is not finished, and there will be no time to analyze any testing data.
- The project is sunsetting.

Project strengths:

- This is an innovative project that addresses important technical issues in the successful deployment of a practical cryo-adsorbent hydrogen storage system. The project team and the collaborators have expertise in all areas relevant to successful prototype system development. Throughout the project, the PI and his team have been responsive to reviewers' suggestions and recommendations. This project is a critical component in the overall HSECoE effort.
- The project has made good, practical heat/mass transfer contributions to the HSECoE.
- Collaborations among the partners are an area of strength.
- Development of a MATI system is a strength.

Project weaknesses:

- The overall pace of the effort in this reporting period was not consistent with the pace in prior years. The progress in 2015 was clearly limited by problems with leaks in the instrumented MATI subsystem. It is unfortunate that given the involvement of Hexagon-Lincoln (tank expertise) in this project, and in the HSECoE as a whole, so many problems with cryo-tank leakage plagued the important later stages of this effort.
- Clear connections need to be made between technical goals and accomplishments and progress toward achieving (or approaching) DOE targets.
- Project weaknesses include the slow final year and high expenses for the current deliverables.
- The incomplete evaluation is an area of weakness.
- There are tank design problems relative to cryogen containment.

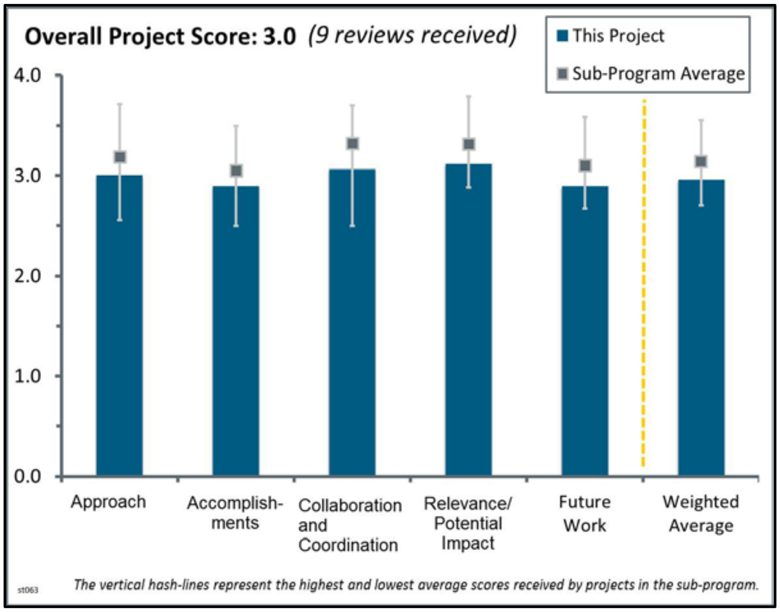
Recommendations for additions/deletions to project scope:

- This question is not applicable—the project is ending.
- This question is not applicable.

Project # ST-063: Reversible Formation of Alane

Ragaiy Zidan; Savannah River National Laboratory

Brief Summary of Project:



The overall goal of this project is to develop a low-cost rechargeable hydrogen storage material with cyclic stability, favorable thermodynamics, and kinetics to meet U.S. Department of Energy (DOE) onboard hydrogen transportation goals. Specific objectives include (1) development of cheaper techniques to synthesize alane (AlH_3) that avoids the chemical reaction route that leads to the formation of alkali halide salts such as LiCl or NaCl, (2) utilization of efficient electrolytic methods to form AlH_3, and (3) development of crystallization methods to produce alane of the appropriate phase, crystal size, and stability.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- Past work has focused on improving the electrochemical efficiency of AlH_3 production from $LiAlH_4$ and Al electrodes (made by compressing spent alane). This year, the focus appeared to be more on methods to crystalize the AlH_3 from the ether adduct.
- The relevant barriers addressed are intrinsic to the project design. Alane as a material has properties close to meeting many automotive targets, and the project can do no better than this. The electrochemical regeneration proposed is a relatively efficient process, and therefore, the project focus should be on attaining the highest efficiencies and yields.
- This alane project is unique within DOE. Barriers for small and medium storage applications are well addressed. (The project is not applicable to DOE vehicle targets.) The project is very well designed, feasible, and integrated with at least one commercial effort. The project is based on an elaborate, but novel, electrolytic/adduct method of AlH_3 manufacture.
- Electrochemical synthesis is very efficient, and the follow-on procedures to remove the solvent also provide control of particle size and polymorph of alane formed.
- The approach is effective at the laboratory scale and contributes to overcoming most barriers. Its efficiency should be proven while it is scaled up.
- The electrochemical generation of the alane adduct is the right approach to regenerating the material.
- This work is all empirical. It is lacking any features of experimental design. At this point, this should not be scouting work anymore, as the chemistry of alanes is well established. If there is only 80% regeneration for one step, then after three steps, less than 50% will be generated from the starting material, which is unacceptable for use in any sector. The flashpoint of ether is not stated. It is not clear that this process can be used for any real industrial processes. The team members do not understand thermodynamics. They do not understand Lewis acid-base interactions and how they work. It makes little sense that a pure solid material can have different amounts of hydrogen in different phases. There must be impurities, so nothing can be compared. It is not clear how the team will control crystallization. The project needs a physical model and does not have one. Crystallization needs to be controlled over a very narrow temperature range for success, so the whole concept is not likely to be feasible. It would be good to have examples of an industrial process in which crystal morphology is controlled and size is controlled. How the project will control dendrite formation is unclear.

- The approach, i.e., electrochemical synthesis of AlH_3 in $LiAlH_4$-based electrolyte, is relatively well established. The work seems to be focused on crystallization of alane adduct from the solution and on preparing adduct-free alane in correct polymorphic form, i.e., alpha- alane. The following remain to be addressed:
  - The achievable rate of the electrochemical synthesis of AlH_3 (perhaps per unit area of Al electrode) is unclear, and it is uncertain whether this rate is high enough for potential commercialization.
  - Concentration on preparation of adduct-free alane seems a bit out of scope. Etherated alane adducts and their desolvation have been relatively well studied in the past.
  - It is unclear how critical the concentration on recycling of spent aluminum is. Cost estimates indicate that aluminum represents the bulk of the cost; however, the cost analysis does not account for expense in collecting, necessary pre-processing, and transportation of spent aluminum.
- The stated approach is to develop a low-cost route to the synthesis/regeneration of alane consistent with onboard vehicle applications. However, as stated on slide 4 of this presentation, this is anything but low-cost, as the estimate for large-scale production of alane is stated as $100/kg, inferring $1000/kg hydrogen—orders of magnitude away from the fuel cost target. This presentation would be improved if the presenter acknowledged this fact and that the stated focus of the work is on medium-power or niche-type applications in which fuel cost may be less sensitive to success. Whereas the regeneration costs are likely unimportant for certain military applications, the first fill costs are still important if those costs are substantially greater than the rest of the system that the fuel supplies. *[DOE note: neither the presentation nor the principal investigator (PI) stated the project is aimed at vehicular application; in fact, it was indicated that the project partner, Ardica, is developing man-portable, low-power systems that use AlH_3 as the hydrogen storage technology.*]

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

This project was rated **2.9** for its accomplishments and progress.

- The contractor has made excellent progress during the duration of the project, especially during the last year. Much progress has been made with the electrolytic approach and the important crystallization of the optimum alane final product from intermediate adducts. The production of AlH_3 from recycled Al and H-depleted AlH_3 (Al powder) has shown significant cost reductions approaching DOE small and medium power storage targets. In particular, the potential to recycle alane has been demonstrated. The work has been pioneering, with many publications generated. Some practical problems remain, but this DOE project has clearly shown the potential for a solid state storage for special applications. As indicated by the PI, as well as the Ardica presentation (ST-116), alane has nearly zero probability of ever meeting DOE cost targets for light-duty vehicles; thus, these projects are focused on low-power applications.
- There is good progress in the project, with a focus on avoiding formation of dendrites of alanates during formation of alane.
- Outstanding accomplishments were achieved (80% yield).
- The basic results are very interesting, and there have been many improvements during the last years.
- It was not clear how much was accomplished over the past year. The cost analysis was the same as the previous year. The project reports a near-80% regeneration efficiency for $LiAlH_4$ in fiscal year (FY) 2015 that compares well to the regeneration efficiency of $NaAlH_4$ for FY 2014. The PI discussed two areas of progress: (1) reducing dendrite formation by using a reverse pulse technique during reduction and (2) approaches to crystallize the alane adduct to produce the optimum size and phase of alane. It is unclear whether the cost analysis changes if the reaction needs to be run in reverse pulse mode. It seems like it would affect cost, so it is not clear whether the team is suggesting this as a solution or believes other approaches are necessary. The elimination of dendrite formation is suggested in future work, but no details were provided.
- Accomplishments presented are mainly the reduction of dendrites, a demonstration of 80% yield for one step, and a demonstration of crystallization of the alpha phase. The dendrite slide shows a before and after comparison, but the other results are shown without context, and it is difficult of assess how much progress has been made in the current year. The results are generally one-off comparisons; in the crystallization

study, for example, it would have been preferable to see something like a results-based phase diagram that showed how changing the conditions led to various phases and/or crystal sizes. Such information would be more valuable for the community (and partners) than a "here's a good result" slide.

- Progress seems to have stalled, as there were no substantial experimental results reported in this year vs. previous years. The crucial problem areas still reside in the electrochemical area, and it appears that these problems may be beyond what this team can solve quickly. Last year, an area of criticism was that the kinetics of the regeneration process were miserable; there was no evidence that this was addressed this year. One area in which there was progress was in the reduction of dendrite production, which can be very problematic for large-scale production. Progress was shown in reducing the formation of dendrites by using a pulsed electrochemical approach. This approach, however, reduces the duty cycle by perhaps 30%, thus decreasing the space-time yield of alane by probably 30% in any continuous process, and likely increasing the cost of alane even more; this is counter to the stated project goal. It was also unclear from the presentation and from the question-and-answer session whether the 80% yield of alanate regeneration resulted in 20% material that could be recycled in a second pass, or if that material was "waste"—which would be an absolute "must" to resolve. The purity of the hydrogen gas was also questioned, and while a residual gas analyzer (RGA) might be somewhat useful in looking for impurities, a long-path-length infrared cell and/or gas chromatography–mass spectrometry to look for adducts, adduct fragments, etc. might be a more appropriate and powerful set of analytical tools to judge hydrogen purity. However, this should not be a priority; solving the remaining electrochemical problems should be the priority if this project goes forward.
- The work is empirical only, without experimental design. The regeneration percentage is poor. The project team needs to be careful of the energy associated with electrochemistry. The team needs to count electrons as well. It is very hard to tell what was really accomplished. How crystallization is controlled was not well described. The cost is very high. It is not clear that the electrochemistry cost is viable in industry for large-scale production. No data were provided to indicate the nature of the catalyzed and activated Al for regeneration. Basic science is needed for what is essentially an engineering application—control of crystal structure, size, and morphology. The project does not have it. The team is still scoping the process, not working toward an industrial application. No real progress was observed.
- Accomplishments during the last year are not quite clear. There were no new publications or presentations after the 2014 Hydrogen and Fuel Cells Program (the Program) Annual Merit Review.

Question 3: Collaboration and coordination with other institutions

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

- There are excellent working collaborations with Ardica (a commercial cooperative research and development agreement) and SRI International.
- Having twice-weekly discussions demonstrates an intense collaboration between SRNL, Ardica, and SRI International.
- The collaboration with SRI International and Ardica appears to be good to excellent.
- Judging from the information given, there appears to be a good collaboration within the project.
- There are good communications and collaborations with partners, although there were signs of duplication with the sister project led by Ardica. The projects seemed to share some future work (dendrites, conductivity), and concentrating on the strengths in each project could be more effective.
- It would be useful to see an independent cost analysis from Argonne National Laboratory or Strategic Analysis, Inc., to compare with the preliminary cost analysis provided by Savannah River National Laboratory (SRNL).
- The internal group collaboration is acceptable, but the project has no outside collaborations and needs them.
- Collaborations could be expanded to other partners with relevant expertise.

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

This project was rated **3.1** for its relevance/potential impact.

- Development of a low-cost rechargeable hydrogen storage material with favorable thermodynamics and kinetics, fulfilling the DOE onboard hydrogen transportation goals, is highly relevant. The utilization of alane is already demonstrated by the U.S. Army. Although the method regenerates the storage material "off-board," the approach is still highly relevant and efficient.
- Alane is one of the few current metal hydrides showing the potential to meet 2020 DOE onboard system targets.
    - SRNL is world-leading in this field.
    - The project is very important and being performed by the right team.
- The project is critical to the Program and has potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives.
- The project is clearly focused on addressing barriers for regenerating alane and doing this in a cost-effective and efficient manner. It therefore has strong potential to make progress toward meeting DOE goals.
- This project has demonstrated clear advances and progress toward the Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan for small and medium off-board storage applications.
- The potential for impact is excellent, as alane can be used in a variety of applications.
- Regeneration of off-board materials is highly relevant to the Program goals, and reducing the costs of fuel from off-board regenerable systems might have a significant impact, were the effort to be successful. However, this is likely not the materials system of choice on which to expend effort to provide low-cost fuel for vehicular applications. This topical area has more impact and relevance to lower-power niche applications in which the sensitivity to fuel cost is less.
- The current and proposed work will have no impact. The cost is too high. The regeneration percentage is too low for a single step. The team members have to deal with the issue of ether vapor in an industrial setting. They have not shown that the work is practical in terms of controlling crystal size, purity, or morphology at the small scale, much less at a larger industrial scale. They are not addressing or meeting DOE needs.
- DOE has recently appeared to indicate that off-board regeneration is not of interest, so it is more difficult to justify off-board electrochemical regeneration of alane.

Question 5: Proposed future work

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

- The project is progressing according to the plan. The future focus on reduction of dendrite formation is very relevant. Developing cheaper techniques to synthesize alane that avoids the formation of alkali halide salts such as LiCl or NaCl is extremely useful.
- Critical barriers are tackled: increase the rate of production, eliminate dendrite formation, and optimize crystallization for large-scale production.
- Future work is good. The project may need some additional unexpected work to enable the scale-up of the process.
- The plan for future work is well crafted and expressed. The project should proceed as planned.
- Aside from the possible duplication of effort with the Ardica project, the proposed work is directed at overcoming the challenges identified. However, the proposed work is vague in some cases, e.g., "develop efficient method for…", "explore additives to …", "develop techniques for the crystallization…". A little more detail is needed to assess whether these approaches are likely to result in substantial progress.
- It would be prudent to measure the efficiency of removing the tetrahydrofuran (THF) from the THF-AlH_3 adduct on an authentic sample before too much effort was expended on the electrochemistry in THF. If reaction conditions are not found that minimize decomposition of alane, then this may not be a viable

direction. If alane slurry is used, it is not clear how the presence of the slurry material will affect the process. The team proposes exploring additives to increase conductivity, but no details were provided. It was believed that the project had done this in the past, e.g., with LiCl.

- Several points are unclear:
    - Which additives could be used to increase conductivity
- Whether they will affect formation of alane
    - Whether alane will be formed if sufficient conductivity is reached
    - What reducing the distance between the electrodes is going to accomplish, even if dendrite formation can be prevented
    - How much alane formation can be accelerated as a result
- The project is focusing on the wrong issues. The team is not addressing the low conversion percentage. The project needs a proposed work plan to understand the physical processes that need to be controlled, and the project does not have such a plan. The approach is too Edisonian.
- Little specific detail was expressed as to the guiding scientific principles of how the electrode and electrolyte conductivity problems were to be resolved. The "what" is obvious, but regarding the "how," it is not apparent what the specific experiments to implement the approach might be. There were no comments this year about whether any improvements in kinetics have been achieved.

Project strengths:

- This is a very well-organized and productive project led by a very experienced and professional principal investigator. The project aim is highly relevant. There has been good progress in improving preparation techniques. The project is progressing according to the plan and will likely fulfill the goals and soon finalize very successfully.
- Materials that are being used are of great safety concern, i.e., extremely volatile and highly flammable solvents, as well as unstable phases of alane. The SRNL research team members appreciate the need to be extremely careful in their operations and might do more to communicate this to their new partner, Ardica.
- The project is focused on a material that advances toward DOE targets and is investigating efficient methods for regeneration. Regeneration has been a frequent stumbling block for many promising materials.
- The project is built around a simple hydride clearly capable of approaching DOE goals for special small and medium storage applications.
- The correct approach is being taken by the correct team.
- This is a small company collaboration that has a real application in mind.
- This is good basic research.
- The project aims at cost-effective preparation of alane.
- The only strength is that alane is an interesting material. There are no others.

Project weaknesses:

- No weaknesses are observed.
- It is unfortunate that high alane cost will preclude light vehicle applications.
- It is not clear that the idea about the temperature window is 100% correct. Good crystals of the pure alane were obtained in boiling toluene and higher-boiling solvents.
- Results are frequently presented without a more systematic exploration that would assist commercial partners and others. Given that DOE is funding an associated scale-up or pilot commercialization project, the current project should concentrate on providing understanding and knowledge that would guide this. The project appears to treat each step in isolation. While this is suitable for providing the understanding, at some stage the project should address the overall electrochemical regeneration to understand what efficiencies can be achieved in a full pass from spent alane to regenerated alane. Regeneration of 80% for one of the steps will rapidly result in loss of material, and the yields and efficiencies need to be known when the whole process is strung together, preferably in multiple cycles (this may improve yields if some of the material is simply dissolved in solutions that will be reused).
- Electrochemical efficiency is strongly correlated with conductivity. Unfortunately, the optimum reaction conditions that favor formation of an adduct that can crystallize to the alpha-phase of alane are counter to the optimum reaction conditions to optimize increased conductivity. There is little information about the

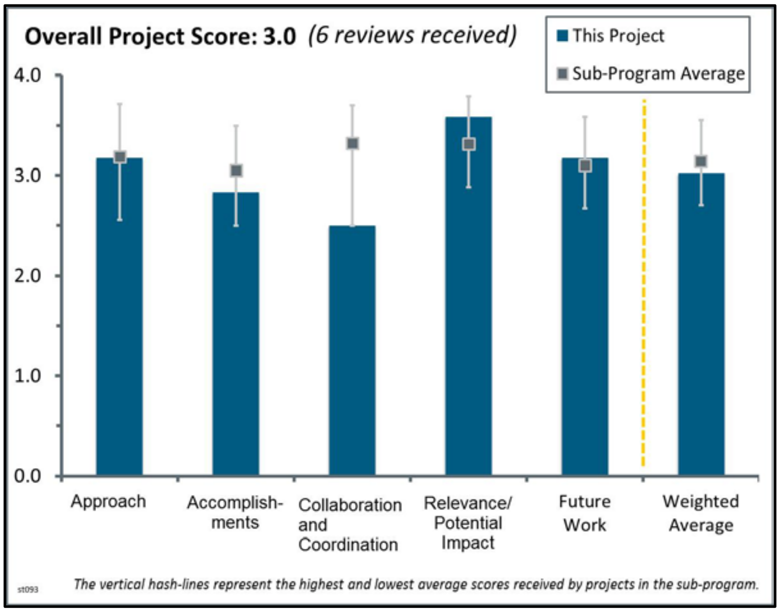
cost analysis of regeneration of the consumable electrolyte ($LiAlH_4$). The presentation shares that yields >80% are achieved, starting with LiH, but the source of the LiH was not clear—perhaps it is the $LiAlH_4$ formation from Al. It is not clear whether the process will be viable if recycling of $LiAlH_4$ is not much more than 80%.
- There are many weaknesses. The team members have a poor choice of complexing agent, ether, which could be dangerous to use at the temperature needed for crystallization. They need to use experimental design tools. They need to get a real physical understanding to minimize the Edisonian approach. There is no guarantee that they can control crystal size, morphology, and level of impurities. They have no explicit go/no-go decision points.
- The team may have reached the asymptote of the remaining available improvements to make in cost. The team members may need to add some electrochemistry expertise if they hope to make additional progress at a more rapid rate.
- The electrolyte is expensive. Currents are very low, and resulting yields are low. Side reactions, e.g., formation of Li_3AlH_6, are unknown.

Recommendations for additions/deletions to project scope:

- The project should continue.
- The results from this project are very promising and call for further research and development in this field. Alane remain one of the most promising hydrogen storage materials, with very high capacity.
- The project should focus more on the electrochemical regeneration and less on the recrystallization. The project has a little over a year to run, and the best value will be achieved by overcoming the barriers to efficient regeneration of the alane adduct. The main disadvantage of poor crystallization is instability of the resulting alane; this should not inhibit multiple cycles since it needs to be dehydrogenated anyway. There is little point in perfecting the crystallization if the adduct cannot be formed with high yield and efficiency from spent material (with $LiAlH_4$ and LiH produced in situ as indicated) through multiple cycles.
- The project should (1) use experimental design, (2) focus on getting to 100% in regeneration, (3) focus on understanding what controls crystal morphology and size and get away from an empirical-only approach, and (4) deal with the impurity issue.
- The team needs to pay attention to the overall rate of throughput, e.g., kinetics, even for military applications in which fuel cost may not be that critical. If it is too slow, the reactors get too big, and the costs might then exceed even the military’s ability to pay.
- The project should focus on the fundamentals of electrochemical preparation of alane rather than on solving minor issues related to scale-up. (Ardica has a separate project to do just that.)

Project # ST-093: Melt-Processable PAN Precursor for High-Strength, Low-Cost Carbon Fibers

Felix Paulauskas; Oak Ridge National Laboratory



Brief Summary of Project:

The objective of this project is to significantly reduce the manufacturing cost (>25%) of high-strength carbon fibers (CFs) by (1) introducing high-quality polyacrylonitrile (PAN) precursor melt-spinning techniques; (2) developing alternative formulations for advanced precursors capable of being melt spun in high volumes; (3) developing and demonstrating appropriate conventional and/or advanced CF conversion technologies; and (4) advancing properties, scaling, and overall economics to meet high-pressure storage targets.

Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The overall approach of the project is good because it pursues melt-spun processing as an alternative to the solution processing. It is excellent that the project is focused on PAN-methyl acrylate (MA) to attempt the targeted performance rather than the vinyl acetate (VA). The basic steps of the project are appropriate and include precursor chemistry, melt spinning, and hot fiber drawing.
- The project's approach of building on the past patents is very sound. Appropriate actions have been taken to address the equipment deficiencies experienced last year.
- This work directly addressed cost barriers for the use of CFs. The approach of trying to modify the process covered under BASF patents is straightforward.
- This project aims to prepare PAN-MA precursors and use melt spinning, which is expected to result in lower production costs by simplifying the production process.
- The approach of using melt spinning to replace wet spinning the CF precursors could have a tremendous impact; however, this project still seems to have problems progressing to make long tows for evaluation.
- The overall approach was good; however, it would have been good to see stronger support from Virginia Tech (VT).

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

This project was rated **2.8** for its accomplishments and progress.

- Proof of concept was completed; i.e., the project demonstrated the ability to melt the precursor prior to crosslinking, resulting in an acceptable strength of the fibers. However, the project has been experiencing delays due to the engineering challenge with filament production.
- The project is finally on the verge of making significant progress with the new hot fiber drawing machine, but it is also on the verge of missing many critical milestones, and it seems as though the VT partner should be reevaluated. If DOE really wants progress made in this area, more funding to build specialized equipment will be required; however, this is probably outside the scope of the Hydrogen Storage sub-program and more of a manufacturing issue.

- The principal investigator (PI) reports difficulty with the process scale-up work, and this has caused slips in schedule. The explanation offered—that detailed direction on the process was not provided in the BASF patent information, and the nature of the engineering effort involved complications, including a combined flow, control of a complex chemical process, and a mechanical process that varies with scale—is believable. However, DOE should monitor the effort, in case assistance to the PI or project is warranted. Success may pay big "dividends."
- The equipment improvements are the most notable progress for the year. However, the improvements could have been made faster and with better collaboration on the part of the university and its resources. The resultant properties of the CFs from the switch to MA are needed.
- The project has experienced significant delays due to engineering issues associated with the spinning scale-up at VT. It is unclear what approaches are being taken to resolve these issues. A systematic approach to problem resolution would be recommended, along with a consideration of external assistance.
- Per the presentation, all fiscal year (FY) 2015 milestones have slipped. It is questionable that the roadblocks with VT will be eliminated.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- The collaboration on this project appears to be good, but it could be improved by including other partners to assist in the process engineering, because it appears that much of the delays are due to VT. It was encouraging that the Oak Ridge National Laboratory (ORNL) PI has made contact with the engineers at BASF who previously developed this melt-spun PAN precursor.
- The drive and collaborative effort on the part of the PI are excellent. However, with the unfortunate change in resources at VT, a similarly driven proponent within VT is very much needed. This is valuable and important research that needs to be a high priority for all parties.
- While the combined acumen of institutional partners should be adequate, it seems that additional experience is required in this effort. The PI has taken the initiative to find experience associated with the original BASF effort. The short-term outcome of this interaction should be monitored for effectiveness.
- It seems that discussion has been initiated with companies such as BASF. However, CF manufacturers should be involved to assess these engineering issues.
- The collaboration with VT seems to be strained at the moment, so other possibilities should be evaluated. The addition of Izumi International and ReMaxCo to address the equipment is a move in the right direction.
- It does not seem like there is strong collaboration with VT, and it does not seem like it will get better in the future.

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

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

- The project is highly relevant because it is focused on the main cost factor (i.e., precursor) associated with the CF, which is clearly the highest cost driver in the compressed hydrogen tank system. The potential cost savings of 31%–33% would have a notable impact on reducing the cost of the tank system and fuel cell electric vehicles.
- Melt-spun precursor has the potential to make a significant impact on the cost of the CFs used in hydrogen storage, as well as on the rest of the high-performance composites industry. This research needs to become a priority with DOE, and resources should be expanded as needed, or the true potential may never be realized or even identified. The timing to bring in other sponsors or collaboration parties, such as a CF producer, is right to expand the resources provided to this project. Equipment vendors also represent a key element that is not currently being leveraged.
- Melt spinning, rather than wet spinning, the CF precursor could have a great impact on the price of tanks and could have further-reaching impacts into decreasing the costs for high-strength fiber that could be used for vehicle body parts.

- The overall relevance of the project was very good, and the technology has the opportunity to increase the throughput of the PAN precursor.
- If realized, the potential impact would be outstanding.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future plans are well developed and show a good path to success. However, a critical juncture is being reached where further resources are required to keep the project on schedule and allow the team to complete the future work plans.
- The refinement and scale-up of the process will be very beneficial to this project, which has the potential to have a positive impact on the industry.
- The proposed future work includes the necessary steps to prove-out the melt-spun scale-up. The team needs to consider contingency plans for the engineering issues to avoid further delays.
- The work plan seems reasonable, but the team should initiate communications with CF manufacturers.
- The milestones seem to be slipping, so Milestone 6, which is due on 12/31/15, will be critical. If the project hits that point, then it should be well on its way to meeting Milestone 10. However, it seems both of these will depend on the partnership with VT and the team's ability to produce lengths of tow that can be further processed and tested.

Project strengths:

- The team is very competent and knowledgeable with the precursor chemistries. The use of the melt-spinning process may simplify the production process and reduce costs of the CF, pending the economic model planned in the future.
- The PI and the approach both represent strengths of this project. With these strengths, the real potential of melt-spun precursor should be able to be identified, and further efforts should be able to be planned for commercialization.
- The key strength is the ORNL team's background and expertise in CF. In addition, the project has high importance because it could significantly reduce the CF cost.
- The overall work in this project was very strong, and it will be good to see the results in FY 2015.
- The success in this project's approach would address cost issues at a fundamental level.

Project weaknesses:

- The project is based on a cost improvement, but the economic model has not been updated for many years. The benefit of the melt-spun techniques should be quantified with a current cost model. There have been several delays, and a plan needs to be developed to ensure the project can meet the future milestones without additional delays.
- Where good progress was realized early in the year, the passing of the key leader at VT has left a deep void. This has now become a weakness that urgently needs to be addressed to keep momentum. The lack of a CF supplier and a key equipment supplier as part of the team also represents a weakness.
- There seem to be engineering challenges associated with the production and upscale of the filaments so that they could be ultimately used in tanks. There also seem to be several delays due to unforeseeable technical challenges.
- Success requires control of a number of engineering parameters that may be "art" as much as "engineering."
- There were major roadblocks with VT and ORNL, and it is questionable that they will be overcome in the near future.

Recommendations for additions/deletions to project scope:

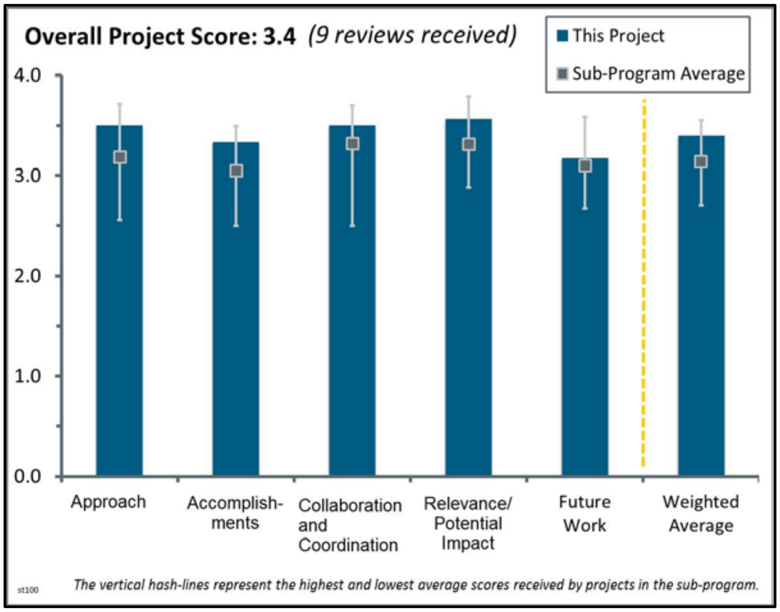
- The project should consider evaluating the composite properties in addition to the fiber properties. The team should also accelerate the economic model update to help understand the process cost drivers and influence the project earlier, rather than later, in the timing. The researchers should provide information to Strategic Analysis, Inc., to complete a cost analysis. In addition, the team should consider additional funding and/or partnerships to improve the timing and accelerate solutions to the engineering problems.

- It is highly recommended that CF producers are involved in this project to help overcome the engineering challenges and to provide cost estimates related to upscaling the processes proposed.
- The project team should redefine the priority of this project at VT and identify the key investigator, as well as consider adding a CF producer and a melt-spinning equipment vendor to the collaboration effort.
- Additional time may be needed to complete the engineering goals.

Project # ST-100: Hydrogen Storage Cost Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:



The goals of this project are to (1) conduct independent Design for Manufacture and Assembly (DFMA)® cost analysis for multiple onboard hydrogen storage systems, including 700 bar pressure vessel systems, adsorbent systems (Hexcell and modular adsorption tank insert [MATI] concepts), chemical systems (alane and ammonia-borane [AB]), and metal hydride for forklift applications (Hawaii Hydrogen Carriers); (2) assess/evaluate cost reduction strategies; and (3) identify pathways to reduce the cost of onboard hydrogen storage systems by 15% compared to the U.S. Department of Energy's (DOE's) 2013 record and meet the DOE 2020 target of $10/kWh for onboard hydrogen storage for light-duty fuel cell electric vehicles (FCEVs).

Question 1: Approach to performing the work

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

- This project focuses very well on very important cost barriers via design optimization of onboard storage systems. By the end of the contract, all DOE candidate systems will be cost-quantified: 700 bar pressure vessels, adsorbent systems, chemical systems (alane and AB), and conventional metal hydrides for forklift applications. The project should provide at least preliminary answers to the long-open questions on comparative system costs. The project is well integrated with other DOE projects, including the Hydrogen Storage Engineering Center of Excellence (HSECoE). The target of 15% cost reduction of compressed hydrogen (CH2) systems under the 2013 DOE base is reasonable.
- The approach for this project was very strong. It appears that the cost analyses will be valuable for those in the industry.
- The project focused on translating technology developments into cost, which provides useful guidance to engineering teams to meet cost targets. The project seems to be well integrated.
- The approach is thorough for gathering information and putting it in a usable cost model. The one area of improvement would be the incorporation of more "what if" scenarios in those models. An example would be "what if" production volumes were significantly different from the 500,000 assumed. Another example would be "what if" 15% weaker carbon fiber (CF) were used but at a 25% cost savings on the price of the fiber.
- The project utilized DFMA cost analysis to directly compare 700 bar, Hexcell, and MATI sorption concepts.
- The project used DFMA analysis to develop estimates.
- The approach is generally good. However, there are other projects within Fuel Cell Technologies Office (the Office) initiatives that are producing data that could be relevant to the cost analysis. It seems like only partner projects are being considered in data input.
- The approach is generally effective but certainly can be improved. The cost analysis is based on single-tank, and some assumptions are very optimistic. The $/kWh should include uncertainty.

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

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

- Thus far, 700 bar CF tanks (from Oak Ridge National Laboratory CF) and two HSECoE systems (Hexcell and MATI) have been optimized and cost-quantified. Potential cost reductions have been identified, both in the tanks and balance of plant (BOP) components. The 15% reduced cost target for 700 bar CH2 has been essentially met. The three analyzed systems seem to be roughly competitive in price. For the two adsorption systems, the operational disadvantage of cryogenic operation seems to add complexities and possible lifetime restrictions. The presenter indicated there are more uncertainties in the adsorbent cryogenic systems, but the best estimates have been made based on 500,000 annual production. Work has begun on the other storage systems (e.g., the forklift tanks). It is not certain whether there will be time to complete them by the time the contract ends next year. Perhaps this important effort should be extended a few years.
- It is good that Strategic Analysis, Inc. (SA) is looking into component and system integration of the low-pressure system for the BOP. If SA is able to reduce the number of fittings used in the system, it will make the BOP much more robust and cost-effective.
- The results generated are very useful because they integrate tank designs obtained from the HSECoE.
- Considerable cost reduction was estimated from integrated design and low-cost CF—approaching DOE goals. There has been nice progress with the adsorption system. Cost estimates (~$2,500) are comparable (on an energy basis) to 700 bar CF. It is not clear that tank life has been considered in cost estimates. It seems a true cost would be normalized by life expectancy. No accomplishments were listed for chemical hydrides (alane and AB), so it is not clear whether any progress has been made in this area.
- Progress has been excellent in identifying specific targets for cost reduction, particularly through proposed integrated pressure regulators and valves, which reduces the overall complexity and risk of the systems. However, what is not clear is whether there is buy-in for fabrication of these integrated structures, and thus the question remains as to whether the identified cost savings can truly be realized.
- This is excellent analysis and work but lacking the "what if" evaluation that would allow DOE to take the results and formulate research plans. Especially critical is that the sensitivity to different production volumes be conducted and presented, possibly as a series of curves.
- For the cost comparison of Hexcell and MATI systems, the assumption should be clearly stated. The cost-per-kilowatt-hour difference between these two systems is within 5%. It is not certain that this is real and not just noise.

Question 3: Collaboration and coordination with other institutions

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

- The project has close, timely, and appropriate collaboration with other institutions; partners are full participants and well-coordinated. The project is working with the National Renewable Energy Laboratory and Argonne National Laboratory to provide complementary analysis.
- There have been numerous outstanding collaborations in this project. This includes the HSECoE, manufacturers, and national laboratories. They have been critical to the success of this project.
- It appeared that the project had strong and close collaboration between laboratories, original equipment manufacturers (OEMs), and manufacturers.
- The team engaged the tank manufacturer and OEM early on. They were able to obtain input from experts in different fields of expertise.
- There are a number of active collaborations (Pacific Northwest National Laboratory, Hexagon Lincoln, and Ford, with some input from HSECoE for cost analysis).
- Visible collaboration exists with other partners.
- Coordination with the identified partners has been excellent. However, there are a number of other ongoing Office-funded projects that could offer contributions to the cost analysis. It does not seem like there has been an effort to seek out or include these projects.

- The researchers do an excellent job of gathering the data from researchers and suppliers. The one gap is in referencing or bringing in other cost models.

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

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

- The project sheds light on costs of future tanks and gives valuable information on potential paths to minimize cost. For example, the finding that the metal–organic framework (MOF)-5 tanks have costs similar to the 700 bar tanks, despite the much lower pressure, is very important and unexpected.
- The cost analysis has done a good job of identifying targets with significant potential for further cost reduction through the fabrication of integrated pressure regulators and valve systems. It remains to be seen whether resources will be allocated for these activities so that the cost savings can truly be realized.
- This is very important. If more scenarios for production volumes are included and comparisons to other cost models are made, the output of this project can be better used to guide future decisions.
- This project has given, and is giving, excellent support to DOE goals to quantify and reduce hydrogen storage system costs.
- The cost analyses that SA is completing are very relevant, and the work that is ongoing for the low-pressure system will provide a great benefit for the industry.
- This project has critical value to the DOE Hydrogen and Fuel Cells Program.
- Analysis of MOF tanks (Hexcell and MATI) seems redundant with HSECoE. Certainly, there is some value in comparing the two analyses and resolving discrepancies, but considerable funding was consumed in the process, which might have been better spent targeting key issues (such as volumetric capacity or loss of usable hydrogen).

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- It will be interesting to learn the results for endothermic and exothermic chemical hydrogen storage carriers. An independent analysis of the electrochemical regeneration of alane would be useful.
- The plan addresses future potential paths to reduce costs of high-pressure tanks and other materials-based tanks, which is helpful in future materials selection.
- The work progression from year to year is right on track.
- The project should continue as outlined.
- Some further exploration of the benefits of integration seems reasonable. As HSECoE winds down, it is not clear what the source will be for the new input, required for these analyses. Projected MOF tank cost is similar to CF, but there are considerable outstanding issues with the MOF system (loss of usable hydrogen, volumetric capacity, etc.). More systems analysis may not be worth considering. A cost analysis of a chemical hydride, volume displacement tank may be worthwhile. However, it is probably not worthwhile to evaluate multiple chemical hydride tank designs at this stage. The key challenge with the chemical hydrides is the cost of regeneration, and this should be addressed first.
- The proposed work seems to fit nicely within the scope of that already planned. It would be nice to see inclusion (or at least mention) of other projects that might be generating data that could contribute to the overall big picture of the analysis.
- The initial estimates for the MATI and Hexcell costs are nearly identical. Given the uncertainties present in any projection, it may be better/safer to state this interpretation rather than state that the “Hexcell is cheaper” (as was done in the slides). When the MATI analysis is complete, it will be helpful if the team presents the total uncertainties (i.e., range of possible costs) for both systems back-to-back. Perhaps refueling costs over the lifetime of the Hexcell and MATI systems can be included in the analysis.
- With more OEMs announcing their hydrogen FCEV programs, there will be more and more 700 bar hydrogen tanks in the market. The future work should include some cost validation using real hydrogen tanks rather than compressed natural gas tanks.

- The reviewer looks forward to component integration and alternative materials but is a little skeptical of the relevance of the chemical storage work.

Project strengths:

- Overall, this is a strong project. Costs of MOF tanks are complex, and this type of analysis is essential.
- This is a very broad cost analysis that attempts to address all areas contributing to the cost of hydrogen storage, both in the near term and long term. The team has done a reasonable job of identifying the major contributors to overall cost and has identified a few pathways for significant cost reduction.
- Overall, this project was extremely valuable, and no major weaknesses were seen. The reviewer looks forward to seeing the progress in fiscal year 2015.
- Using DFMA, the project sheds light on costs of future tanks and gives valuable information on a potential path to minimize cost.
- The project team is very appropriate and well qualified—excellent work.
- This is an extremely important cost analysis for all important candidate systems.
- The project has excellent collaboration with different organizations.
- The project team is responsive to DOE and Technical Team suggestions and directions.

Project weaknesses:

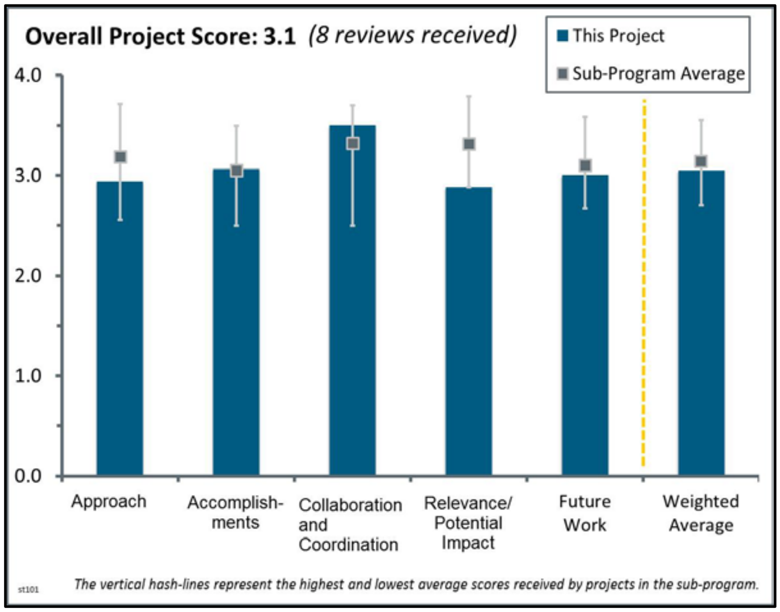
- There is only one weakness—the relevance of the chemical storage work—and it is not a major weakness.
- Three items need attention:
  - 1. Projections for different production volumes
  - 2. Projections for various cost/performance ratios for CF.
  - 3. Cross-references of existing cost models, when available.
- It would be useful to clarify the underlying assumptions of using the DFMA tools to avoid incorrect estimates, especially for materials-based tanks.
- The MOF tank analysis is redundant with HSECoE. Detailed cost analyses on chemical hydride or metal hydride tanks are probably a little premature because there are no materials that come close to meeting targets.
- Cost modeling does not necessarily cover unexpected problems and all service life considerations.
- Because the project is so broad in nature, potentially useful contributing data may have been overlooked.
- The cost uncertainty in this analysis is not clearly stated.

Recommendations for additions/deletions to project scope:

- The project is appropriately scoped.
- The duration of this important project should be extended.
- The project should get the cost-per-liter value for different hydrogen storage tank options.

Project # ST-101: Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks

David Gotthold; Pacific Northwest National Laboratory



Brief Summary of Project:

The primary goal of this project is to reduce pressure vessel cost, mass, and volume in hydrogen storage systems through efficient use of carbon fiber (CF) in engineered materials for storage tanks. The project tasks focus on improving the individual constituents of materials, design, and cold gas operating conditions to synergistically enhance tank performance and reduce cost.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project's approach represents a sound approach to meeting the objectives. This is much improved over last year and has finally provided some real learning for the team. After working to understand the effects of wind patterns, wind process parameters, and key CF aspects, the team has been able to now focus on a portion of the original project that may yield real, commercial results: the resin system. However, the relationship of fiber, resin, and process beyond only burst strength is a key element that is not being addressed by the approach. The absence of this understanding (e.g., impact and cycle) may lead to a retraction of the learning to date and may force a new look into the winding process and/or fiber reinforcement.
- This is a good, systematic approach. The one missing factor was that a switch was made with the CF from 24,000 fibers per tow to 12,000 fibers per tow when switching from epoxy to vinyl ester, but the team did not account for the additional cost of the smaller tow.
- This project attempted to improve overall Type IV tank costs by changing alternative resin materials and investigating additives, while retaining sufficient strength to provide sufficient safety margins. The team members examined various formulations and process variables. They fabricated a number of tanks and destructively tested them to detect whether any improvements were achieved. The project team chose to store hydrogen at approximately 200 K to allow a lower tank mass. Fiber-resin properties were evaluated primarily using test specimens rather than actual vessels. In summary, a rather straightforward methodology was followed to search for better combinations.
- The approach entails the pursuit of three ideas; success in any of these three will lead to a cost reduction, and together they could be synergistic. The number of potential variables is large, but as a "scoping" study, the results will be useful. It is not clear how this work relates to the low-temperature evaluation of composite overwrapped pressure vessels to be conducted by Lawrence Livermore National Laboratory.
- The project employs a multipronged approach to reduce the tank cost by 30%. The most significant method is the use of cold gas storage. The main challenge is to maintain the vacuum in the vacuum insulation throughout the life of the tank. This challenge and the associated maintenance costs are not addressed by the project.
- Using alternate resins and alternate fibers could potentially offer improved hydrogen storage densities and reduce the cost of high-pressure hydrogen tanks.
- There may be too many trade-offs for the vinyl-ester resin, which may result in no net gain.
- More detail is needed in the Approach section, particularly with regard to decision points.

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

This project was rated **3.1** for its accomplishments and progress.

- The team made significant progress last year, having built and burst tested 60 tanks. The test results for low-cost resin alternatives were excellent. The projected $0.5/kWh savings appears to be on target. The projected $0.8/kWh savings for the alternate winding pattern is now eliminated, based on the test results. The savings projected for cold gas storage was revised up from $3.5/kWh last year to $4.2/kWh. There was no explanation (analysis or data) to support the upward revision.
- The team has finally delivered on some real test bottle production and has gathered some good learning from this experience. The progress made this last year is the first notable progress and data achieved by the team. The burst results show a much improved failure mode, and efforts to understand this ideal failure mode should have been further identified or, if known, shared during the presentations. The failure mode experienced from these test specimens and the knowledge of how to produce such a pressure vessel laminate are learnings that could be shared throughout the industry.
- The project made good progress: building 60 tanks to evaluate the actual performance improvements.
- Burst tests were conducted using real tanks to demonstrate the properties of the resin proposed and to show reduction of the tank's mass. However, using alternate fibers was not as successful because of the increased shear strain.
- The lower-cost resin substitution is going well, but the nanoparticle incorporation, while progressing, does not seem to be founded on a strong scientific principle. It is doubtful that putting particles in the resin will improve load translation because that is a function of the fiber/resin interfacial strength. It will likely stiffen the resin.
- While the accomplishments have been good overall, the results under constant operating conditions (i.e., temperature) have not shown a significant potential to reduce cost.
- The team made tangible progress with the fabrication of tanks; however, results are still pending.
- While the team examined a number of combinations of resins and fabrication options for the tanks, there was little indication that any significant improvements were being achieved to reduce the quantity of materials or lower costs. The team members were able to modify their simulations to improve correlations of burst test of tanks with modeling predictions. They identified some candidates for lower-temperature (i.e., approximately 200 K) resins, but evaluations were behind schedule. It appears the team will not reach its objectives, even with a no-cost extension of the project.

Question 3: Collaboration and coordination with other institutions

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

- There was strong collaboration among all team members. The monthly call with team members; Strategic Analysis, Inc. (SA); and Argonne National Laboratory was very useful in helping SA with its cost analysis.
- Multiple collaborators across a spectrum of skills/experience appear to be contributing in useful ways.
- The collaboration on this project appears to be excellent. In particular, Hexagon Lincoln's openness and willingness to wind so many test bottles should be noted. However, the presentation did not show the fiber supplier's level of involvement—a switch from 24,000 to 12,000 fibers per tow and only the comparison of two commercially available sizings does not lend itself to optimizing the fiber surface characteristics for use with these resin systems.
- The interactions and distribution of effort are generally strong. The production and characterization of resins appear to be well handled by the partners, from the formulation stage through burst testing and modeling efforts. The only potential exception is that the specific contributions from Toray were not clear.
- There was strong collaboration with the project partners.
- The researchers have assembled an excellent team.
- The current collaborations with tank manufacturers are useful.
- The collaboration appears to be working.

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

This project was rated **2.9** for its relevance/potential impact.

- The work is directly relevant to the DOE objective of bringing the system cost down to $10/kWh by 2020.
- All of the project goals directly support hydrogen storage objectives.
- Reduction of the hydrogen tank mass and cost may be enabled with the proposed designs.
- The primary focus of this project has been to substantially reduce the cost of the most expensive component of the Type IV hydrogen storage vessels, while still retaining adequate safety margins and the durability of these tanks. Although a number of alternatives were examined, there do not appear to be any resin formulations developed to significantly impact the cost of ambient temperature vessels. Furthermore, variations in winding geometries were not found to improve vessel properties. While the development of a 200 K storage vessel will potentially reduce system mass, volume, and cost, issues related to mechanical behavior over the desired operating conditions and identification of suitable effective insulation materials have not yet been clarified.
- The work on developing a new resin system is notable and could improve the prospects for hydrogen storage. However, this aspect alone will not advance the project to achieve its goal. Based on last year's comments, the change to a 500 bar storage vessel may have much merit, and if this is truly believed within the Hydrogen Storage sub-program, then the specifications and targets for the hydrogen storage efforts should appropriately reflect this result. The decision on whether to proceed with a 700 bar or 500 bar system should be made. This decision could then have a significant impact on the overall goal of the Hydrogen and Fuel Cells Program.
- The project is certainly relevant. Aside from a change in operating conditions (to cold gas), there does not appear to be much potential to significantly change the cost of gaseous storage.
- The project is well aligned. The use of the lower-cost resin may provide some benefit, but the nanoparticle portion of the work has not shown much progress.
- It seems like the cost savings achieved with the vinyl ester and the cost increase due to the 12,000 tow may result in zero net gain.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is appropriate for wrapping up this project.
- The proposed future work is sound and consistent with the work plan.
- The future work is well planned. However, the improved modulus of the laminates must be considered in more types of testing analysis than just burst strength. The 60 bottles that have been produced should be considered for additional test analysis using natural gas vehicle type test standards to determine the effects of impact, fatigue, and cycling. Cold testing and thermal cycling relationships using the modified vinyl-ester resin system need to be accelerated to understand whether this would be a barrier in the near future.
- The burst, fatigue, and impact testing will be very beneficial, but more work should be done to reduce the cost of the 12,000 tow and bring down the cost of the system.
- In the remaining months of this project (with a no-cost extension due to the lack of some key equipment), the team will primarily validate some of the unresolved postulates and complete burst and other tests. It is less clear how far the team will progress toward finalizing its full-scale cost models with updated experimental results. Completing the low-temperature characterization also seems to be in question.
- More detail should be provided concerning future testing of insulating materials' cost and performance.
- In addition to completing the initial test goals, the team should also pursue the proposed fatigue testing.

Project strengths:

- The five-member team brought diverse viewpoints and expertise to address the challenging issue of reducing costs of high-pressure hydrogen storage vessels. Another positive is the sequential approach of

forming and testing modified resins, fabricating prototype tanks with property testing, and conducting burst tests.
- Project strengths include that the team's original equipment manufacturers in both the tanks and resin areas have superior expertise.
- Strengths include the knowledgeable team and its appropriate expertise, as well as the project's unique concept.
- The teams involved must be considered a strength of this project because all of the companies have the necessary resources and expertise to complete this project.
- An excellent selection process was used for determining which lower-cost resin to use. The validation test plan is appropriate.
- Overall, the project was very strong. The vinyl-ester resin has potential, but further testing is required.
- The project's straightforward approach to investigation is a strength.

Project weaknesses:

- The project appears to be dancing around an optimized tank design with a target pressure lower than the original target. The decision needs to be made that savings will truly be achieved if the team is allowed to let the future work address the lower bottle properties, and that this work will fully show and prove these savings. Also, the lack of non-burst testing means the team has not completed the full picture on the performance of the fiber, resin, and process improvement combinations. Degradation in impact, fatigue, or other commercial specifications could negate any progress to date.
- The presentation did not include the expenditures to date, making it difficult to gauge progress relative to budget. The potential cost savings from resin modifications appear rather modest, at about 7%. The threshold for continued investigation of resins is unclear.
- The intended systematic feedback loop between materials development and mechanical strength did not seem particularly effective in producing fiber-resin combinations with greater mechanical strength and improved cryogenic properties. It was unclear how active the Toray partner was in this project.
- The lion's share of the projected cost reduction relies on the success of cold gas storage. There are many uncertainties and unknowns that have yet to be discovered. Therefore, the intrinsic risks are high, and there are no alternative pathways within the scope of this project to mitigate the risks.
- With the cost savings from vinyl ester and the cost increase for the 12,000 tow, the project may end up revealing zero net cost savings.
- It is necessary to further consider real-life operating conditions when these new systems are tested. For example, the effect of operating temperature needs to be considered under the right cycling conditions.
- The project appears ambitious, in that the effort could have been split into several projects. It may overlap with other DOE efforts.
- The nanoparticle work is unlikely to produce positive results.

Recommendations for additions/deletions to project scope:

- Rather that focus on developing a full-scale tank model, emphasis should be placed on completing as many characterization measurements at low temperatures as possible to correlate performance with predictions and subsequent final burst tests. A thorough documentation of these relationships would serve future studies on identifying robust and less expensive Type IV storage tanks.
- The practicality of a low-temperature gaseous system (including changes on the infrastructure side) is not clear. It would be good to know the potential failure modes and their effects on loss of thermal control/insulation.
- The team should complete the modeling effort to optimize the pressure rating and tank size for hydrogen storage. It should take very seriously the impact, cycle, and fatigue testing efforts to complete the picture on whether the new resin, fiber, and process combination produces a superior pressure vessel.
- It is necessary to further consider real-life operating conditions when these new systems are tested. For example, the effect of operating temperature needs to be considered under the right cycling condition.
- In light of the success of the low-cost resin tests, the principal investigator may want to consider testing tanks that use other low-cost resins that have even lower viscosity than XR-4079.

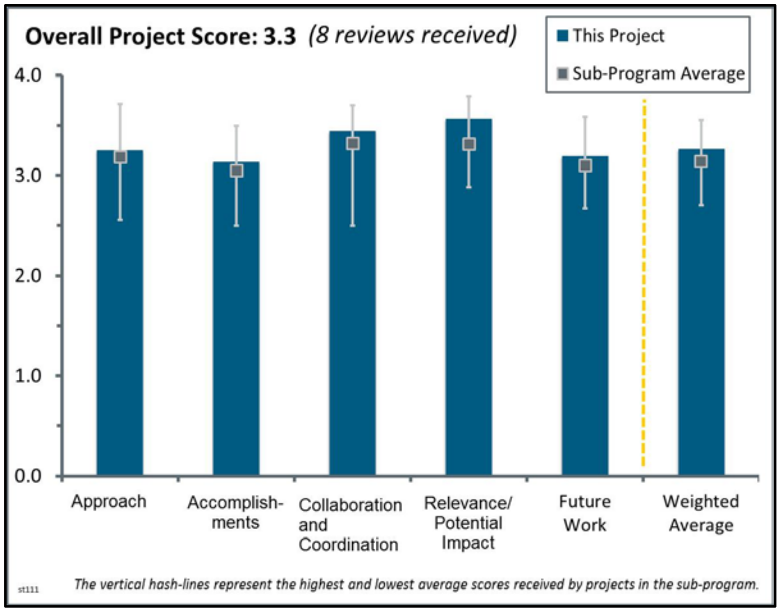
- The project team should delete the nanoparticle work and focus more heavily on validation of the lower-cost resin.
- There are no recommendations at this time.

Project # ST-111: Thermomechanical Cycling of Thin-Liner, High-Fiber-Fraction Cryogenic Pressure Vessels Rapidly Refueled by Liquid Hydrogen Pump to 700 bar

Salvador Aceves; Lawrence Livermore National Laboratory

Brief Summary of Project:

The objective of this project is to demonstrate the cryogenic durability of 12-inch thin liner hydrogen storage vessels cycled 1,500 times and able to achieve 50 gH_2/L_{sys} and 9 wt.% hydrogen. The project will also evaluate a liquid hydrogen cryo-pump that can rapidly and consistently refuel cryogenic onboard hydrogen storage to 700 bar, with the potential to exceed U.S. Department of Energy (DOE) weight and volume targets with substantial dormancy improvement for modest cost with ideal scalability.



Question 1: Approach to performing the work

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

- The project approach is well organized, with proper milestones. The strength of the approach is shown in the project's ability to reset priorities as obstacles are experienced and further understanding is gained. The focus on developing and implementing proper safety standards for fill systems is notable, and the project's ability to couple the development of these safety standards with proper fill and vehicle storage equipment should result in standards that will be established for this industry. In summary, the practical approach will be able to safely determine the effects of cycling through the filling process and lead to standards that may become industry standards.
- The approach addresses quantity barriers directly. Building and qualifying a facility capable of performing the necessary tests is important by itself.
- The work plans appear reasonable to achieve the goals of evaluating thermal cycling of small 700 bar tanks. It is especially positive that there is an allowance for testing a more "conventional"-looking system in the event that the more aggressive designs prove insufficient for the application.
- This project consists of two major tasks:
    - Design, fabricate, characterize, and pressure/temperature cycle prototype 5 kg-hydrogen capacity 700 bar cryo-compressed vessels that may meet ultimate DOE gravimetric and volumetric targets.
    - Establish a unique pressure cryogenic liquid hydrogen filling and testing facility to demonstrate critical operating behavior, integrity, and durability of the cryo-compressed vessels. This is an ambitious plan but has important objectives.
- The project addresses the critical barriers in hydrogen storage, such as volumetric capacity, gravimetric capacity, and possibly cost; however, dormancy can be a tremendous issue with this technology, and super multilayer vacuum insulation should be a focus for this project in the design of vessels. The focus on achieving 700 bar cryo-compressed operation is concerning because (1) this technology is not widespread, (2) it is uncertain that there has been a complete analysis of the energy and cost demands of this delivery technology, and (3) it is not clear that it will ever be available on a widespread commercial basis.
- The project approach is focused on 700 bar cryo-compressed operation, which is interesting, although it combines two difficult parameters (high pressure and extreme cold). The benefits of a 700 bar demonstration rather than using lower pressures should be clarified. The project should not reduce the

priority of the insulation. In fact, this effort should be increased because the insulation is the key feature that could enable or prevent this storage technology from being used onboard a vehicle.
- The approach is generally OK. However, there should be some safety and cost comparison of a traditional 700 bar compressed gas system versus a cryogenic compressed system.

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

This project was rated **3.1** for its accomplishments and progress.

- The accomplishments realized to date (creation and practice of the safety standards for liquid hydrogen stations) are impressive. The development of a 12-inch diameter tank with its improved volumetric efficiency is also notable. It should also be noted that the team has postponed certain parts of the project to ensure safety without compromising the overall flow and targets of the project. The physical equipment installation is impressive.
- As of this reporting, progress is good. Hydrogen Safety Panel (HSP) participation drove consideration of a variety of factors, including a thicker-walled containment vessel, which has been incorporated. Progress toward completion of the facility alone is a substantial accomplishment.
- The demonstration system is quite impressive.
- Considering the bureaucratic challenges of safety and permitting a unique high-pressure cryogenic hydrogen facility, progress with installation and commissioning has been good. It would have been good to see more progress on completing the design and fabrication of the 12-inch cryo-tanks. It was not apparent how soon these prototypes will be available for evaluation and testing.
- Because of the need for facility design and safety approvals, it is difficult to tell how much progress has been made toward the goal of evaluating thermal cycling. However, this will likely be overcome before the next review, now that the necessary facilities and approvals for the thermomechanical cycling are in place.
- The vessel modeling and manufacturing are progressing toward the goals, but it seems like the station testing facility is falling somewhat behind schedule, which could have a major impact on the project's ability to meet future milestones.
- The progress on the pump performance appears to have been delayed. The timing indicates the project is near the midpoint, and a significant amount of effort is needed to accomplish the deliverables.

Question 3: Collaboration and coordination with other institutions

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

- Coordination between partners on the facilities design side seems to have been very effective in getting things up and running. Production of the tanks needed for evaluation also seems to be proceeding well at this time.
- This team has been working with an original equipment manufacturer (OEM) and the expert in this area for a number of years. The team is well equipped for this kind of study.
- The partners are well known. Collaboration includes working with the HSP, which brought in wide-ranging safety acumen.
- There seem to be excellent interactions among all of the partners in this project. The level of communication appears high, with substantial cooperation on complementary capabilities.
- In the early phases of this project, Linde appears to have been a very important and cooperative partner. BMW and Spencer also show good involvement, but it is difficult to fully understand BMW's influence and participation. The presentation of the project could be improved to better understand the depth of the partners' involvement, because one could derive from the presentation that Lawrence Livermore National Laboratory (LLNL) is yielding very strong control over the project. Next year's review should more clearly show the industrial partners' influence and resource participation.
- The project involves collaborations with Linde, BMW, and Spencer Composites, which are very appropriate collaborations. It would be nice to see some of the other gas companies involved in order to demonstrate complete commercial market pull and support for the technology.

- The project appears to have the right mix of industry leaders. An improvement could be to add a domestic OEM and/or a series-production tank supplier.

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

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

- This project directly addresses critical engineering issues with both the vessel design and construction and the filling of nominal 700 bar cryo-compressed hydrogen storage systems. It also examines lifetime behavior on the operating life of the cryogenic hydrogen pump and the pressure/temperature cycling of the tank. These results are important to establish whether cryo-compressed tanks are practical onboard storage systems for vehicles. LLNL is also breaking new ground toward safety regulations of future liquid hydrogen dispensing stations for commercial applications.
- This project is very relevant to the overall goals of the Hydrogen Storage sub-program. Though much of this work is based on developing safety standards and determining the effects of cycling, this is critically important to creating standards for commercialization. The provisional patent and records of invention need to show authorship and relevance to better understand whether this project is creating new, applicable technology or simply creating standards for the safe commercialization of hydrogen storage.
- Understanding both the effects of thermal cycling on the thin-walled cylinders and the effects of repeated 700 bar fueling on the pump system is critical for implementation of hydrogen as a fuel source for consumer vehicles.
- The project is highly relevant because cryo-compression is estimated to have high volumetric and gravimetric energy densities, but robustness testing is still required to increase confidence in the technology.
- Successful demonstration of composite overwrapped pressure vessels (COPVs) for cryogenic liquid hydrogen service at 700 bar would be a substantial technology coup and advance progress toward realizing DOE volumetric capacity goals.
- This technology can potentially have a key impact on the DOE Hydrogen and Fuel Cells Program (the Program).
- The project aligns very well with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan and specifically, the goals of the Hydrogen Storage sub-program, but it is critical at this juncture to get support across all gas companies before continuing to invest in this technology.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Overall, the future plans are good. It is agreed that the project should postpone fabrication and testing of the 163 L 700 bar vessel until Phase III of the project. Assessing the properties of the 65 L prototype is much more valuable. Completing construction and getting safety approvals for filling/testing the pressurized liquid hydrogen system looks very time consuming, and it will probably require considerable effort to achieve the goals specified for this project. Obtaining safety approval and licenses may need more time than estimated in the schedule.
- The future work is well organized and follows the original approach of the project. Completing the fill station and initiating the much-needed cycling work is very good. The thin liner technology includes a good plan, but the small number of candidates and small DOE investment do not appear to provide enough scope to optimize the tank design.
- The project, as currently envisioned, will go a long way toward addressing currently recognized technical barriers. However, the project will presumably identify additional barriers as it proceeds.
- The project team has a well-structured technical approach with go/no-go milestones.
- The future work represents a logical progression from current efforts.

- The cycle testing and station build-out are critical for this technology to move forward. The fact that the station's initial 700 bar operation is not scheduled until July 2015 does not give much room for error in meeting the 1,500-cycle go/no-go in December 2015.
- The future work is aligned with the deliverables. Further evaluating the vacuum insulation for robustness and durability could benefit the future work.

Project strengths:

- The project is pushing to demonstrate the performance and reliability of a 700 bar cryogenic hydrogen filling station for cryo-compressed storage vessels. Behavior of the prototype vessel is very important to ascertaining whether this would be a viable and safe solution for fuel cell vehicles. LLNL and BMW each have more than a decade of experience in the development and testing of cryo-compressed hydrogen vessels, while Linde is a commercial vendor of liquid hydrogen.
- The accomplishments in creating safety standards and in understanding safe pumping conditions and liquid hydrogen handling reflect the strength of the project. These are key areas critical to the commercialization of hydrogen as an effective alternative fuel. The design of a thin-liner pressure vessel will also prove to be a key technology in the future. The well-organized approach and the phased approach to achieving targets are also strengths.
- Data generated during the course of this project will contribute greatly toward optimizing designs for both 700 bar pressure vessels and for the associated fueling systems.
- The project provides a useful assessment of the cryo-compressed tanks in an extreme mode to evaluate fatigue with various tank designs.
- This team has been working in this area for many years and is well positioned to conduct this kind of study.
- This is a simple, direct approach to evaluating COPV technology for cryogenic hydrogen storage.

Project weaknesses:

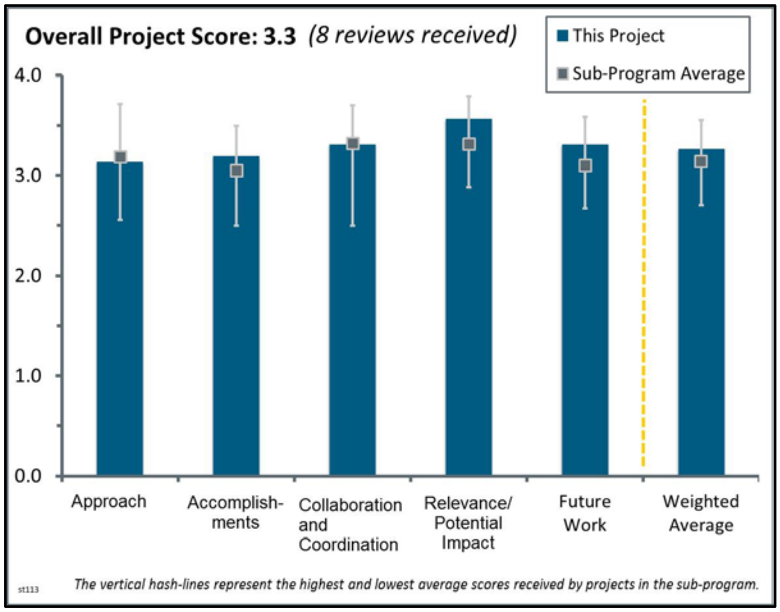
- The effort is ambitious. It relies on the facility test system to perform challenging testing that involves numerous cycles and tests in parallel in a fashion that has not been demonstrated elsewhere.
- There are no obvious weaknesses at this time.
- This project may be too broad in scope in addressing handling, storing, and pumping as well as cycling influences from a newly designed tank. This project, though very relevant, could actually have been split into two projects. This larger scope appears to force LLNL to take a controlling stance and to segregate the industry partners, all of whom are focusing on their own influence but not learning from one another.
- Considerable resources and labor are required to fabricate and certify both the filling/cycling facility and the prototype and larger vessels. The important issues of the dormancy and thermal stability of the vessels may not be getting sufficient attention.
- The project is focused on too high a pressure and should consider additional work in the area of insulation robustness.
- The acceptable hydrogen boil-off rate at the fueling station, both from the regulation side and from the experimental validation side, is not clearly stated.

Recommendations for additions/deletions to project scope:

- There are no suggested changes in scope for the project at this time.
- None should be considered.
- This project needs to focus on closing the fill station phase, which will allow focus on the cycling phase to understand the filling and emptying influence on thin-walled tanks. More information on the liners would help explain why the number of candidates is so small.
- With so many years of effort spent in this area, there seems to be only little interest from the OEM side, other than one OEM that showed strong support. The team may consider contacting other OEMs and forming a steering committee for this project.
- The project could benefit by further evaluating the vacuum insulation for robustness and durability.

Project # ST-113: Innovative Development, Selection, and Testing to Reduce Cost and Weight of Materials for Balance-of-Plant Components

Chris San Marchi; Sandia National Laboratories



Brief Summary of Project:

The overall objective of this project is to identify an alternative to high-cost metals for high-pressure balance-of-plant (BOP) components for onboard hydrogen storage systems. The project goals are to (1) reduce weight by 50%, (2) reduce cost by 35%, and (3) expand the scope of materials of construction for BOP.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This project aims nicely at the U.S. Department of Energy (DOE) barriers of system weight and cost via metallurgical optimization of austenitic stainless steels (especially lower Ni content and process strengthening) of the BOP components of hydrogen storage systems. This is a long-neglected, yet very important, area. Sandia National Laboratories (SNL) have world-renowned expertise in hydrogen materials interactions and safety. SNL will use fatigue testing in hydrogen environments, the most logical testing procedure for the purposes of the project.
- This project employs a two-pronged approach to identify low-cost, lightweight alternatives to annealed 316L stainless steel for use in BOP components. The computational effort complements the experimental testing program to identify new alloys.
- The approach of evaluating low-Ni steels (lower cost) on the basis of fatigue life and stacking fault energy (SFE) theory makes good sense. If a methodology can be validated, this would be an advance.
- Overall, the effort's approach is well-thought-out. The integration of the experimental and computational paths could be better defined in the approach section (details can be found in the future work section).
- It is always a good approach to have both sides (experiments and simulations) together in one project. However, there must be a strong coupling with experiments and simulations. Even if it is one project, it still has some characteristics of two different projects. The planned experimental work and the planned computational work have to be attuned to each other in a better way. If this is already happening, the presentation should emphasize it more. The experiments should give results that can be used or should be reproduced by the simulations and vice versa. In that way, a much deeper understanding could be gained.
- The approach is generally good, including both experimental and computational effort. However, there is no clear indication of how the experimental results will be used to validate the computational model.
- The alloys to be examined computationally are all compositionally complex (i.e., typically contain many components). It is unclear how this complexity will be addressed in a high-throughput-compatible fashion, given that large cell sizes may be required (an example cell with 400+ atoms is given as an example). In addition, the local chemical composition in the vicinity of the stacking fault could have a strong effect on the SFE; this ordering may differ from alloy to alloy. Sorting this effect out will also limit the throughput of the calculations. It is unclear whether the SFE alone is a good descriptor for the performance of these alloys in this application. This is mentioned in the presentation, and a literature search is proposed to address it. It is not clear what the fallback plan is if a good correlation is not possible. Related to this, calculating the SFE is a good starting point, but it is not clear why unstable stacking faults (i.e., barriers along the deformation path) or twinning energies are not part of the research plan.

- Evaluating lower existing Ni-containing alloys may or may not substantially reduce the overall BOP costs, especially at high volumes. The costs are higher at low volumes, but much of this work, especially developing new alloys from the computational effort proposed here, will take time and may not have much of an impact in the near term. A greater reduction on BOP costs may be gained from designs that eliminate valves, long tube lengths, etc., than from changing from one stainless steel material to another.

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

This project was rated **3.2** for its accomplishments and progress.

- The results obtained so far are very good (considering that the project was started only one year ago). The project has characterized 316L stainless steel as a reference system and found it to be very suitable for hydrogen applications. The team has tested ab initio calculations for Ni. The model is consistent with known literature. The computational effort for ternary Fe-Cr-Ni stainless steel alloys has been assessed. Everything is in line with the overall project and DOE goals.
- This is Year 1 of the project. The team has made very good progress toward the milestones. In the slide on relevance and objectives, the project goals are to reduce system weight by 50% and system cost by 35%. It should be clarified in next year's presentation that the reductions are intended for BOP components only (not the system). BOP cost consists of materials cost, processing cost, and assembly cost. It is not clear whether the project goal is for a 35% reduction of the total BOP cost or just the materials cost.
- The project is less than a year old and is effectively still in the startup stage. However, much early progress has been made in planning, collaborations, and prior technology assessment. The contractor has been able to start some computational (density functional theory [DFT]) and cost reduction efforts on paper.
- The plan described is straightforward, and progress as stated follows the plan. Accomplishments thus far for the materials chosen for evaluation are proving out the approach.
- Given the fact that this project is new and only spent $300,000, the accomplishments and progress are reasonably good.
- Accomplishments to date are reasonable. About one quarter of the project period has passed, with about one eighth of the budget expended.
- This is a new project. Most of the effort thus far was to benchmark existing 316L stainless steel.

Question 3: Collaboration and coordination with other institutions

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

- There are excellent collaborations with a fatigue testing organization, fitting manufacturer, and stainless steel producer.
- SNL has assembled a well-qualified team. The partners are instrumental in the success of this project.
- The project has good collaboration, with each party's responsibilities well defined.
- Having a component manufacturer (Swagelok) and steel manufacturer (Carpenter Technology) on the team for advice and direction is good.
- Partners are all experienced, and the mix is appropriate. It is early in the effort, and the contributions of the partners are not yet clear.
- Collaborating institutions have good reputations.
- Collaborations exist with SNL, Hy-Performance Materials Testing, Swagelok, and Carpenter Technology. Internal collaboration (experiments and simulations) is essential for the project and should be deepened.

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

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

- This project is highly relevant to DOE Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan. The project has a previously unexplored potential for BOP cost and weight reduction.
- Identifying suitable materials that result in cost reductions and communicating these results to materials and component manufacturers could help make appreciable progress toward DOE goals.
- This is a very important project and will have critical impact on the Hydrogen and Fuel Cells Program.
- This project could make a big impact on cost and weight associated with BOP.
- Hydrogen embrittlement is one major obstacle to the cost-efficient commercial usage of hydrogen technologies.
- The work is directly relevant to the DOE objective for bringing the system cost down to $10/kWh by the year 2020.
- If a methodology for identifying low-cost materials and evaluating necessary design data can be validated, the cost of BOP components could be reduced. Designers would have greater flexibility in identifying materials for use.
- This work should lead to a better understanding of the merits of various high-strength steels in hydrogen service. However, the risk is high that the project will not meet its short-term objectives of having an actual impact on near-term BOP costs simply by changing out materials for others with somewhat less Ni content in existing components.

Question 5: Proposed future work

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

- Both planned experimental and computational work is focused on critical barriers. The question as to whether a correlation exists between SFE and experimentally measured effects of hydrogen on mechanical properties is essential for this project and will be reviewed.
- The proposed future work is sound and consistent with the work plan. It should be noted that the Al-6061 alloy is increasingly being used in BOP components for hydrogen systems. Therefore, it is recommended that future work include a comparison of the results (cost and weight) with the Al-6061 alloy.
- This project has a well-scoped project plan with clearly defined go/no-go decision points.
- A decision point on whether modeling can be used to predict SFE and whether SFE can be correlated with other material properties should be accelerated.
- The integration of experimental and computational approaches is carried through the effort in a rational manner.
- Pursuit of the plan by examining candidate low-Ni alloy is logical.
- Future work is very appropriate.
- There are some concerns with the computational approach. The future experimental work seems sound.

Project strengths:

- The team is very experienced in this area and has done some similar work for others. The team can move quickly in this project by applying lessons learned from other projects.
- Team members are experienced and well qualified.
- This is a well-thought-out project with potential to materially reduce BOP component costs.
- Experimental and computational approaches are combined, which is very good.
- This is a metallurgical/mechanical properties look at containment and BOP components.
- The project has a straightforward approach that should be pursued as is.

- The experimental program to evaluate other potential lower-Ni-content steel for hydrogen service has potential.

Project weaknesses:

- This reviewer cannot identify any project weaknesses but is not a metallurgist.
- Modeling efforts need to be evaluated quickly to see whether they indeed have the potential to make a difference during this project. It appears that this is a longer-range research effort.
- It is not clear how the computational model will be validated.
- The project focuses only on austenitic stainless steels.

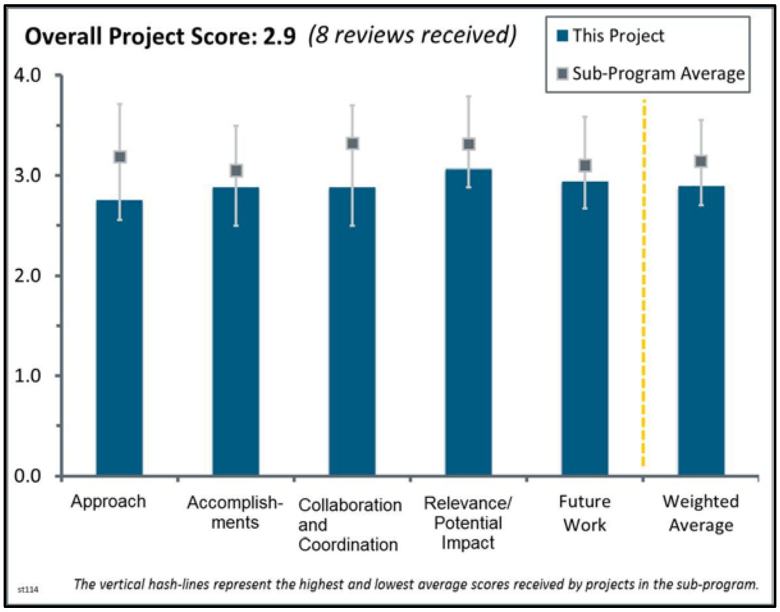
Recommendations for additions/deletions to project scope:

- Computationally derived alloy compositions may not be available commercially (or at all). The cost implications of uncommon alloys should be explored.
- The team members should try to work very tightly together; experimental and computational work should overlap significantly.
- The project should continue experimental work and decide whether modeling efforts should continue based on whether results can be provided in the proposed project time frame.
- The computational component has the potential to make a strong contribution to this project. However, for that to be the case, the relationship between the properties to be calculated and performance needs to be more clearly demonstrated. Fortunately, the project team seems to be well aware of this issue.
- Al-6061 should be included in the comparison of results/analysis.
- The team should consider including Al alloys in the study.

Project # ST-114: Next-Generation Hydrogen Storage Vessels Enabled by Carbon Fiber Infusion with a Low-Viscosity, High-Toughness Resin System

Brian Edgecombe; Materia

Brief Summary of Project:



The objective of this project is to develop and demonstrate a 700 bar, Type IV tank with (1) a reduction in carbon fiber (CF) composite volume by 35%; (2) a cost of composite materials of $6.5/kWh, which is an important element of the U.S. Department of Energy (DOE) 2017 system cost target of $12/kWh; and (3) maintained performance (burst strength of 1575 bar and 90,000 cycle life).

Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach is to use a polyolefin-based resin that has low viscosity in an infusion process to make a Type IV composite overwrapped pressure vessel (COPV) to reach a cost of $6.5/kWh for the composite portion, demonstrate performance of 1.8 kWh/kg at 700 bar, and meet an overall cost of $12/kWh. The infusion process can drastically reduce voids, which will increase fracture toughness, and the lower viscosity should increase wetting to increase the overall tensile strength of the composite. If successful, this would have a large impact on the growth of fuel cell electric vehicles (FCEVs).
- The project offers new processing of CF wounds through vacuum infusion processing of the fiber wounds to reduce the voids content. Ultimately the project would like to use new winding patterns. Although the project strives to reduce the tank’s cost, there exists no preliminary calculations that help predict extra costs that may be introduced through this additional processing
- The approach is OK in general, but there was a lack of manufacturing complexity comparison between the “dry” and “wet” process. When using a new resin for onboard application, the resin property comparison (slide 6) should also include the effect of temperature and hydrogen.
- This approach may or may not work out, but is worth pursuing. The proposed plan of attack makes sense.
- The approach generally seems to make sense. However, the lack of real data, particularly in comparison to conventional carbon/epoxy composites makes it very difficult to tell if the approach is truly viable to achieve the desired goal of such a huge reduction in CF content.
- The general approach of the project identifies a potential break-through technology, but does not adequately address the benefits and how it addresses the cost goals of the Hydrogen Storage sub-program. Critical cost to produce items such as winding efficiencies, resin cost, cycle time, etc. are not addressed and thus, leave this project with little focus. However, the resin technology is excellent, and the effect of reduced void content is valid technology.
- The work is based on an assumption that lowering void content in the resin will allow for substantially improving the composite material properties. Void content affects resin’s dominated properties. Pressure vessels are designed to minimize the impact of resin properties and maximize the use of the fiber properties. Therefore, minimizing void content further is unlikely to have a big impact. The approach is primarily a vacuum assisted resin transfer molding (VARTM) process. Flat plaques were produced, and the void content was measured, but no data was given. This has been done many times by many researchers. The team does not have a baseline of what void content is in current tanks, so it does not know how much it should improve.

- The approach is based on the premise that tank wall thickness can be reduced by eliminating voids, improving fatigue properties of the resin, and developing dry-winding patterns. The linkage from these improvement tasks to the reduction in wall thickness for a current state-of-the-art 700 bar tank was not established. In fact, the voids are low in current tanks and fatigue is not a design driver for Type IV tanks, so it is unclear if the approach will result in any improvement. The dry-winding approach is interesting, although further investigation is needed to ensure proper wetting of the fiber and to confirm a lower cost including the additional process steps for the vacuum infusion.

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

This project was rated **2.9** for its accomplishments and progress.

- Considering this is a new project and for $350,000, the team has achieved a lot.
- The team has initiated the winding process through vacuum infusion of a filament wound and investigated the presence of voids. This effort is coupled finite element analysis (FEA) modeling to understand the effects of voids on the mechanical properties and explore new resins
- Accomplishments suggest that the project should continue.
- The principal investigator has down-selected the resin based on panel tests from a triaxial wound fiber. Performance has been demonstrated in previous projects at the panel level, but the projects could not get the performance to translate to the tank, primarily because of winding conditions.
- Additional information could have been provided regarding the resin selection including material and process cost. The consideration of the baseline epoxy properties and selection process of alternative resins would have enhanced the accomplishment. It was unclear that how the infusion of the thick panel fabric related to a reduced thickness dry-braided tank. More effort is required to demonstrate the feasibility of a 35% CF reduction.
- The ability to infuse low void content panels using the Materia resin system was already well known. The efforts to make a thick, flat laminate are notable, but not necessarily new or applicable to this project. The effect of this resin in a pressure vessel are not yet known and key to achieving a tank with 35% less fiber content. There does not appear to be any tangible, new progress as the resin system was, presumably, already known. Pressure vessel production should have been a higher priority and earlier accomplishment.
- The accomplishment of the proposed work seems just a little behind schedule, but because they did not establish a baseline from existing tanks, they do not really know what they are shooting for as far as final void content. No cost model projections or goals were given.
- The only things really demonstrated at this point are a very low-viscosity resin with high elongation, and the production of a very low void content in a thick panel. Neat resin properties that could be used in predictive models and composite data, particularly in comparison with the baseline system, were not available and probably should have been. Wall thickness of the baseline case tank was not specified—this will be where the reduction of fiber comes from. The fabric panel thickness of 32 mm is about 30% thinner than current wall thicknesses for 700 bar pressure vessels, but there was no modeling presented to support the contention that this is, in fact, possible. The bottom line is that some modeling based on constituent properties would have helped to provide evidence that this approach is feasible for reducing CF content by 35%. At this point, the evidence is not convincing.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The partners appear to have clear roles and responsibilities. It was good to see the addition of Hypercomp Engineering and Powertech Labs. The project would benefit from having a series-production tank manufacturer either as a partner or in a consulting role.
- The collaboration with Montana State University (MSU) and Spencer Composites are appropriate and well defined.
- The team appears knowledgeable and experienced.

- It appears that there are decent collaborative relationships in place. However, the contributions of collaborators have been minimal at this point in the project (at least based on the material presented).
- The project has collected the right collaborative partners with each having distinct tasks. It remains to be seen if the partners will execute these tasks. It is not clear how the association with MSU and its efforts will impact the overall cost to produce a hydrogen tank, although modeling is an important technology.
- The team is working well together but lacks a tank manufacturer.
- There is some collaboration. For a project like this, the early involvement with a tank manufacturer and getting its input is very important.
- Collaboration with tank manufacturers is advised to expedite the progress of this project.

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

This project was rated **3.1** for its relevance/potential impact.

- The project has high relevance because it is focused on the main cost factor of the compressed hydrogen tank system, which is the CF. The potential of a 35% CF reduction would have a notable impact on reducing the cost of the tank system and FCEV cost.
- The concept of developing a breakthrough technology using a high performance, unique resin system shows good relevance to optimizing hydrogen storage system. This project could lead to improved efficiency and cost, which may result in a satisfactory impact for the overall DOE Hydrogen and Fuel Cell Program (the Program).
- Showing a reduction in CF composite volume by 35% and cost of composite materials of $6.5/kWh addresses DOE 2017 system cost targets.
- If successful, this project has a potential big impact for the Program.
- This could have high impact if the project can successfully demonstrate a 35% reduction in composite cost. It would be interesting to compare the cost of the infusion process to the typical wet wound process to understand the total cost impacts on the COPV. This should be less costly as the infusion process would lead to less wastage and hopefully better incorporation of the resin in the composite.
- The use of dry winding and vacuum infusion for tank production is interesting and may improve throughput and tank performance. Without modeling or other data, however, it is really difficult to assess what the true impact will be.
- Costs associated with the process are not known at this point
- No cost model was provided nor were goals for tank fabrication speed. The only test data was on a flat plaque, and the jump to filling an entire tank mold using VARTM is highly challenging, but no plan for doing that was given other than using a less viscous resin.

Question 5: Proposed future work

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

- The testing through March of 2016 should really confirm the success of this project. The work proposed seems adequate to meet the goals and is on schedule.
- Proposed future work meets DOE targets.
- The proposed next steps are appropriate.
- The team had a reasonable work plan, but there are no clear defined go/no-go decision milestones.
- The plan going forward looks reasonable. It is suggest that the team consider fiber sizing effects for its matrix resin because it is very different in chemical structure from most resins that are traditionally used in composites. This could affect the ability to achieve a good fiber/matrix interface and could result in significant reductions in fiber property translation in the composites.
- The general steps to prove-out the infusion are good, but the key deliverable of the project is to demonstrate a cost savings. The team should develop a cost projection model that includes the vacuum infusion cycle time and capital. The project should review the cycle life requirement target for tanks since the proposed

future work suggest a 90,000 cycle target, which is greater than required by current standards (e.g., United Nations Global Technical Regulations, EC 79, or SAE International J2579).

- The future work to produce tanks and prove the infusion technology is adequate. The overall project needs to address all factors that affect the cost of producing a hydrogen tank. In addition, key performance characteristics such as cycle and impact testing need to be better identified and a focus of the project.

Project strengths:

- The project is strong in that it offers a novel approach to tank fabrication that, if successful, will result in higher quality composites and a potential reduction in the amount of CF required.
- The resin system and the expertise of the collaboration partners represents the strength of this project.
- The idea of using the composite processes and the thermoset resins to reduce the amount of CF is a project strength.
- The approach is unique and includes experimental validation and theoretical estimation.
- The project is focused on the key cost driver for compressed hydrogen tanks.
- The project takes advantage of known improvements in resins, processes, and winding techniques.
- The team's understanding of resin chemistry is a project strength
- Using a less viscous resin and VARTM may reduce void concentration.

Project weaknesses:

- The major weakness of the project at this point is that modeling and/or data supporting the approach was not presented. Without access to the proposal for the project, the basis for the aggressive project goals are unclear. Some baseline property data—for neat resin, composites, or both—should have been acquired early and models constructed to illustrate where the project is going.
- There is no modeling work to direct the experimental setup. All the parameters used in the experimental work are not well explained.
- Costs associated with the process are not known at this point and collaboration with tank manufacturers seems necessary to justify the viability of the project. In addition, testing of the materials should be done based on real-life operation conditions of the tanks.
- The project needs to conduct further assessments of the baseline to evaluate the potential improvements of the approach. A review of the current tank design requirements, such as the cycle life target, is needed. The linkage of the proposed improvements to the 35% CF reduction is not shown.
- The lack of progress and the lack of overall cost impacts show a weakness in the approach. The back-up slide showing the cost targets of the Program are a good example of the overall project. This slide shows the work of others, but this project should already know and project its own cost model. The testing of flat panels also shows a technical weakness where pressure vessel mechanics and laminate failure modes are different than that found in flat panels. Progress is not being made in an adequate fashion.
- No correlation between void concentration and performance is given, except for resin-dominated properties that tanks are already designed to avoid. The project did not provide cost models or specific performance metrics relating to void content.

Recommendations for additions/deletions to project scope:

- The project should consider adding a tank manufacturer to the team.
- Costs associated with the process are not known at this point, so it suggested that these are evaluated in addition to considering collaborations with tank manufacturers.
- The project would benefit from having a series-production Type IV tank manufacturer either as a partner or in a consulting role. The project should reduce the emphasis on fatigue and evaluate other parameters that could influence the wall thickness, such as burst strength and impact.
- Focus efforts on infusing pressure vessels and begin testing. This includes cycle and impact testing. The efforts to test flat panels are not relevant and add unnecessary cost to the project. Understanding how the Materia resin performs in a pressure vessel needs to be understood, and comparing that performance to typical wet wound tanks is necessary. The resin is interesting enough that a pressure vessel wet wound with

the Materia resin would provide a good comparison in the tank production techniques (e.g., infusion versus wet wound). This would also provide data to show whether or not the Materia resin is superior to existing resin systems and would result in lower void content even using standard manufacturing techniques.

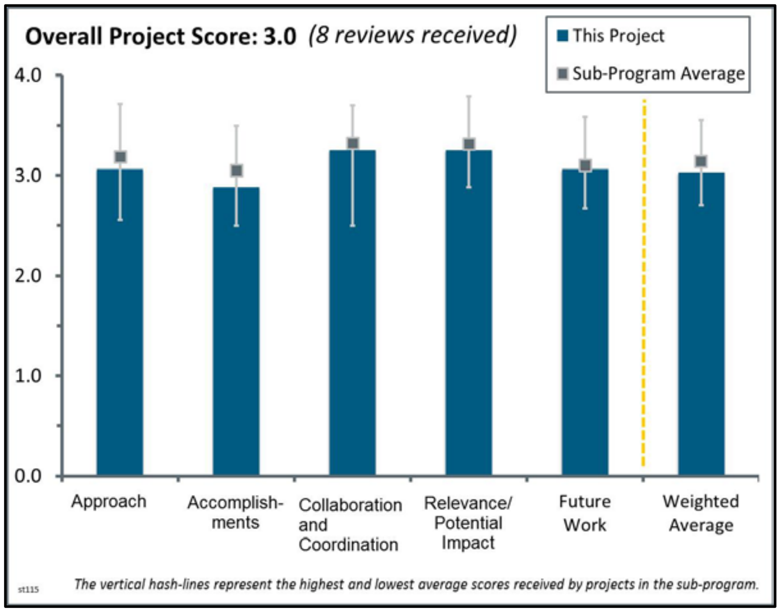
- The project is focusing on the wrong issues to reduce cost.

Project # ST-115: Achieving Hydrogen Storage Goals through High-Strength Fiber Glass

Hong Li; PPG Industries, Inc.

Brief Summary of Project:

The objective of this project is to develop a Type IV composite overwrapped pressure vessel (COPV) reinforced exclusively with glass fiber that has the composite strength to match that of the T700 carbon fiber (CF) composite. The new tank will lower the composite contribution to system cost by nearly 50%, with minimal impact on tank weight and capacity compared to tanks made with T700 CF.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The project approach is well organized, with specific tasks for each participant clearly described. It is not clear what value adding the new test stand and the effort to optimize tabbing brings to the overall project. Testing and tabbing standards are well established and should be followed to ensure that the data can be directly correlated with previous attempts to produce a high-strength glass fiber and to compare results to existing S-glass and CFs.
- This project involving three partners is focused on one primary objective: reduce the cost of Type IV hydrogen storage vessels without significant consequences to mass and volume targets. The pathway is via use of presumably inexpensive glass fiber in lieu of aerospace-grade CF without a significant impact on the other properties. PPG Industries, Inc. will develop and produce the resins and glass fiber for structural characterizations at Pacific Northwest National Laboratory (PNNL) and prototype tank fabrication and testing at Hexagon Lincoln.
- The ability to replace T700 CF with high-strength glass offers the potential for significant cost reductions in the production of 700 bar COPV for onboard hydrogen storage applications.
- Achieving performance comparable to CF with glass fibers would pave the way for cost savings in the use of COPVs.
- The approach is generally well designed and involves the partners. Additional details regarding the challenges associated with pilot production of new fibers would be helpful. A project schedule in graphical form (e.g., a Gantt chart) would be helpful as well.
- Using high-strength glass fiber as an alternative to CF, if successful, may help reduce the tanks' cost.
- The project has a good approach to looking at the possibility of developing a high-strength glass as a possible CF replacement. The glass development work is well thought-out and the approach is appropriate. The low-density resin and hybrid composite portions of the work seem to have been ignored.
- Using glass fiber to replace CF does reduce the cost at the tank level. However, this approach will incur the penalty of lower gravimetric- and volumetric-based energy density. The overall gain will need to be systematically analyzed.

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

This project was rated **2.9** for its accomplishments and progress.

- This is a new project, but much work has been accomplished in a short period.
- The development of a new high-strength glass fiber is progressing very well.
- Initial results support pursuit of experimental goals.
- PPG reported that, so far, two fiber compositions have been produced with properties similar to baseline CF. Some characterization work has been completed, but there does not appear to be any prototype vessel yet fabricated. Hence, the project tasks appear to have slipped by three to six months, according the dates on slide 25. Substantial recovery seems unlikely, and significant de-scoping of objectives is more likely.
- The presentation suggests that chemistry has been developed with proper temperatures and binders to produce fibers that exceed T700 strengths. However, the box plots of the data show something completely different, with the new glass fiber chemistries showing S-glass type properties. The actual accomplishment is hard to rate because of this discrepancy. The value of the efforts expended on tabbing methods and test stand progress is not clearly shown.
- It seems like a number of problems must have been encountered early in the project, because significant slippage in the schedule is noted. To date, there have been no composite data presented, only filament-strength data, and no modeling was presented. The fact that the stress rupture testing is so significantly delayed and appears to drive a good number of the final fiber selections is a significant problem.
- The presentation of the fiber performance data should be done better and with scales. It is difficult to discern the relative merits of various results.
- The project is new, and the progress is limited at this point.

Question 3: Collaboration and coordination with other institutions

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

- The team showed good collaboration and, in particular, got the tank manufacturer's input early in the project.
- The partners provide an appropriate range of expertise and appear to be engaged and participating.
- The companies involved are excellent, with very good expertise and reputations. The organization of tasks is well thought-out, with all participants fully aware of their level of effort and needed results. However, with each participant's efforts so well defined, it is not obvious how much sharing of information or collaboration is actually taking place.
- Collaboration involves reputable organizations.
- Collaboration with other partners seems to be planned.
- Collaborations seem to be good, although it is not clear exactly why the stress rupture test fixture design seems to be so far behind where it is needed in the project.
- The partners on this project have well-delineated assignments that match their capabilities, and it appears that progress should have been OK. However, some issues in meeting joint targets are apparent, resulting in schedule slippage. There does not seem to be any involvement of other researchers or organizations.
- The team is working well together, but the development of stress rupture fixtures at PNNL seems inappropriate. National laboratories should already have those. PNNL seems to simply be acting as a test laboratory.

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

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

- The development of a new fiber is outstanding. The application of a low-density resin and hybrid composite concept seem to have received little thought. If the fiber development is successful, a follow-on effort will be required to develop a hybrid tank using the fiber.
- The potential for significant cost savings in COPVs for hydrogen storage, even when making a partial substitution of T700 CF, is excellent.
- Replacing CF with glass fiber could ultimately reduce the tanks' cost.
- Glass-wrapped vessels could provide substantial cost savings.
- If successful, this will be a high-impact project for the DOE Hydrogen and Fuel Cells Program.
- This effort is very relevant to the overall goals of the Hydrogen Storage sub-program. The optimization, including hybrid development, of the fiber reinforcement is key to minimizing cost and creating value. However, this effort is not new; others have attempted to create high-strength glass fiber in the past. The novel chemistry is not clear at this early stage of the project. In addition, one of the partners is currently producing pressure vessels using a well-established hybrid fiber system. Again, it is not clear how the technology in this project is different from technologies already in place.
- The project has the potential to significantly decrease composite costs. The impact on weight and capacity in switching to glass fiber should be quantified.
- This project looks almost exclusively at reducing the cost of Type IV hydrogen storage vessels through substitution of glass fiber for T700 CF. However, slide 27 shows approximately 40% mass and approximately 10% volume penalties for about only a 30% cost benefit through use of just glass fiber alone. The team speculates that better performance may be possible by using additives, reducing safety factors, etc. However, still unresolved are possible degradation issues during pressure-temperature cycling of such tanks on vehicles.

Question 5: Proposed future work

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

- The future work is properly organized and addresses the important steps of producing test vessels and completing the testing. The focus on actual tank performance is very good. The efforts surrounding the tabbing and test frame do not appear relevant to project success. Strand and filament testing should follow current standards. The work surrounding the chemistry, thermal parameter optimization, and binders is good.
- The plan moving forward appears to be well thought-out and should provide necessary data for further recommendations. The speaker's comment regarding a preliminary down-select of fiber based on passing the highest planned stress level should help to bring the project closer to schedule. It is not certain that an E-glass reference tank is the best choice because the team is really trying to replace the T700 CF. Reference data using T700 fiber, at the coupon level at minimum, would go a long way toward making the case for replacement with high-strength glass fiber.
- The team proposed a well-structured work plan with a clearly defined go/no-go decision milestone.
- The future work is thoughtfully designed for the remaining decision points and efforts.
- The future work is appropriate.
- The proposed work specifies limited fabrication and testing of test vessels according to project plans.
- With the several months of schedule slip, as shown on slide 25, it would seem that greater effort should be made to accelerate glass fiber development and characterization, along with prototype bed fabrication and testing, rather than cost and performance modeling of marginal materials.

Project strengths:

- A strength of this project lies in the partners' capability and the conscious efforts to prove the new fibers in actual pressure vessels. The overall project organization and outcome by each participant is well organized; the outcome that each is expected to produce is clear. The other strength appears to be the science behind the chemistry and how it relates to the glass fiber's performance. The approach to go from pilot to production shows that the project understands the influence of processing parameters that can affect the cost of the fiber.
- The biggest project strengths are in the potential for cost savings through substitution of T700 fiber with high-strength glass. There is little doubt that the fiber production can be successfully scaled up at PPG.
- A good combination of organizations with experience and expertise should promote a balanced assessment of glass fibers for less expensive hydrogen storage vessels.
- The team has balanced technical expertise with a carefully scoped technical plan that outlines efforts from modeling to experiment.
- The project team is knowledgeable and in the business of producing fibers and tanks.
- The project has the potential to significantly decrease composite costs.
- This is excellent work in developing the new glass fiber.

Project weaknesses:

- The current weakness is the lack of composite data for either the glass-based composites or the control systems. Basic coupon data (or even calculated data) could have been used in (1) models to provide some validation of the approach's feasibility and (2) even some rudimentary projections of cost reduction that would arise from this effort. The schedule is currently a significant concern. A number of tasks appear to be four to six months behind schedule.
- Technical challenges with processing, such as the production of glass fiber at scale and limitations with the melting temperature, are recognized. However, there seems to be no countermeasure plan in place. In addition, economic estimates would need to be presented to justify the lower cost claims and demonstrate whether high costs could result from the processing itself.
- The report made at the Hydrogen and Fuel Cells Program Annual Merit Review sheds little insight into why the schedules for the fibers and components have slipped so far. Also, the fundamental limitations of glass fibers compared to high-strength CF may severely limit achieving large (i.e., >30%) cost savings without having an impact on both vessel weight and volume.
- Mass, volume, and cost targets are lacking. Hybrid design work is lacking.
- Even though the participants have great reputations and expertise, it is hard to determine whether any cross-team activities are leveraging the expertise in a way that could benefit the overall success of the project. The efforts of the tabbing and test frame do not appear to be adding value.
- The team should get some original equipment manufacturer input when comparing the glass fiber to the CF, because such a replacement will have an impact on the final onboard storage energy density.
- The schedule risk, from both existing slippage and potential production issues (e.g., existing furnace limits), is significant.

Recommendations for additions/deletions to project scope:

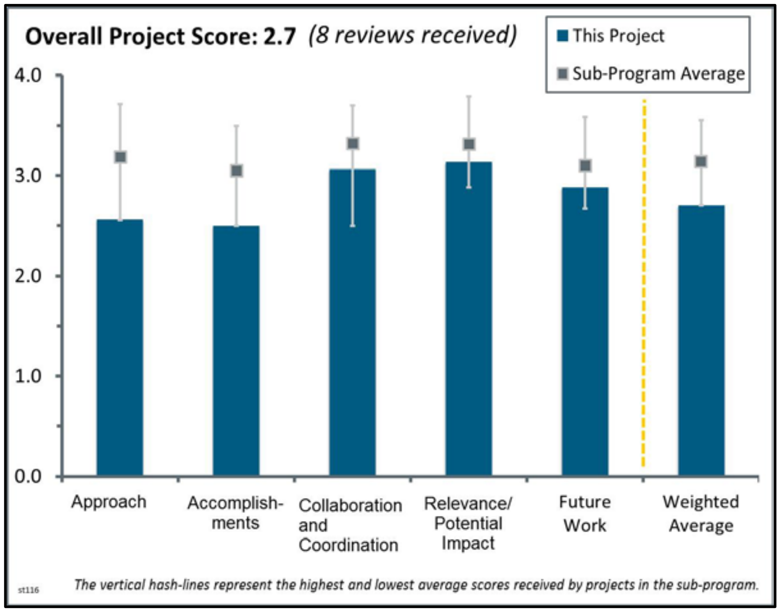
- Technical challenges with processing, such as production of fiberglass at scale and limitations with the melting temperature, are recognized. However, there seems to be no countermeasure plan in place, and this needs to be addressed. In addition, economic estimates would need to be presented to justify the lower cost claims and demonstrate whether high costs could result from the processing itself.
- A reference tank based on T700 CF should be used, rather than an E-glass control. Because the project is trying to replace T700 with the high-strength glass, the former would be a more valid comparison.
- With a little over a year left for this project, no further cost or design modeling is recommended. Instead, more effort should be made to develop and test glass fibers and resins with greater potential for high strength, along with fabrication and testing of prototype tanks.
- The project is early in its progress. The efforts and resources expended on behalf of the tabbing and testing portion should be reconsidered if they could be used to add more value in other areas of the project. Current

strand and filament testing standards should be used to keep the data relevant to understand the overall performance of the glass fibers.

- It is not clear whether the fiber translation loss is within the current project scope.
- The project should drop the low-viscosity resin idea and focus on the hybrid fiber design.

Project # ST-116: Low-Cost α-Alane for Hydrogen Storage

Richard Martin; Ardica



Brief Summary of Project:

The overall objectives of this project are to reduce the production cost of α-alane (AlH_3) to meet the DOE 2015 and 2020 hydrogen storage system cost targets for portable low- and medium-power applications. Results enable broader applications in military and consumer electronics (e.g., smartphones, tablets, and laptops), backup power, unmanned aerial vehicles, forklifts, and vehicles.

Question 1: Approach to performing the work

This project was rated **2.6** for its approach.

- The Office of Energy Efficiency and Renewable Energy reorganized, and the Fuel Cell Technologies Office (FCTO) now falls under sustainable transportation. There does not appear to be a path for alane for hydrogen storage for light-duty vehicles. Alane can be viable as a storage material for portable power, and it is encouraging that such a niche application is receiving research and development funding. It appears that the cost model for the economic analysis needs to be redone and verified by an independent organization, such as Strategic Analysis, Inc. The presentation shows insufficient details about the major assumptions that went into the economic analysis. The capital cost of electrochemical processes tends to scale with current density. The current density that was used for developing the capital cost estimate was not reported. How much progress was made toward an economically viable current density was also not reported. The researcher reported that the alane adduct was present at only a low molar concentration, which creates concerns about a possible high operating cost of the separation and crystallization steps (e.g., high solvent volumes). It will be important to report the alane cost as a function of the annual production capacity because it will take a while to reach the point where 4 million cartridges per year will each be filled with 80 grams of alane (i.e.., 320 metric tons/year).
- The project focuses on cost reduction of alane production and investigates scale-up of the synthesis process, both of which are indeed relevant.
- Conducting economic modeling prior to launching the experimental work is an excellent approach, provided a realistic cost estimate can be obtained. A complex fluidized bed is a risky approach to solving the electrochemical and economic problems with this system.
- The project has the right approach to an electrolysis process to reduce cost significantly.
- Employing more of an engineering approach to the electrochemical regeneration of alane is a useful addition to this topical area. The process and cost modeling area should help in setting research or development priorities for alane regeneration and help in making go/no-go decisions.
- This project intends to adapt the electrochemical synthesis process of AlH_3 that was conceived and demonstrated on a small laboratory scale at Savannah River National Laboratory (SRNL). The current effort focuses on improving the overall efficiency of producing the alane adduct from various sources of aluminum metal other than the expensive alanate compounds. The team has performed cost analyses of the chemical processes to produce alane and built small test reactors to assess the performance of the electrochemical method. However, the team provides only vague, general statements on the processes necessary to purify the electrochemical product into the desired alpha-AlH_3 phase or stabilize this material against ambient decomposition or violent reactions with air. There appear to be very few plans to characterize the compositions and purities of the products at different stages of the reaction. The project

milestone table on slide 21 is misleading because several tasks appear to be currently "underway" rather than 100% complete.

- The cost estimate and technological approach could use additional improvements:
    - According to slide 7, the economic modeling has been done "using standard chemical engineering methodology" whose details are not explained. Thus, it is safe to assume that the team used the cost of building and operating a standard explosion-proof chemical facility at its partner's site. Because explosion-proof ratings exclude the presence of volatile solvents and sources of a potential discharge (sparks) or open flame in the same confined space, the "standard" approach cannot be used for electrolytic generation of pyrophoric materials (alane/activated aluminum-based by-products) in diethyl ether (the presented approach) or even THF (the approach proposed in the past).
    - Because of the process' non-conventional nature and the high explosion risk at the facility, the qualification and number of employees required for safe operations—i.e., the cost of labor—would have to exceed those projected for standard air-sensitive operations at a traditional chemical plant.
    - Safety and security measures would also have to be enhanced; to localize potential disastrous events, the facility would have to be designed in a remote area with a very low moisture content in the air (e.g., in a desert), which will further increase the cost of operations.
    - Thus, it should be expected that for at least the first three to five years of operation, the alane production cost may easily exceed $350–$400/kg and remain higher than $250/kg, even after an exhaustive optimization of the process, versus the $87/kg projected by the team.
- Because cost analysis is a critical aspect of this work, the team should provide the reviewers (at least) with a more detailed description of the methodology and criteria used for determining the numbers that were presented. Justification for the numbers used is lacking. The presentation could have been clearer about each chemical step of the new route and how it compares to the chemical route used in the past.

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

This project was rated **2.5** for its accomplishments and progress.

- Cost reduction is clearly envisioned. More details about the economic modeling are desirable—not only because it has an influence on some of the milestones. Important milestones have been met.
- Initial experiments at the laboratory scale confirmed the initial SRNL results. However, the "moving bed" experiment shown at the Hydrogen and Fuel Cells Program Annual Merit Review cannot represent the "fluidized bed" approach. In the fluidized bed approach, the aluminum particles are dispersed in the organic solvent, which will cause their isolation from the source of electricity, while such contact is still maintained in the "moving bed" approach. Low concentrations and large solution volumes represent another challenge, which the team has not addressed.
- An economic analysis was performed that predicted that the costs for making alane can be substantially lowered by using Al metal from different sources in variations of the SRNL electrochemical process. Thus, alane should be economically suitable for various low- and medium-power devices, but it would still be far too expensive for most fuel-cell-powered vehicles. Preliminary studies at SRI International suggest that these reaction schemes may be viable; however, there does not seem to have been much characterization of the intermediate and product phases so far. Designs for improved electrochemical reactors have been described but not yet built or tested in the laboratory.
- Progress toward a continuous fluid bed process seems quite slow. The flowsheet used for process modeling seems quite sparse to generate what those skilled in the art might consider a reliable, realistic chemical engineering model of cost and energy, etc. The process entails a few key separation operations (e.g., adduct separation and extraction of the alane adduct) and a moderate-to-high-pressure operation (alanate regeneration). The presentation of the flowsheet is not nearly detailed enough for one to understand whether the team is adequately representing those and other key unit operations and whether the estimated costs are representative of reality. More detail in this portion of the discussion would improve the presentation. The scale of 372 mg of alane would seem to be quite a small step on the way to a large,

continuous process. The fluid bed process, while being discussed last year, seems to be still quite a way from practical realization with high conversions and high space-time yields.

- Detailed economic analysis was either not carried out or glossed over in the presentation. In addition to the electrochemical step, there are three other steps in this proposed method of alane synthesis. Analysis should have a breakdown of the costs associated with each step. The estimated cost of $87/kg seems very unrealistic. It is not clear how only 80% recovery of $LiAlH_4$ (or $NaAlH_4$) in each cycle can possibly meet cost targets. Raw yield rather than percentage yield information was given. It is not clear what the percentage yield of 4-ethylmorpholine adduct is or what percentage of 4-ethylmorpholine is recovered. It was stated during the question-and-answer session that 4-ethylmorpholine would not be used, but it is not clear what the alternative is.
- Alane does not provide a path toward meeting the onboard hydrogen storage targets. DOE has established some targets for portable power applications. The reported system-specific energy density of 466 Wh/kg and 577 Wh/L appears to be quite a bit lower than DOE's 2020 target of 1,000 Wh/kg and 1,300 Wh/L for a medium-power rechargeable system or 1,300 Wh/kg and 1700 Wh/L for a single-use system. The project reported that only 372 mg of the Alane adduct had been isolated from the electrochemical cell. It is not clear that such a small amount is sufficient for concluding that the 20% of the aluminum present in the alane shall originate from the aluminum electrode in the electrochemical process when implemented at a larger scale.
- It was not clear that the team really has achieved the 100% progress toward goals that was claimed. Perhaps this was just a reflection of how the team members presented their work. It is recommended that they improve the content of their slides for better clarity.
- The project follows the proposed plan.

Question 3: Collaboration and coordination with other institutions

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

- The project has a strong team. The first year of the project has been completed, but the amount of AlH_3 generated from the actual electrochemical process (372 mg of the adduct) appears to be low. It is not clear whether there is a means to accelerate the knowledge transfer from SRNL to Ardica Technologies and SRI International so that the electrochemical process development and the critical subsequent processing steps (e.g., crystallization and adduct removal) can be accelerated.
- Biweekly telephone conferences show an impressive coordination and collaboration.
- The interactions between Ardica and SRI International seem very closely coordinated; the latter organization is responsible for nearly all of the electrochemical work and characterization performed so far. A consultant from the University of California, Berkeley, is supporting the development of a fluidized reactor bed. It is less obvious what role SRNL and Albermale are playing in the current efforts. There does not seem to be independent assessment of the compositions or purity of the AlH_3 product or intermediate phases. This information from knowledgeable outside organizations would be helpful as a reality check.
- The collaboration with SRNL and SRI International appears effective.
- There is good collaboration between partners. No outside input was solicited in preparing cost estimates.
- It is hard to tell how closely the team works together based on the information presented. It is not clear how often the team meets in person—e.g., whether there are weekly or monthly reviews—or what the program management structure is.
- The information given seems to indicate that there is little collaboration between this project and another DOE project on alane, led by R. Zidan. It may be fruitful if the research results from the other project were better integrated in this project.

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

This project was rated **3.1** for its relevance/potential impact.

- Alane has already been demonstrated as a useful hydrogen storage material by the U.S. Army for personal mobile energy storage units. A closed cycle for the elements is developed in which alane is rehydrogenated, which is very useful. Thus, this project is highly relevant.
- This area of research may be able to achieve the medium-power targets that are relevant to DOE Hydrogen and Fuel Cell Program (the Program) goals. This could enable some non-automotive technology applications of fuel cells, which is also relevant to DOE goals.
- The project is critical to the Program and has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives.
- The cost reduction of alane is essential to enable commercial use in portable low- and medium-power applications.
- New materials research is critical to the success of DOE programs. Unfortunately, there are so few materials programs left, and the DOE scope has narrowed too much. It is interesting to use a military application to highlight project relevance to DOE.
- Large-scale-production AlH_3 at the costs being suggested by this project would make this hydride a very viable candidate for a wide range of small and intermediate fuel cell power systems. However, it is also very important that the AlH_3 is sufficiently pure (i.e., does not contain residual organics from synthesis or processing) and possesses good stability against decomposition during processing into devices and during a finite shelf life. This project does not seem to be addressing these issues very thoroughly.
- It has long been recognized that low-cost alane would open the door to major fuel cell applications in personal electronics. However, it not clear that alane can be made at a lower cost from the electrolysis of $LiAlH_4$/Al than it could through improved chemical methods.
- Alane does not provide a path toward meeting the onboard hydrogen storage targets. DOE has established some targets for portable power applications, but the reported system-specific energy density of 466 Wh/kg and 577 Wh/L appears to be lower than DOE's 2020 targets of 1000 Wh/kg and 1300 Wh/L for a medium power rechargeable system or 1300 Wh/kg and 1700 Wh/L for a single use system. The portable power application appears to be more critical to the U.S. Department of Defense.

Question 5: Proposed future work

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

- The proposed future work contributes to overcoming most barriers.
- There is complete reviewer agreement with the plans to do extensive laboratory assessments of various electrochemical reactors and components to enhance production efficiency and demonstrate formation of high-purity alane. However, more complete characterization will be important to validate independently that appropriate phases of sufficient purity are produced. Step 6 on slide 18 has been attempted by many groups over the years and remains extremely challenging to resolve.
- The project is progressing according to the plan and will likely fulfill its milestones and goals. There is a good plan for future work, but work by the individual partners could be better integrated.
- The proposed future work is generally effective but could be improved. The necessary improvements may be more significant than anticipated.
- Perhaps Future Work Item 2 should be performed before Future Work Item 1. The loss of $LiAlH_4$ at the cathode was identified as a significant problem that may need to be addressed before adding the complication of a fluidized bed of particles at the anode. The discussion did not include how the lithium-conducting membrane material was going to be selected/developed or whether it is already available off the shelf for the operating conditions in the project's electrochemical cell. There is no mention of the current density at which the electrochemical process appears to become economically feasible, or how the project team plans to achieve such current density.

- It appears the team members are going to spend significant effort on the desolvation step. It is not clear what is wrong with the desolvation step of the current chemical route. If the researchers are doing something different, then they should not show their process merging with the chemical route on slide 5. Given the amount of work needed to optimize the electrochemical process alone, perhaps it makes more sense to isolate the product as something that can feed right into an already established desolvation/crystallization process. The Achilles heel of both alane production routes is the desolvation/crystallization process.
- The discussion of future work would be improved by expanding on the technical basis for each task, beyond "optimize deposition." Rather, it would be good to know what the first key experiment is that one will employ to "optimize deposition." Without the details, it is difficult to assess the probability of success of any future approach. A more detailed discussion of what the work at the University of California, Berkeley, will entail to help to solve the moving bed reactor problems would be very nice.
- Bottlenecks in the production scheme and reasonable approaches to circumventing them have been identified. However, the practical value of this work is questionable in view of the shaky analysis of the economic viability of alane production through this method.

Project strengths:

- This project involves both a commercial organization and a research institute to address the challenges of adapting small-scale synthesis of research quantities of alane into a more cost-efficient manufacturing process for much larger production levels. The team is focusing on the important issue of generating the key intermediate (alane adduct) and looking at methods to scale up processing.
- The team has long-term experience with alane. The project has a materials focus. An economic method for preparing alane would be very beneficial for niche applications, given the purity of the gas stream.
- Scale-up of chemical reactions and cost assessment are challenging and extremely important. Thus, this project is highly relevant.
- The project started just one year ago. Nevertheless, good progress can be seen, and a very precise vision of where to go is given.
- The team has good collaborations and represents a small company with a potential market outlet for low-to-medium-power applications.
- The project has a strong team with SRI International, SRNL, and others.
- Team member SRI International has a great deal of experience in alane synthesis.
- A strength is the fundamental results collected by SRNL.

Project weaknesses:

- The following are project weaknesses:
    - The presentation did not show the details of the cost analysis.
    - For alane, the most critical barrier to scale-up is the desolvation/crystallization step. The electrochemical approach does little to affect this step. It is not clear why the team has not demonstrated scale-up above 20 g/batch yet in the crystallization step—a step that has been optimized for years by a number of groups.
    - Random switching between $NaAlH_4$ and $LiAlH_4$ as starting materials is confusing. There is a big difference in cost between the two; perhaps the team is claiming numbers for Na but using Li because of the solubility issue with Na.
    - The project did not provide details on the electrochemical reaction, such as concentration, alane adduct yield, how it is separated from LiH, what the purity of the final product is, or what else is in the final product besides alane (e.g., aluminum, $LiAlH_4$, or Li metal). It would be good if the team could show characterization data of as-prepared alane.
    - It is not clear where/how the morpholine was added in and the alane adduct was extracted.
    - Reaction scale appears really small for estimating production costs—laboratory scale rather than pilot scale.
    - It is not clear why slide 13 shows a different amine adduct.
    - The toluene extraction step to isolate the alane amine adduct is not shown on slide 5 in the scheme. It is not certain that this step was included in the cost analysis.

    - It is not clear why the team did not show an engineering diagram of the complete electrochemical process.
    - The fluidized bed seemed fluid only in the top 25% of the reaction flask. It seems that it would be more efficient if all the particles were moving uniformly across the reactor.
- The team is not sufficiently addressing the energy-intensive solvent management issues of converting the adduct into the final alane product that would be suitable for device application. There should be additional characterizations of the composition and purity of both the intermediate species and the alane product using various methods such as x-ray diffraction, electron microscopy, and nuclear magnetic resonance, for example. The researchers on this team have only very limited personal experience on the properties and handling of metal hydrides (especially alane).
- Performing a technical and economic analysis does not appear to be the strength of this team. More information may need to be shared about the assumptions, and those assumptions need to be validated. The project does not show how the Li-ion-conducting membrane material is going to be selected, if available. Validating the alternative cathode approach appears to be critical in order to avoid dendrite formation and the loss of $LiAlH_6$.
- Better integration of work by the individual partners could be fruitful.
- The project did not show details of the cost analysis.
- The project is guided by a shaky economic analysis.
- The approach and technical results to date are weaknesses.
- Progress appears slow.

Recommendations for additions/deletions to project scope:

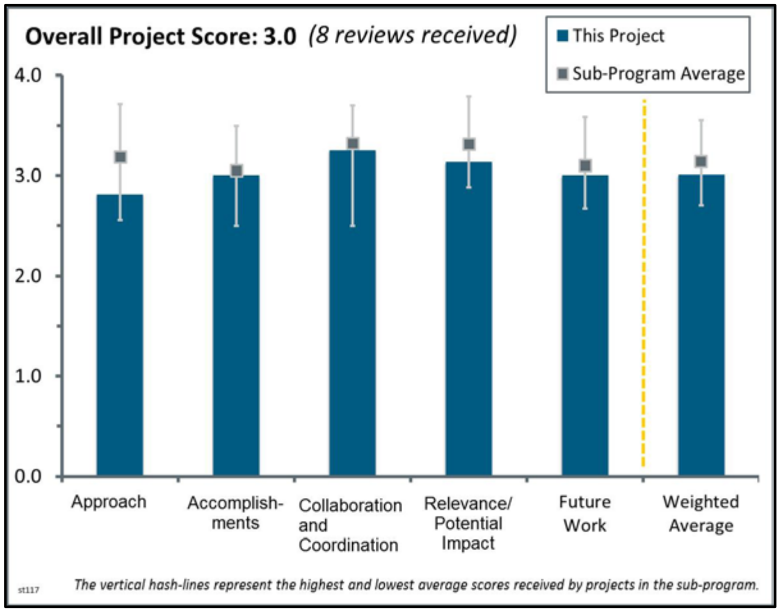
- The results from this project are very promising and relevant. More investigation on the choice of solvent may be needed to optimize the particle size of the obtained product, which is important for the performance of the alane hydrogen storage material.
- The scope of the project is okay, and the project should continue exploring methods to control reactions that occur within the electrochemical cell. The team should also devote more effort to optimizing the solvent removal and stabilizing the alane final product. Finally, the reviewer recommends that the team bring in some consultants with substantial experience and expertise in the properties, characterizations, and handling of metal hydrides (especially the various alane phases).
- An independent organization needs to perform a technical and economic analysis of the electrochemical process that Ardica, SRI International, and SRNL propose. More validation of the assumptions that form the basis for the economic analysis is needed. An activity should be added that will make the project move faster to demonstrating, for instance, a 10-gram scale of producing alane with the electrochemical process versus isolating the alane adduct at less than 1 gram.
- The project should expand the effort by adding alternative approaches to the electrochemistry and the traditional batch chemistry, which may increase project’s chances for success.
- The applied cost model should be presented in a very detailed and comprehensible manner. Capital, maintenance, and labor costs seem to be rather low when compared to materials costs.
- A more detailed economic analysis should be carried out. There appears to be duplication of several of the tasks included in the companion SRNL project; these should be eliminated.
- A more complete process spreadsheet presentation might allay fears that some key unit operations have been overlooked in the process modeling activity.
- The project should describe the pathway for scaling up the chemistry from laboratory scale to pilot plant scale.

Project # ST-117: Boron-Based Hydrogen Storage: Ternary Borides and Beyond

John Vajo; HRL Laboratories, LLC

Brief Summary of Project:

Boron-based materials have been identified as a versatile and high-capacity option for hydrogen storage. The primary goal of this project is to improve kinetics in onboard hydrogen storage systems by (1) eliminating multiphase kinetic barriers in ternary borides/mixed-metal borohydrides that maintain single phases during cycling and (2) minimizing B-atom rearrangement with lithiated boranes that cycle, while preserving the B-B framework.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The basic research proposed and carried out is interesting and may produce results that could not be obtained by previous researchers.
- The project utilizes an interesting approach that focuses on enhancing kinetics by attempting to minimize multiphase or multistep hydrogen release pathways. The two concepts are novel and, to a great extent, counterintuitive. The team uses computational screening to guide experimental design.
  - One approach attempts to form borides by mixing transition metal borohydrides with Mg borohydride and avoiding B-B bond formation. This will require the different borohydrides to react with one another to provide an alternate reaction pathway, instead of independently, to yield ternary boride products. If there is precedence for different borohydrides to react together to provide alternate reaction pathways, it would be helpful to share this with the reviewers. Additionally, it would be helpful to learn what precedence gives the research team confidence that the hydrogenation of the borides will not lead to phase separation of the regenerated borohydrides.
  - The other approach has potential for greater novelty in that "borohydrides" are proposed to react with lithium "hydrides" to form hydrogen and a lithiated borane. This sounds like a higher energy reaction pathway that will require formation of very unstable species. On the other hand if the Li-B species can be formed, it should be reversible. If this concept were to work, starting with a less "stable" metal hydride (Na or Mg) might provide some proof of concept of the novelty. Maybe the predicted enthalpies of reaction with the B framework with Na and Mg hydrides can be investigated to learn whether the enthalpy is not as large as with LiH.
- A lot of previous research has focused on the synthesis of new metal borohydrides, but with little focus on the dehydrogenated state. This project presents a new approach to focus on the design and preparation of the dehydrogenated state.
- The tandem exploration of both the hydrogenation of borides and the dehydrogenation of the corresponding borohydrides is an excellent approach. Prototype electrostatic ground states (PEGS) calculations seem to be a weak theoretical basis for launching an effort to synthesize and develop a new hydrogen storage material. Ball milling of LiH and neutral polyboranes will certainly produce Li salts of polyborane anions, not "lithiated boranes."
- Mg-transition metal borides may be a viable route toward complex borohydrides. Theoretical predictions are being verified. Li-B systems are difficult to assess for their viability as hydrogen storage materials at this time, but the idea is interesting.

- A focus is on ternary borides and lithiated boranes, and a focus is on kinetics of hydrogen release. The team uses computational methods to help guide the experiment, and it uses lithiated borons to control B-B bonding. It uses solid-state or mechanochemistry (ball milling) to synthesize new materials. It is not clear what is really new, compared to what has already been done in this area.
- The approach is designed to improve kinetics of hydrogen cycling in B-based materials, and therefore it addresses important barriers for U.S. Department of Energy (DOE) targets. It is somewhat speculative, and the chances of success are unclear. The mixed-metal borohydrides are still more likely to undergo release via polyborane anions, and there are limited acidic hydrogens in the polyboranes that may be replaced by Li.
- PEGS is not a viable approach for modeling systems of this type. The co-principal investigator (PI) stated during the question-and-answer (Q&A) session that the values were "not real" but that they can be used for comparison. This invalidated all of the assumptions made on the modeling. Diboranes will be a by-product; it appears some of the peaks ascribed to B-H interactions on slide 12 could in fact be diborane. Many other issues associated with entropy effects, kinetics, etc., need to be addressed in a more in-depth analysis of the results.

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

This project was rated **3.0** for its accomplishments and progress.

- This is a new project, and the researchers have gotten off to a good start. The presentation did not clearly identify the computational methods in use. PEGS is not reliable for energetics. The solid-state electronic structure calculations are good and of reasonable quality for the metal alloys. The PEGS calculations are not reliable for energies. The energy differences are very small and within the error limits of the methods, so there is no differentiation (slide 6). There are too many decimal places—the energies are not accurate to even ±10 kJ/mol (more like 20 kJ/mol). The researchers need to be careful in interpreting the calculations and their accuracy. They need to understand the computational limitations. None of the calculated energetics are reliable enough for the researchers to make the decisions they are making. They need to benchmark the computational methods—especially density functional theory (DFT) for the molecules—which are not particularly accurate for these B hydrides. The new synthesis of $Mn(BH_4)_2$ is good. The researchers need to be careful about confusing thermodynamics and kinetics, which was done in the presentation. The reaction on slide 10 makes no sense because there are 15 extra LiH. The researchers need to look at the B-Li bond dissociation (BDE) energy versus the B-H BDE versus the Li-H BDE. The Li_7B_6 alloy is interesting. It is not clear how much hydrogen is lost on polymerizing $B_{10}H_{14}$. The researchers' interpretation of their IR spectra could be improved by using results from the calculations. The synthesis work is quite nice.
- DFT and PEGS have provided significant guidance for the experimental work. It was not clear whether the goal was to cycle through a boride that remained a single phase to minimize the multiple phase kinetic limitations (e.g., Mg_3MnB_8 disproportionate to Mg_2MnB_6 and MgB_2). It is not clear whether this means this boride will be down-selected. Hydrogen uptake by the Li_7B_6 alloy was interesting, and formation of $LiBH_4$ is consistent with a report presented at the 4th Symposium "Hydrogen & Energy" (2010), although those results came at much higher temperatures.
- Some results, such as the preparation of phase-pure metal hydrides and understanding of their phase transformations, may be of substantial practical importance.
- A number of relevant compounds have been investigated and characterized by experimental methods. A number of higher boranes are suggested by theoretical methods.
- Accomplishments so far are commensurate with the fact that the project was only about nine months old when the report was submitted for this presentation.
- The project has delivered a good quantity of results in a relatively short time. However, progress toward DOE goals is limited, with only modest demonstration of reversible storage so far.
- While some progress has been made over previous years in materials synthesis, the interpretation of said results is questionable. The researchers are strongly advised to move away from PEGS.
- Rapid progress has been made on the synthesis and screening of new materials. Only the ill-characterized material made upon ball milling "polymerized decaborane" with LiH has been found to undergo reversible

dehydrogenation, and then only approximately 1 wt.% at approximately 300°C, thus little progress has been made toward the DOE goals.

Question 3: Collaboration and coordination with other institutions

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

- The project features good external collaborations with the University of Utah and the National Institute of Standards and Technology (NIST) for BH nanoparticles (former) and characterization (latter).
- There is excellent collaboration within the project team and with researchers beyond this group.
- The project is well organized and coordinated, and the partners appear to be well integrated in the project.
- The collaborations are ongoing and appear to be effective.
- This is a good team effort, with specific expertise provided by all partners.
- The project features reasonably good collaborations.
- The partnership between theory and experiments is well coordinated, with experiments guided by computational results. There is a clear distinction and synergy between the experimental partners. The coordination would be clearer if the future computational work was not presented under its own heading, but instead integrated with the experiments under the materials headings.
- The collaboration was evident during the Q&A session; however, the experimentalists need to work more closely with the theorists to obtain more relevant interaction.

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

This project was rated **3.1** for its relevance/potential impact.

- The project is highly relevant and focuses on new approaches to obtain materials for reversible hydrogen storage.
- Project aspects align with the Hydrogen and Fuel Cells Program (the Program) and DOE research, development, and demonstration objectives, but they are far from practical applications in real hydrogen storage systems.
- The project aligns well with the Program’s goals. The materials and approach are somewhat risky and therefore lower the likelihood of making advances.
- The goals of the project are sound, and the results could be very important; however, in their current state, the results themselves are questionable.
- While this project has the potential to identify materials that could meet DOE targets, it is exploring compositional space that seems to at least border territory that has been previously covered by DOE-funded research.
- The researchers are developing a potentially interesting material, but they will need to work on regeneration processes.
- This is an 18-month seed project to investigate two novel, independent approaches to store hydrogen.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is in line with what is needed: testing of the novel chemistry. Doping boranes with more electronegative elements (e.g., C, O, N) makes sense to stabilize potential B-Li species. The team should try to find out what structure is responsible for the 1 wt.% cyclable hydrogen in the polymerization sample. It would not be surprising to find the formation of Li $B_{11}H_{14}$, $B_{12}H_{12}$ and $B_{10}H_{10}$ from pyrolysis of $B_{10}H_{14}$.
- The project is progressing according to plan and will likely fulfill the goals. Overall, this is a very productive and successful research project. A large number of materials can be produced by the project processes, and many could be under consideration.

- The future work is based on the results obtained so far and properly addresses the project goals.
- The researchers will need to optimize the polymerization of $B_{10}H_{14}$ to lose as few hydrogen atoms as possible. The BH nanoparticles are very interesting. The focus of the electronic structure on the solids is good because the computational work on the molecules is of low quality and not carefully thought-out. The researchers need to use composite correlated molecular orbital methods such as G3 and G4. They need to think about the accuracy of the electronic structure calculations. It is not clear how they will predict solubility and critical temperatures.
- The studies of the dehydrogenation of the Mg/Mn borohydrides need to be conducted using in situ IR or Raman spectroscopy so that any elimination of diborane gas can be detected.
- C-substituted boranes (i.e., carboranes) and polyboranes were extensively studied in the past; this part of the future work should be downscaled.
- Given the relatively short term of this project, there are probably too many avenues suggested. Work that is vaguely described (e.g., "optimize polymerized borane," "consider doping") is especially low priority.
- The team needs to utilize other theory approach than PEGS, especially with respect to the lithiated boranes.

Project strengths:

- The project features good integration of theory and experiments to focus the experimental studies, although the theory might need some experimental validation. For example, some dismissed ternary boride systems might have good thermodynamics, and it could be beneficial to test at least one of these.
- The project deserves praise for looking into materials that have a potential for more than 10 wt.% hydrogen content, as well as for studying both mixed-metal borides and borohydrides, plus extended B-B networks.
- The prompt-gamma neutron activation analysis conducted at NIST was a Specific, Measurable, Attainable, Realistic, and Timely (SMART) quantitative approach to measure hydrogen uptake and provides a maximum theoretical hydrogen storage density.
- The synthesis work is quite nice. Other strengths include the development of potentially interesting materials, the good team, and the attempt to integrate theory and experiment.
- This is a very well-organized and productive project. The project aim is highly relevant, and the project has a high degree of novelty.
- The highly efficient synthesis and screening of materials is a project strength.
- The approach used by the experimentalists in this project is a strength.
- The project features good fundamental research.

Project weaknesses:

- The researchers need to benchmark the computational methods. DFT is not as reliable as they think. PEGS should not be used for any energetic calculations. The researchers need to use their computational results to help in their spectral interpretation.
- The project is a very long shot to meet the vehicular targets, but it might discover some novel chemistry and should provide some interesting insight into kinetics.
- The project lacks a clear and believable path to meeting DOE targets. The project is too speculative for the Office of Energy Efficiency and Renewable Energy.
- The team may not have enough time to complete the planned experiments, with only about six months left. Li-B materials appear to be irreversible below 100°C.
- Weaknesses include the theoretical approach and the misinterpretation of some x-ray diffraction and IR spectra.
- There is very limited characterization of the novel borides and products upon ball milling "polymerized decaborane" and LiH.
- The project is far away from any practical applications.

Recommendations for additions/deletions to project scope:

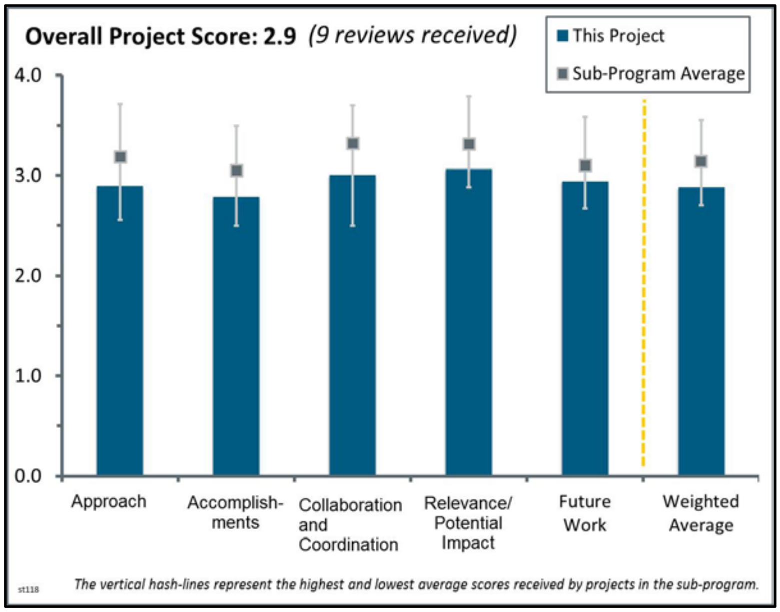
- The team should consider validating the theoretical prediction. The polymeric boranes/LiH composites are produced by high-energy milling and are likely to produce similar compounds, no matter the source. The team should concentrate on one source and pursue compositions that increase reversible hydrogen. Because the maximum observed so far is 1% from a theoretical 7.7 wt.%, this group of compounds could be out-selected if significant improvements are not seen in cycling experiments.

- The researchers need to provide benchmarks of the computational methods. They need to go beyond PEGS for the evaluation of the solid materials. They should consider using nuclear magnetic resonance (NMR) to help evaluate the chemical composition of their materials.
- Another strategy may be to consider Mg-Ni-B, which absorbs hydrogen, but the mechanism remains not fully understood. Understanding the mechanism may lead to new knowledge and other new hydrogen-adsorbing metal borides.
- If the project is unable to obtain more computing power, hence the use of PEGS, the PI should reach out to a national laboratory or an academic institution with the ability to develop more complex modeling systems.
- The team may need to concentrate on the mixed-metal borides and borohydrides because these appear to hold most of the potential.
- The material made upon ball milling “polymerized decaborane” and LiH should be characterized by NMR.

Project # ST-118: Improving the Kinetics and Thermodynamics of $Mg(BH_4)_2$ for Hydrogen Storage

Brandon Wood; Lawrence Livermore National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) combine theory, synthesis, and characterization techniques at multiple length/time scales to understand kinetic limitations and possible improvement strategies in $Mg(BH_4)_2$ with relevance to light-metal hydrides, and (2) deliver a flexible, validated, multiscale theoretical model of (de)hydrogenation kinetics in "real" Mg-B-H materials and use predictions to develop a practical material that satisfies the Department of Energy's (DOE's) 2020 onboard hydrogen storage targets. Current project year objectives are to synthesize and characterize high-purity MgB_2 and $Mg(BH_4)_2$ materials, measure hydrogenation kinetics of bulk MgB_2, and establish and calibrate an initial modeling framework and test its computational feasibility.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The team uses a combination of experiments, models, characterization, and synthesis to demonstrate a new approach to fuel design in solids. This approach is similar to the approach of the Chemical Hydrogen Storage Center of Excellence. The multiscale computational framework is good. The phase-field approach for a mesoscale model combining experiments and density functional theory (DFT) electronic structure calculations are good. Synthesizing very pure materials is a very good idea. The project is using x-ray spectroscopies at the Advanced Light Source at Lawrence Berkeley National Laboratory. DFT electronic structure data collection and subsequent analysis is not new in chemistry or in solid materials. The team has good ideas about connecting the properties of phases to kinetics and has done good work connecting interfaces to bulk thermodynamics and kinetics. The only weakness is that the material is not very exciting.
- This project combines advanced theoretical models with selected experimental measurements on high-quality samples to investigate phase formation and atomic transport in light-metal hydrides. The emphasis is on identifying the atomic processes that control hydrogen absorption and desorption in order to understand and enhance the rate-controlling reactions that impact the hydrogen storage properties of these materials. Attention is focused on the hydrogen interactions at surfaces and interfaces for non-equilibrium conditions. Two explicit example systems are Li-N-H and Mg-B-H.
- The team is using a good approach. It is nice to see well-integrated theory, synthesis, and characterization. Multiscale characterization and modeling are essential for understanding these complex reactions and identifying ways to improve their properties.
- The project has a good team and a good balance of theory, modeling, synthesis, and characterization.
- The theory approach to investigate multiple length and time scales is very ambitious. The principal investigator (PI) has the background and tools to initiate this task. It is not completely clear how much the team will use published work in the literature or perform kinetic measurements in its laboratory. There are advantages to both approaches.
- The multifaceted approach adopted in this project provides a solid strategy for gaining a more complete understanding of kinetic limitations and rate-limiting steps in complex hydrogen sorption reactions in light-

metal hydrides. Although there are reasons to have serious reservations about $Mg(BH4)_2$ actually emerging as a practical material that meets DOE goals, the understanding that will be gained from the studies of that material will undoubtedly extend to other light-metal systems as well. A combined theory (DFT and phase-field modeling), synthesis, and characterization approach conducted at multiple length and time scales should provide important insights into the daunting challenge of inhibited kinetics in those materials.

- The combination of DFT and phase-field modeling is a very powerful tool for probing the $Mg(BH_4)_2$ dehydrogenation process. However, these studies are not focused on the pathways established through solution studies in the 1960s or recent solid-state studies for the reversible dehydrogenation of $Mg(BH_4)_2$ to polyborane anions. Instead, the approach has been to validate the modeling on a $LiNH_2$ system, which is irrelevant to the $Mg(BH_4)_2$ system. Likewise, the approach of characterizing the "B-H" products through x-ray absorption spectroscopy (XAS)/x-ray emission spectroscopy (XES) rather than nuclear magnetic resonance (NMR) techniques is off target.
- The budget appears to be low for this formidable task of improving the kinetics and thermodynamics of such a well-studied material as $Mg(BH_4)_2$. The researchers appear to rely heavily on collecting their own experimental results versus analyzing results that have been already reported by others. There is already a lot of information available about the effect of nano-confinement on $Mg(BH_4)_2$, the reduction of the dehydrogenation temperature, and the high temperature that is required to form some $Mg(BH4)_2$ upon hydrogenation. The project will benefit from incorporating existing information in its analysis. The laboratories involved in this project have extensive analytical and computational capabilities, but it is not clear whether the right analytic capabilities have been made available to quantify the different phases that form upon $Mg(BH_4)_2$ dehydrogenation and during hydrogenation of its reaction products. It is not clear how the project plans to collect all the properties of the intermediate phases and the interaction between the intermediate phases in order to complete a phase-field analysis.
- The approach for the project is not clear; several theoretical methods and multiple experimental methods are mentioned without a clear plan for their utilization.

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

This project was rated **2.8** for its accomplishments and progress.

- The researchers have been successful in using a combination of experiments, models, characterization, and synthesis to demonstrate a new approach to fuel design in solids. They have developed a multiscale computational framework. They have connected a phase-field approach for mesoscale model combining experiments and DFT electronic structure calculations, which is good. They have synthesized and characterized very pure materials. Their work on connecting the properties of phases to kinetics is of high quality. They have done good work on connecting interfaces to bulk thermodynamics and kinetics. One issue is how they will make the software and data sets/materials available to the community, which is the basis of success for the project, not the hydrogen storage material they are initially focusing on, which is not very exciting. Automation of the DFT calculations based on the missing data in a spreadsheet is a good idea, but it has been previously addressed in computational chemistry applications.
- Considerable progress was shown regarding the development of the theoretical framework of integrating a range of modeling techniques to predict the different phase pathways for the reactions of bulk and nanoparticles in Li-N-H. The experimental effort seems to have been somewhat slower. For example, while presumably high-purity samples of MgB_2 and $Mg(BH_4)_2$ were synthesized, and a number of experimental methods are shown on slide 7, only powder x-ray diffraction (XRD) and XES/XAS results were presented.
- The successful development of a theoretical and computational framework for predicting phase fractions as a function of pressure, temperature, and particle size is a critical advancement. It will be challenging to adapt these tools to address multiple reaction intermediates. As pointed out in the presentation, this will carry a very high computational cost. Noteworthy progress was also achieved on developing a construct for exploring phase nucleation and non-equilibrium effects in the mesoscale kinetics code. These effects may be critical to understanding kinetic pathways in hydrogen sorption reactions in light-metal systems. It was unclear why the team "switched gears" from its preliminary studies of the Mg-based system to studies of the Li-N-H system. It is not clear whether this was because of major obstacles (e.g., prohibitively slow kinetics) in the Mg-system or whether there were other reasons for taking that detour. Some clarification

would be helpful. The identification of challenges, obstacles, and proposed mitigation strategies was important and led to useful additions to the presentation.

- This is a new project but good progress has been made on synthesizing and characterizing MgB_2 and $Mg(BH_4)_2$ and on establishing the theory and models.
- The preliminary synthesis and hydrogenation results look interesting. Spectroscopy shows some B-H formation, but it is not clear what progress is being made with XRD. This could be tracked (in situ) at a number of synchrotron facilities. The team should be able to see hydrogen insertion or the formation of new phases. Preliminary results with nano-Li_3N look interesting. A more detailed understanding of reaction pathways is critical to further improving the properties of these reactions. It is unclear how the internal structure of the particles is determined (especially at intermediates states of reaction). This will likely play an important role in the reaction pathway, but measuring this will not be easy—transmission electron microscopy has many challenges, the biggest of which may be beam damage.
- It will be helpful to use theory in combination with other spectroscopic techniques such as IR and NMR to better understand the evolution of structures involved in the hydrogenation of MgB_2. The addition of catalysts may be required to increase rates, but this will add some additional variables to the computational modeling.
- A small hydrogen uptake in MgB_2 was detected, but the reaction product remains unclear. This contrasts with the system MgB_2-LiH (and other similar composites), which readily absorbs hydrogen. $Mg(BH_4)_2$ was successfully prepared, but it is not clear what the next step is in the experimental characterization process. A high number of polymorphs of $Mg(BH_4)_2$ are described in the published literature, along with decompositions using different additives. This experimental information needs to be taken into consideration.
- The studies of the lithium amide system, which appear to have dominated the efforts today, have contributed little toward improving the kinetics of the reversible dehydrogenation of $Mg(BH_4)_2$. The most meaningful accomplishment to date has been the benchmarking of the hydrogenation of bulk MgB_2. Unfortunately, the extremely slow and low-level hydrogenation that is observed at >350°C brings the feasibility of hydrogenating MgB_2 in a practical system into serious question.
- The synthesis of bulk MgB_2 and $Mg(BH_4)_2$ is well known, and the study of the hydrogenation and dehydrogenation of the material in its bulk form is unlikely to result in new information that will improve the kinetics and thermodynamics, because the bulk properties have already been studied for such a long time. There is information in the literature about the dehydrogenation of nano-confined $Mg(BH_4)_2$, but such information, even if incomplete, does not appear to have been introduced to the modelers to test their models. Instead, the modelers tuned their models to the lithium amide system, which does not appear to be relevant to $Mg(BH_4)_2$. It will be important for the modelers to review the nano-confined $Mg(BH_4)_2$ literature first because it will take considerable time before the project will have collected and analyzed data about the hydrogenation of nano-confined MgB_2 and the dehydrogenation of $Mg(BH_4)_2$.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- A well-qualified team with expertise in all areas of ab initio theory, phase field modeling, nanostructure synthesis, and characterization is conducting the work on this project. Extensive collaborations with external partners are also evident, and they should generate important, new information that complements the core work on the project.
- The project has a strong team. The challenge is to perform the modeling in parallel with the nanoparticle synthesis, testing, and characterization. The modelers first will need to depend on literature data before experimental results will become available from the materials that have been synthesized as part of their own project.
- The interactions with the theoretical team appear very strong and clearly integrated to the Sandia National Laboratories (SNL) experimental group. It is much less clear whether outside researchers (e.g., the National Institute of Standards and Technology for neutron scattering) are actively involved.
- The project has a good technical team with excellent capabilities, and it is very commendable to develop a Google tools platform to share DFT data, but it might also be good to have some additional outside collaborators identified.

- The project has a strong team with a number of active collaborations. In general, the new materials projects seem to be working somewhat independently. More coordination among all materials projects (forming a mini-materials Center of Excellence) would be worthwhile to minimize overlap and ensure the expertise and capabilities of all partners are fully utilized.
- There are good collaborations with SNL on nanophases and nano-confinement.
- The project has good connections and collaboration between experiments and theory.
- The collaboration among team members seems adequate. However, this effort seems completely insulated from the many other ongoing worldwide efforts to develop $Mg(BH_4)_2$ as a practical hydrogen storage material.

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

This project was rated **3.1** for its relevance/potential impact.

- Understanding kinetic limitations in hydrogenation and dehydrogenation reactions in light-metal hydrides is critical to overcoming existing barriers to successful use of those materials in practical hydrogen storage systems. Gaining a deeper fundamental understanding of kinetics and reaction mechanisms will be key to developing improved low atomic number, lightweight metal hydrides that operate at temperatures and pressures commensurate with fuel cell operation. This work is highly relevant, and it directly supports the goals articulated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- The project addresses interesting concepts that are of real interest and value to the hydrogen storage community. Success will be measured by the release of codes, data sets, and materials to the storage community and their use by the community. The linking of theory and experiments is good. The mesoscale work is good and relevant, as is the development of theories to cross scales.
- The project goals and approach to "combine theory, synthesis and characterization…to understand kinetic limitations," are critical to providing insight into the development of a rational approach for enhancing kinetics.
- Efforts from this work should lead to a better understanding of the mechanisms that control the absorption and desorption of hydrogen in lightweight hydrogen storage materials.
- This project has the possibility of providing very insightful descriptions of the processes that limit the light element hydrides from meeting storage capacity and reaction rate targets. It may provide guidance to changes in chemical compositions, phase dimensions, and structures that lead to overcoming some of the barriers. However, it probably will not provide major modifications of the equilibrium thermodynamics parameters or address the role of volatile decomposition products, such as NH_3 or B_2H_6, or the irreversibility and degradation of these storage candidates.
- Overcoming the high kinetic barrier to the reversible dehydrogenation of $Mg(BH_4)_2$ is key to the development of this highly promising hydrogen storage material. Thus, the modeling studies could be of high relevance and impact. It would be good to get at least some preliminary results on the dehydrogenation of $Mg(BH_4)_2$ (not $LiNH_2$) to see whether it is useful and in agreement with previous studies on $Mg(BH_4)_2$. MgB_2 nanoparticles will, of course, not remain nanoparticles on reversible hydrogenation to $Mg(BH_4)_2$. However, the nanoparticle studies can at least determine whether the "nano-MgB_2" approach is worth pursuing.
- The impact of the project likely lies with the models and their online and open-source tools. $Mg(BH_4)_2$ has been exhaustively studied, so it is somewhat difficult to imagine that the performance will be improved substantially. However, the importance of this project will come from better understanding the reaction pathways and kinetics, and how these properties are affected by particle size and catalysts.
- Magnesium borohydride is a highly relevant compound to study in detail.
- $Mg(BH_4)_2$ is a well-known hydrogen storage material, and many groups have tried nano-confinement as a means to establish reversible hydrogen storage at moderate conditions, but so far these efforts have been unsuccessful. The project has not reported what it will be doing differently from the previous attempts to turn $Mg(BH_4)_2$ into a practical hydrogen storage material, other than working with a purer starting material.

Question 5: Proposed future work

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

- The proposed work on transport is good. The team must focus on developing the toolset and making it available to the community. The team needs to discuss its plans for how to release its tools and data sets for use by others. The Office of Energy Efficiency and Renewable Energy should sponsor a materials library for benchmarking experiment and models.
- There is a good mix of experimental and modeling activities planned for the rest of fiscal year (FY) 2015 and FY 2016.
- The future work planned is appropriate for this project. The team may want to investigate nano-confined $Mg(BH_4)_2$ (if it is not already part of the plan).
- The proposed DFT studies on $Mg(BH_4)_2$ and hydrogenation of MgB_2 nanoparticles for the coming year are much more on target than the work that has been accomplished in the previous year.
- The future work is clearly stated and represents a straightforward and reasonable extension of the work conducted thus far. However, the critical issue of how multiple-phase formation during sorption reactions will be addressed was not adequately described. Likewise, the diversion of the initial effort on the Mg-based systems to studies of the Li-N-H system should be described more thoroughly. Both “nanosizing” and catalytic doping are entirely reasonable pathways to enhancing sorption kinetics. However, the project team must clearly recognize that hydrogenation/dehydrogenation cycling in media containing “free” nanoparticles can frequently lead to unwanted agglomeration and clustering of the nanoparticles, thereby defeating the purpose of creating the nanoparticles in the first place. This is far less problematic in nano-confined media (e.g., nanoparticles confined within a framework or template structure). Adapting theory and modeling tools to nano-confined media should be an important research thrust.
- The team provided a list of “remaining challenges,” but having more details of how the challenges will be addressed would be beneficial.
- The work on the lithium amide system appears to be distracting the team from making progress on the $Mg(BH_4)_2$ system. The characterization method that is being proposed in the future work may not be able to identify quantitatively the fraction of all the intermediate phases that occur during $Mg(BH_4)_2$ dehydrogenation and the intermediate phases that form during an attempt to hydrogenate the reaction products. The researchers have not indicated whether they would consider limiting the dehydrogenation of $Mg(BH_4)_2$ to a point at which hydrogenation of the nano-confined material would still be feasible. The researchers appear to have selected MgB_2 as the starting point for hydrogenation, which may be very difficult.
- Additional experimental work (i.e., macroscopic kinetic and XAS/XES measurements) is planned for the Mg-B-H samples, but no indication of any supplemental studies using neutron scattering or insightful spectroscopies (i.e., Raman, NMR, or mass spectrometry) was given. It is not clear that the proposed kinetics and x-ray techniques will be sufficient to validate the theoretical predictions reliably.
- It is not clear how experimental science will proceed and be correlated to the theoretical work in the project.

Project strengths:

- Gaining a deeper understanding of the kinetic limitations to hydrogen sorption reactions in light-metal hydrides is a critical need. This project offers an important and valuable opportunity to gain keen insight into reaction kinetics and mechanisms in these systems. Although the challenges are numerous and difficult, the extensive expertise and experience of the project team in all areas relevant to the proposed studies provides confidence that solid progress will be achieved.
- This project has assembled a diverse collection of theoretical tools to model and predict phase transitions and possible reaction pathways in great detail. With appropriate experimental results, a substantial increase in key reaction processes may result. The ability to produce high-quality sample materials should help with obtaining more reliable test data to compare with calculated properties.
- Project strengths include the development of new computational toolsets and databases for the hydrogen storage community, the development of new theoretical methods, the development of data sets, and the new very pure materials for testing.

- The models and the "platform for collaboration, data management, and data sharing using online and open-source tools" will be an important contribution to the community. In addition, a better understanding of the kinetics and reaction pathways will help guide future work in this area.
- The research team has successfully prepared pure $Mg(BH_4)_2$, following a published procedure, which is a good starting point for further experimental research. Some theoretical results are also presented using different approaches.
- The project has a strong team of experts and a good balance between theory and experimental activities.
- The project has a strong team. It has great analytical and computational capabilities.
- The project demonstrates good connections and collaboration between experiments and theory.
- The combination of DFT and phase-field modeling has the potential to provide valuable insights.

Project weaknesses:

- The PI is relatively new to the research topic and will make a greater impact after having more time to catch up on published work in the field. A few reviewers seemed to think the team missed an opportunity to test some of the modeling using literature data on nanophase $Mg(BH_4)_2$ instead of Li_3N.
- Selecting an Mg-B-H system may have been a problem because of the system's very slow kinetics. While $Mg(BH_4)_2$ has high potential as a storage material, it might have been better to select $NaAlH_4$ as a baseline material, especially to better understand the effects of catalytic doping.
- It is unclear whether adequate attention has been given to characterize enough properties of the Mg-B-H and Li-N-H materials experimentally to confirm that the modeling correctly includes actual species or intermediate phases that are responsible for the kinetic and capacity behavior during the hydrogen absorption and desorption reactions.
- The project team is tackling a very difficult problem. The team must avoid the temptation to solve the "entire problem" and instead concentrate on tractable pieces of the puzzle. However, it is not entirely clear whether information gained from one simple system is readily transferrable to others. This is especially true in cases where multiple phases are at play. Also, the team must recognize that nanoscale "free particles" most likely will not remain small upon cycling. It seems that a more thorough investigation of nano-confined media should be included in the research plan.
- The storage material is not very interesting. The team has no plans for releasing software and data sets.
- It is not really clear what is expected from the XAS measurements. These studies take considerable time and planning, but it was not exactly clear what the team hopes to learn from them. If it is just a test for hydrogen absorption, as indicated on slide 12, there are probably easier spectroscopic methods (e.g., Fourier Transfer Infrared Spectroscopy or Raman Spectroscopy to look for B-H modes). $Mg(BH_4)_2$ has been well studied, so it seems unlikely that tailoring particle size or catalysts will significantly improve performance (kinetics) beyond what has already been reported. The project should focus on understanding the materials and reactions.
- The project has been sidetracked on studies of $LiNH_2$. The project is apparently being carried out with no connection and very little awareness of other research efforts on the dehydrogenation of $Mg(BH_4)_2$.
- A high number of experimental methods are mentioned without a clear plan of utilization. The work does not take published literature into account to a sufficient degree. Therefore, it is not clear what the outcome of the research may be and how experimental and theoretical research will be combined. The theoretical work appears to "stand alone" with little correlation to published knowledge and the experimental part of the project.
- $Mg(BH_4)_2$ has so many intermediates, which can also be different upon dehydrogenation and hydrogenation, that it appears to be an overwhelming task to quantify all the model parameters that will be required for phase-field modeling. It will be important to verify whether DFT calculations can be accurate when applied to borohydride materials. It is not clear how thorough the literature search has been for data that could help the modelers with setting up their models for $Mg(BH_4)_2$. It is not clear how the researchers plan to further improve the $Mg(BH_4)_2$ kinetics and thermodynamics beyond the doping and nano-confinement that has already been reported in literature.

Recommendations for additions/deletions to project scope:

- The team should extend the “nanosizing” studies to include nano-confined media (e.g., nanoparticles confined within structure-directing frameworks or templates).
- It is useful to understand some of the unique properties of the nanophase; however, in cyclable material, there has been little precedence to describe how the nanophase will be reformed after the initial hydrogen uptake or release step, so it will be imperative to study “real systems.” SNL has the capability of kinetic measurements in bulk materials, as outlined in the presentation. The experimental measurements are a critical component to benchmarking the computational work, but the focus with limited resources should be on bulk, not nanophase, materials.
- In order to adhere to the project schedule, the team should perform an extensive literature search for data about nano-confined $Mg(BH_4)_2$ that can be used to start developing and evaluating the computational models while data collection efforts start for experimental data (which is time consuming).
- The authors need to study the published experimental literature in detail (rather old literature is mentioned on slide 5).
- Opening the project to look at other materials, especially if the kinetics of $Mg(BH_4)_2$ becomes a problem, is recommended. It might be better to validate the models against better-known materials, similar to what was done with the Li-N-H system.
- Additional techniques should be included in the experimental portfolio to establish whether the models are for the actual processes that are responsible for these hydrogen storage materials.
- It is not clear what is new in the Google spreadsheet. The team should connect to the computational chemistry community that has developed some of these types of tools. Also, the team should develop a plan and approach to release software and data sets.
- The team should stop all work on lithium amide immediately.

2015 — Fuel Cells
Summary of Annual Merit Review of the Fuel Cells Sub-Program

Summary of Reviewer Comments on the Fuel Cells Sub-Program:

Reviewers felt that there was a good balance between near-, mid-, and long-term research and development (R&D) in the Fuel Cells sub-program. Reviewers agreed that cost and durability are the major technical challenges and praised the sub-program's approach to identifying and addressing these issues. Reviewers also agreed that current year successes and overall sub-program progress were clearly described. However, some reviewers commented that this year's successes were not explicitly benchmarked against the prior year to demonstrate progress in specific technologies. A strength of the sub-program, as noted by most reviewers, is its well-structured, focused, and well-managed projects. In particular, reviewers commented that the catalyst cost reduction projects were exceptionally strong this year. Reviewers praised the sub-program's robust project teams and identified the sub-program's collaboration with academia, industry, the national laboratories, and the community—for example, via the U.S. Council for Automotive Research—as crucial in focusing R&D on the most relevant challenges. Some reviewers expressed a desire to see more validation in single-cell or short-stack experiments in addition to the excellent materials advances achieved so far.

Fuel Cells Funding:

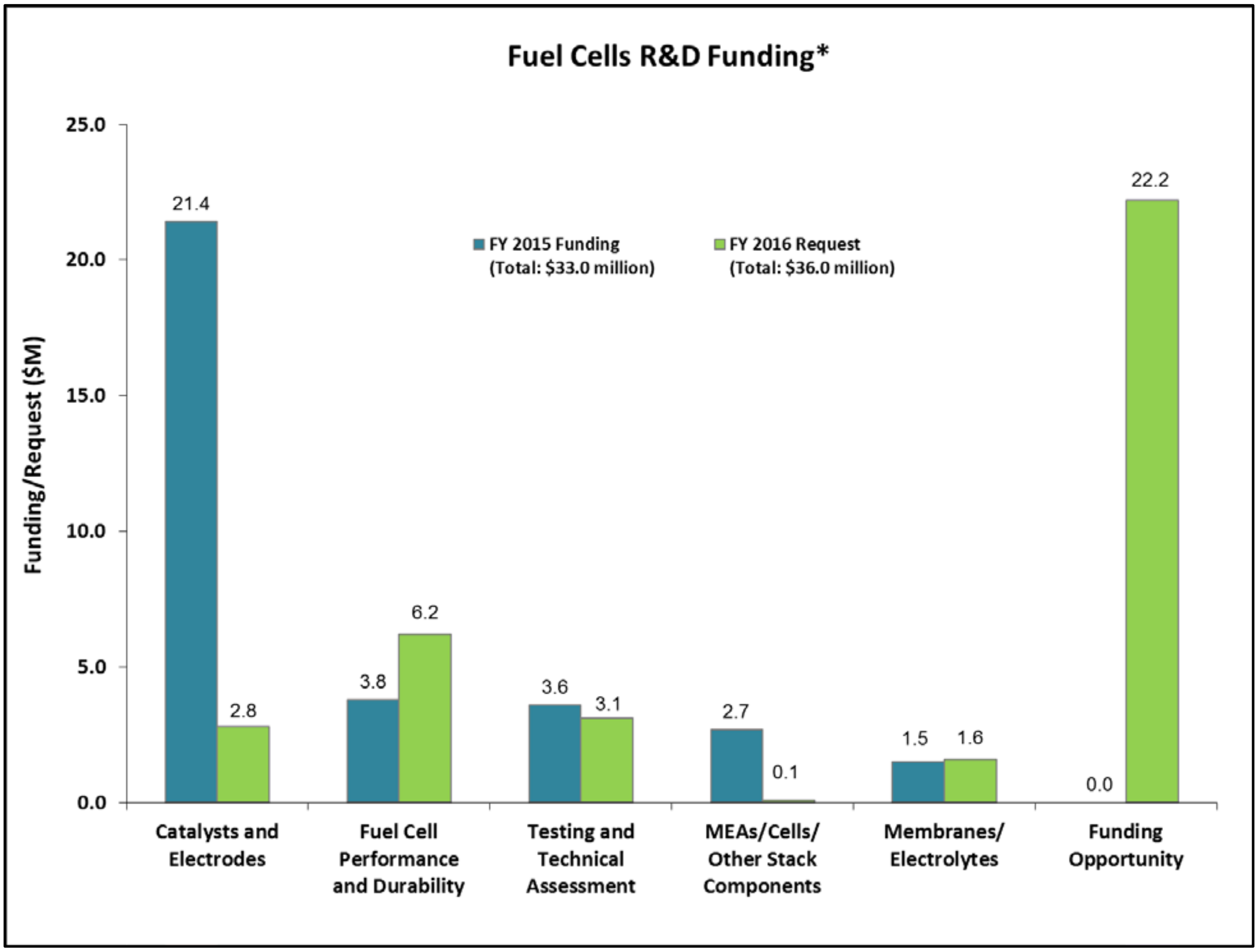
The sub-program received $33 million in fiscal year (FY) 2015, as shown in the chart on the following page. The request for FY 2016 is $36 million. The sub-program focuses on reducing fuel cell costs and improving durability. Efforts include approaches that will achieve increased activity and utilization of platinum-group-metal (PGM) and PGM-alloy catalysts, non-PGM catalysts for long-term applications, ion exchange membranes with enhanced performance and stability at reduced cost, improved integration of catalysts and membranes into membrane electrode assemblies (MEAs), and a better understanding of degradation mechanisms and mass transport. The FY 2015 funding opportunity announcement will result in $12 million in funding for new catalysts/electrodes projects. In addition, $1.8 million in FY 2015 funding will result in five new projects under the incubator program. There is no funding in FY 2015 or planned funding in FY 2016 for balance-of-plant (BOP) components projects.

Majority of Reviewer Comments and Recommendations:

At this year's review, 48 projects funded by the Fuel Cells sub-program were presented, and 34 were reviewed. Projects were reviewed by between three and eight reviewers, with a median of seven experts reviewing each project. Reviewer scores for these projects ranged from 2.7 to 3.6, with an average score of 3.1. This year's highest score of 3.6 and average score of 3.1 were similar to last year's highest and average scores of 3.6 and 3.2, respectively. The lowest score of 2.7 for all projects reviewed in 2015 was a modest improvement over 2014's low score of 2.6.

Catalysts and Electrodes: The scores for the 10 catalyst projects ranged from 2.7 to 3.4, with an average of 3.0. Reviewers praised the highest-rated project for its approach to modeling and characterization of a novel engineered ionomer topology within the catalyst layer, as well as the progress made with the model. In addition, reviewers recognized the importance of reducing fuel cell cost by reducing platinum (Pt) loading in this project. For the lowest-scoring project, which tied for the lowest score in the sub-program, reviewers felt that the results for the selected non-PGM catalysts do not yet meet the performance requirements for use in fuel cells, and that the project should use characterization techniques beyond rotating disk electrode measurements.

Fuel Cell Performance and Durability: Four projects were reviewed, with three projects receiving a score of 3.3 and the remaining project receiving a score of 3.0, for an average score of 3.2. Reviewers praised the highest-rated projects for the strength and design of their approaches, their relevance to and alignment with sub-program goals, and their strong teams and collaboration. In addition, reviewers commented that these projects provide results that industry could use immediately and lauded the use of both in situ and ex situ experimental techniques. However, reviewers recommended that the projects use more state-of-the-art materials and that the researchers review their use of serpentine flow fields, where appropriate. Reviewers felt that the lower-scoring project's approach is



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

reasonable, addresses known durability issues in polymer electrolyte membrane fuel cells, and relies on effective collaboration; however, they expressed concern that the project does not demonstrate or elucidate an adequate understanding of the mechanisms behind the contaminants, and that it does not use MEAs with state-of-the-art Pt loadings.

Testing and Technical Assessment: Eight projects were reviewed and received scores between 3.0 and 3.6, with an average score of 3.4. The highest-rated project in this topic area was the highest-rated project in the sub-program. Reviewers stated that the project is well integrated into the sub-program, providing a critical capability that consistently delivers excellent progress from a highly collaborative team. While the reviewers generally thought the lowest-rated project demonstrates excellent analysis and collaboration, they identified a number of aspects that are inconsistent with real-world applications, and some questioned the project's contribution to cost reduction and customer acceptance.

MEAs, Cells, and Other Stack Components: Four projects were reviewed in this area, with three projects receiving a score of 3.1 and the remaining project receiving a score of 2.7, for an average score of 2.9. Reviewers felt the highest-rated projects are well aligned with the sub-program goals and have strong team members who collaborate well. Reviewers noted that these projects either demonstrate good progress toward the sub-program goals or contribute important findings that are relevant to the fuel cell community as a whole. For the lowest-scoring project, which tied for the lowest score in the sub-program, reviewers were impressed with the project team's ability to quickly engineer, develop, and deploy a semi-automated system for MEA fabrication, but they expressed serious reservations regarding the project's performance on hydrogen/air and recommended identifying the right industry collaborators to resolve these performance issues before proceeding.

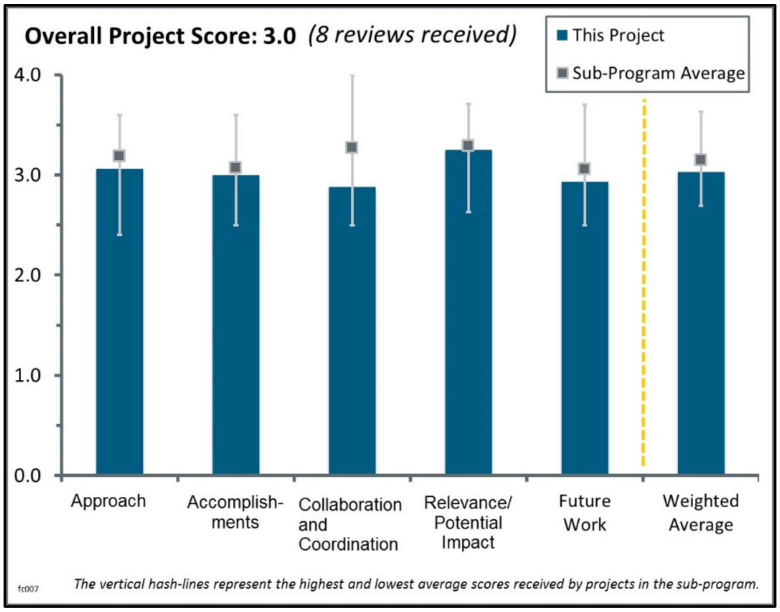
Membranes/Electrolytes: The seven membrane projects reviewed received scores between 2.7 and 3.5, with an average score of 3.1. Reviewers found the highest-rated project to be an effective collaboration among very strong team members that uses a systematic approach to address a challenge relevant to the cost, durability, and performance challenges faced by the sub-program. They noted that the project has met most of its milestones, including a key achievement of 0.1 S/cm at 50% relative humidity and 90°C. Reviewers expressed concern that insufficient details were revealed about the lowest-rated project's approach, prohibiting reviewers from making an accurate assessment of the project's approach or results. They were impressed with the conductivity but concerned that it came from thick membranes for which the project team had done limited or no mechanical properties or stability testing.

BOP Components: One project, development of a compressor/expander unit, was reviewed in this topic area. It received a score of 2.8. Reviewers regarded the focus of this project as very important for successfully launching fuel cell electric vehicles. While reviewers lauded the team's collaboration and expressed interest in validation with a full system, they expressed a greater concern that the project has not met the targets, that there did not appear to be a plan to meet the targets, and that the validation planned did not include the expander.

Project # FC-007: Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:



National Renewable Energy Laboratory (NREL) has pursued synthesis of novel extended thin-film electrocatalyst structures (ETFECSs) for improved cost, performance, and durability. A focus is on increasing Pt mass activity and increasing durability via post treatment processing. NREL will then incorporate these novel cathode catalyst materials and structures into membrane electrode assemblies (MEAs) to meet U.S. Department of Energy (DOE) technical targets for fuel cell cost, performance, and durability.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The approach this year, focusing on the use of several post-treatments and their combinations and interactions, was well performed and understood. There was enough discussion on why the treatments were chosen, and the method and new ideas during the process were excellent. The only part for which there was not enough justification was the reason for choosing Pt/Ni instead of other catalysts. It is clear that the principal investigator (PI) had to make a choice, as it is impossible to test all the catalysts, but some other catalysts with similar mass activities could be evaluated too.
- With the project almost completed, the team appears to have made significant progress toward making electrocatalysts with potential to meet DOE's goals. The annealing approaches appear to have been successful in addressing durability issues. The only concern is that the team pursued a non-scalable galvanic displacement process to demonstrate feasibility and now has only a few months remaining in the project to demonstrate targeted performance and durability with electrocatalysts made with the more scalable atomic layer deposition (ALD) process. Hindsight is 20/20, but it may have been more appropriate to have initiated work with the ALD process much earlier.
- The current approach is very good overall. The nanowire electrocatalyst approach has led to very high activity and durability, key fuel cell commercialization barriers. One issue with the approach is that most activity and durability characterization appears to be occurring in rotating disk electrodes (RDEs) and not in membrane electrode assembly (MEA) electrodes.
- The concept of nanowire as catalyst/support is sound since it promotes charge/mass transport and, in principle, improves the platinum utilization. Using a transition metal-based core is expected to produce a more stable catalyst in terms of oxidation corrosion resistance compared to carbon. However, the potential for membrane performance degradation by leached transition metal ions, such as Ni^{+2}, should have been a major consideration. The PI should have elaborated on the design principle and scientific hypothesis, particularly the concept and steps taken to address concerns raised during last year's DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR).
- Using inexpensive commercial Ni noodles decorated with Pt was originally an interesting and worthwhile idea. The majority of the work over the years appears to have focused on RDE testing. Despite good RDE results, transitioning to MEA testing has been slow and late, given the time frame of the project. The fiscal year (FY) 2014 MEA results appear a bit haphazard, and since it appears that the FY 2015 results require

further catalyst treatments to provide suitable results, it is clear that the catalysts should have seen MEAs earlier and more forcefully in the effort.

- It is an effective approach to increase the electrochemically available surface area (ECA) in the electrochemical solution and achieve good durability. However, the project needs to prove the reproducibility to overcome transition metal ion contamination of the MEA and increase the ionomer/catalyst interface or effective ECA in an MEA in actual fuel cell operation between anode and cathode.
- The approach of making extended, continuous Pt nanostructures has been shown effective in 3M's nanostructured-thin-film-type catalysts in typical 25- and 50-cm^2 single cells. However, it is not clear how the team will solve the issue of obtaining a pinhole-free extended Pt surface having high mass activity and stability under accelerated stress test conditions. It is unclear from the approach how the 2020 DOE target for platinum group metal (PGM) total content can be achieved with the 0.2 mg Pt/cm^2 currently used in 5- and 25-cm^2 cells shown in slides 16 and 17.
- The project is structured around three sequenced stages to (1) improve catalyst mass activity, (2) demonstrate fuel cell performance with the new catalyst, and (3) optimize the fuel cell fabrication techniques.

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

This project was rated **3.0** for its accomplishments and progress.

- The high mass activity materials were developed by galvanic displacement in 2014 but showed poor durability. Therefore the work of the third and fourth quarters (Q3–Q4) of 2014 and Q1 2015 focused on addressing durability concerns of transition metal ion contamination by acid leach followed by O_2 anneal of the platinum nanowire (PtNW) catalysts. ALD processing for Pt alloy NW synthesis was investigated and resulted in faster and easier synthesis over galvanic displacement. Yet the specific activity of Pt alloy NW is not as high as with galvanic displacement. The resulting MEA exhibited higher specific activity than, and similar performance to, reference Pt/C, and fuel cells with PtNiNW showed greater stability over reference Pt/C.
- Significant progress has been made in evaluating the mass and specific activities of ETFECS catalysts both in rotating ring-disk electrodes and MEAs. It would be interesting to know the H_2/air fuel cell performance of MEAs subjected to 0.6–1.0 V and 1.0–1.5 V cycling protocols. However, considering the current project end date of September 2015, the team may not have sufficient time to engineer MEAs for H_2/air fuel cell operation unless the project is extended.
- There has been excellent progress toward generation of high mass activity electrocatalysts that are also durable against potential cycling. Progress toward high-performance hydrogen/air electrodes seems to be substantially lacking; the key focus for future work needs to be electrode integration. Use of RDEs for durability is less aggressive than in MEAs, at least in part because of the substantially reduced cell temperature (room temperature rather than 80°C, as specified in the DOE protocols). Stability against the DOE support cycle should also be assessed and reported.
- In electrochemical solution, the increased ECA leads to high mass activity. The leached catalyst shows good durability. Progress has been made for catalyst durability in the MEA electrode in H_2/N_2. The actual fuel cell operation data will be required to demonstrate the catalyst's performance not only for activation polarization but also for the ohmic and mass transfer polarization so that the contamination issue can be fully understood.
- The team has established a new class of electro-catalysts with potential for meeting DOE's performance and durability targets. However, the performance and durability needs to be replicated with materials made by scalable processes; otherwise, the project will have no lasting impact.
- Judging simply from the results achieved and presented, the project has achieved the DOE goals of mass activity and durability.
- The team has demonstrated an excellent stability of pre-leached PtNiNW during a 6000 cycle (1–1.5 V) cycling test against the benchmark Pt/C catalyst. High mass activity was also achieved at RDE level. Although such mass activity is encouraging, it is essential that it has to be achieved at MEA level.

Unfortunately, this is not the case here. Considering that DOE has provided nearly $10 million in funding over the lifespan of this project, one could not argue that the return on investment is good in this project.

- The primary emphasis of this last year of the project should have been to obtain promising fuel cell performance with these types of catalysts. As shown on slide 15 for previous MEA results, rather poor performance is obtained with low loadings and/or without carbon added. New for FY 2015 is an acid-leached PtNi NW MEA with improved mass and specific activities in oxygen (slide 16), but the MEA performance, as shown by a simple polarization curve on air, is not provided, so it is not clear that any actual fuel cell performance increase was obtained by the leaching. It appears that results for only a single additional MEA are shown for FY 2015 beyond those performed in FY 2014, and even then it is not clear that any MEA improvement was obtained.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The team has established strong collaboration with universities and industry. The objective of including the task “electrospinning of polymer nanowires for electrode incorporation” by one of the subcontractors toward the end of the project is unclear.
- There is good collaboration, but the team may need to closely work with the characterization partners to collect more information about the catalyst, electrode, and membrane.
- The team is excellent, with complementary skills.
- The partnership has significantly evolved along the project duration from 11 partners in 2013, to 5 in 2014, to 3 remaining partners in 2015. While the role of the leaving partners may have been limited to being subcontractors, it is unclear why they detached from the collaboration up to the final stages. In 2014–2015, the interactions and scientific dissemination of the project were ensured by six publications (done or submitted), five presentations in the United States, and one presentation in China.
- The collaborations with university partners seem adequate for this type of project. There was no indication in the presentation materials or in the presentation itself that General Motors (GM) has been an active participant in this project.
- While collaborators are listed, their contributions are not very much in evidence from the presentation slides. Either they are not contributing much, or the contributions are not being attributed.
- It is unclear what the partners are contributing to the project.

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

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

- The project is critical to the Hydrogen and Fuel Cells Program, and it fully supports DOE research, development, and demonstration objectives. In particular it looks at PGM content of 0.125 g/kW, mass activity of 0.44 A/mg, and mass activity loss <10%. The project aims at developing high performing, durable, and low-cost MEA fuel cell technology competitive with battery and internal combustion engine technologies.
- This approach has the potential to be highly relevant to DOE cost and durability goals. Demonstration of high-activity MEA electrodes with even a substantial fraction of what is reported in RDEs would significantly advance the state of the art.
- The project does provide an alternative route to obtain catalyst alloys that achieve higher mass activity and durability—especially the way that it is achieved, with the removal of carbon as the support. This is key to solving some issues, such as start-up/shut-down corrosion. The potential to achieve the research and development targets is high, provided that the catalyst can be synthesized in larger volumes, which is an issue that the project has been trying to address since its inception.
- The project has a clear objective of developing highly active and stable oxygen reduction reaction (ORR) electrocatalysts in accordance with the DOE goals for automotive catalysts.

- The project directly addresses high mass activity and good durability for a low-cost fuel cell catalyst, which aligns with DOE goals.
- This project has a very high potential for impact, given the demonstrated performance and durability levels. However, the key word here is “potential” since the potential will be realized only if the performance and durability are demonstrated on electrocatalysts made using a scalable process.
- Although the knowledge generated through this project is helpful, it is unlikely the catalyst or concept can be implemented in the actual fuel cell system in comparison with some other Pt alloy catalysts under development.
- Based on the underlying issues with Ni contamination and the relatively poor and sparse fuel cell results (and perhaps the need to still require carbon in the catalyst layer), the catalyst does not appear to offer meaningful competition to current technology or other catalyst systems in the pipeline. It was an interesting and worthy approach to investigate, but it appears to have run its course.

Question 5: Proposed future work

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

- The proposed future work of “focus on reproducibility/increased batch size” is a key area on which to focus energies, now that it has been shown that the catalyst meets the minimum requirements at a laboratory scale; therefore, this is nicely proposed. What is not clear in this proposed work is how and with whom this will be done. To scale a new approach like this, an industrial catalyst partner is highly desired, but none appears in the list of collaborations. Of course the project is at its end, but if there is a need for further funding, integrating a catalyst manufacturer is recommended. On the topic of “electrode structure/fuel cell studies,” this is a large body of work. Even though this is an area that needs to be addressed, it was unclear why there was a decision already on optimization of catalyst ink and composition. The right process is first to characterize the new catalyst in other typical automotive operating conditions, such as hot operation, cold operation, pressures, stoichs, concentrations, and humidity; and from there, to derive what the issues are with the catalyst and propose the necessary electrode optimization work.
- The project has identified the remaining barriers: improved synthesis of catalysts at larger scale and investigation of fuel cell behavior to meet the performance targets. The cost assessment is not sufficiently considered, although costs are mentioned as a barrier by the project; hence the financial benefits should be measured at some point.
- There is very little time left on this project, and the team’s stated plans for focusing the remaining effort on demonstrating fuel cell performance on electrocatalysts made by the ALD process is appropriate. The project should abandon any work on scaling up the galvanic displacement process unless the team can identify a viable scale-up approach.
- The project is in its last year, so future work covers only the remainder of FY 2015. Work needs to be done on the catalyst layers, as the polarization curves on slide 15 indicate that there are curious effects going on as the loading is increased. Apparently, substantial transport improvement is obtained when high surface area carbon (HSC) is added to the electrode, which is unfortunately counter to the objective of removing carbon materials from the active area (indeed, slide 29 seems to indicate that the carbon durability is as much of a problem as it is with Pt/C catalysts).
- ALD coating may not be an effective way because the catalyst nanomaterial cannot be coated with a thick ALD layer; otherwise, the catalyst’s mass activity will be reduced. If the ALD layer is thin enough, it cannot maintain its coverage on the catalyst’s surface, especially when the catalyst is leached or annealed or utilized in the fuel cells. The team should carefully think about it. The team has considered the scale-up and reproducibility issues, as well as the MEA fabrication issue.
- The proposed future work is reasonable and sound. However, such tasks should have already been completed within the allocated budget and effort.
- The team had proposed to “isolate the overpotential losses in MEAs made with ETFECS materials” as the future work in the 2014 AMR meeting, with no significant progress made thereafter. Considering the time left in the project, the team may not have sufficient time to complete all of the proposed future work.
- MEA electrode optimization should be the primary focus.

Project strengths:

- The excellent team made significant strides this year. Very good activity was demonstrated at the RDE level. Very good durability improvement over Pt/C has been shown.
- The project has a very good approach, and the team has made necessary go/no-go decisions to identify a catalyst system with high mass activity and stability. Since the beginning of the project, the team has made significant collaborations with academic institutions, national laboratories, a catalyst developer, and original equipment manufacturers.
- The project team has identified an extraordinarily promising route to high-activity, durable (cyclic) alloy electrocatalysts using pragmatic approaches.
- The project involves demonstration of a new class of electrocatalyst materials with potential for meeting DOE performance and durability targets, as well as identification of annealing approaches to optimize performance and durability.
- Lack of carbon supports does eliminate one of the biggest failure modes. A new rational approach for depositing the catalyst does provide a new area of optimization in electrode structure.
- The team has long-term perspective and a commitment to converge toward DOE targets.
- The team has good resources.

Project weaknesses:

- (1) There is no catalyst industry partner to scale up the processes proposed (as they are not typically used by catalyst suppliers). (2) Even though GM is cited as an automotive partner for development, it is not clear whether the catalyst is being tested—or testing is planned—under other typical automotive conditions such as hot operation or cold operation, conditions under which this type of catalyst structure would frequently fall short of requirements.
- Mass activity is still lower than DOE targets at the MEA level. The transition metal leaching issue was not addressed.
- There has been insufficient consideration of cost assessment for the catalyst fabrication techniques.
- (1) The contribution of each collaborator is not clearly mentioned in the presentation slides. (2) Since the 2014 AMR meeting, the team in fact had ample time for electrode optimization and testing the durability of a promising candidate material under H_2/air fuel cell operating conditions.
- Correlation of the characterization and performance needs to be further analyzed.
- The team is not focusing on the key issue of MEA electrodes.
- Too much work has been performed using a non-scalable synthesis process.
- After this project's many years, ETFECS materials are not much closer to becoming practical fuel cell catalysts.

Recommendations for additions/deletions to project scope:

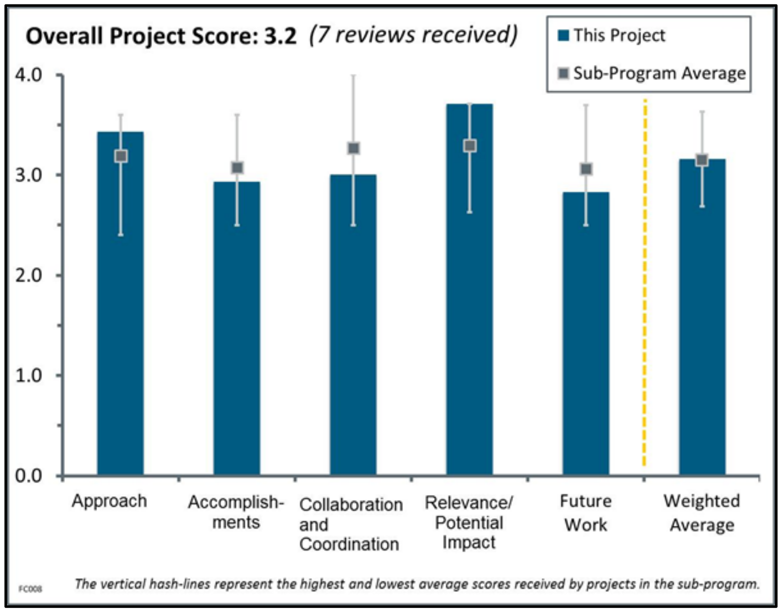
- The project should (1) add a catalyst industry partner now that it seems that the catalyst is ready to be scaled up, (2) perform more characterization work under other automotive requirements, and (3) investigate the effect of the post-treatment work proven successful with PtNi on other alloys with similar mass activity (such as PtCo).
- The project should be extended one year and funded sufficiently to allow a significant focus on electrode optimization only. Collaboration with others that have significant electrode design expertise (either in DOE or in industry) should be stressed.
- The project should abandon work on galvanic displacement and focus all remaining resources on getting the fuel cell test results that provide "proof" that the new electrocatalyst materials are worth pursuing so that the technology is advanced by a fuel cell MEA manufacturer.
- The project should include a cost–benefit study of the manufacturing at the fuel cell level (Pt reduction and fabrication costs).
- The project ends in September 2015. Hence, no additions/deletions to project scope are suggested.
- The project should be wrapped up. No further development in this direction is recommended.
- The effort should probably end, along with the FY 2015 funding.

Project # FC-008: Nanosegregated Cathode Catalysts with Ultra-Low Pt Loading

Vojislav Stamenkovic; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop highly efficient and durable multi-metallic PtMN nanosegregated catalysts for the oxygen reduction reaction with ultra-low platinum content. Argonne National Laboratory (ANL) will conduct a materials-by-design approach to design, characterize, understand, synthesize/fabricate, test and develop advanced nanosegregated multi-metallic nanoparticles and nanostructured thin metal films.



Question 1: Approach to performing the work

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

- The team went from analyzing the catalytic phenomena during the oxygen reduction reaction (ORR) that damage Pt/C catalysts to the approach of mixed metals. The team systematically investigated the effects when adding other metals, supported that by modeling, and synthesized new catalysts. In a first stage, the focus was on non-Pt metal additions, then nanostructuring came in until the Ni-framed Pt catalysts were achieved. This very scientific approach is a good example of how successful use-inspired basic research can be if it is clearly targeted and a strong team of academia and industry is formed. Hence, this project is considered outstanding.
- The project approach overall has been excellent, with significant achievements made in new catalyst designs, characterization, and understanding of activity and stability impacts. The project team has achieved what appears to be a scalable catalyst design with ability to control surface structure and morphology. The current work on understanding fundamentals required for the next step in membrane electrode assembly (MEA) design is good, but while still at the rotating disk electrode (RDE) level, e.g., ionomer adsorption. At the MEA level, more work will be required on the voltage loss breakdown and modeling of the results in order to achieve understanding of catalyst layer optimization opportunities.
- Enhancement of ORR catalyst activity is imperative for the automotive fuel cell. This project is looking at the atomic-level structure of the ORR catalyst to enhance the performance. The novelty of this approach is outstanding.
- The approach to the work in past years has been consistently novel and outstanding—catalyst species have ranged from non-perylene modifications of 3M nanostructured thin films to the nanoframe catalyst that has been the subject of recent work. The remaining approach to the project is to scale up synthesis and perform fuel cell measurements. In the course of doing this, the investigators understood that re-confirmation of the nanoframe structure would be needed after fabricating the MEA, and they also understood that ionomer might have an effect on activity, so they redid RDE experiments with ionomer. This year's approach was compromised by lack of an industrial collaborator, which may have assisted with earlier delivery of results, as well as with analysis of voltage losses in the cell. Furthermore, the scale-up of catalyst fabrication was only up to 60 milligrams, which could have been improved with industrial collaboration.
- The research team members are world leaders in the nanoengineering of Pt particles. The approach is very interesting from a science perspective. From an industrial processing viewpoint, it is significantly more challenging than conventional synthesis. There is little doubt that the approach improves the electrocatalyst performance under RDE conditions.

- No presentation materials on this project were available on PeerNet, nor was the presentation included on the presentation flash drive handed out at the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review. This makes proper review more difficult. Sufficient respect should be shown for everyone in the review process to get presentations in on time. There were no dramatic new results (since the submission deadline) in the live presentation that might have partially justified the lack of a pre-submitted presentation document. The presentation included a comment that the project had been forced to change focus, moving from fundamental to more applied work. Argonne National Laboratory (ANL) is one of the few places in the world equipped to do really fundamental work on electrocatalysts, including work on single crystals. That fundamental work has had a profound impact on the field of electrocatalysis as a whole. A major mission of the national laboratories is to do technology-supporting experiments that can be done nowhere else. Even national laboratory research funded by the DOE Office of Energy Efficiency and Renewable Energy (EERE), which overall has more of an applied cast than DOE Basic Energy Sciences (BES) work, should support this mission of the laboratories. The very long delays in getting the catalyst scale-up laboratory running at ANL demonstrate the inefficiencies inherent in diverting national laboratory resources to what is perceived as more applied work.
- The general approach is to discover new catalyst configurations and structures that promise high activity. Superior MEA performance and durability should have been the major objective of this project in order to demonstrate the value of these highly touted catalysts (some of which were developed prior to this particular project) to the fuel cell DOE program and community. Considering the status of the technologies, both at the beginning of this five-year project and now in its last year, the approach has fallen short in carrying the catalysts to a level of development that is useful for fuel cell manufacturers.

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

This project was rated **2.9** for its accomplishments and progress.

- The project technical targets are three times the DOE targets for mass and specific activity and for lower total platinum group metal content. Much of the presentation was focused on prior years' accomplishments. In the 2014 reporting year, a huge step was achieved due to the discovery of the highly active nanoframe structure. In the current reporting year, the work appeared to focus on the catalyst scale-up and MEA testing. The results in these areas show a work in progress. The MEA performance with the nanoframes achieved a mass activity of ~3x that of Pt, which exceeds the DOE target, but the MEA performance falls short of targets. However, this was at a very low Pt loading. There is still a fundamental gap in achieving high current density results, which is disappointing, but maybe not surprising. The scale-up has been challenging; the catalyst produced is still highly active, but approximately half of the activity was lost. In an MEA, the nanoframes do not appear to be any better than the nanostructured thin film, but they might provide additional opportunities for catalyst layer design, and there is certainly considerable room for an additional upside. It is difficult to assess whether the targets will be achievable in the project timeframe.
- The 2015 accomplishments include limited scale-up of the nanoframes and successful determination of MEA performance. The MEA results were on small 5 cm^2 cells, most likely because of the difficulty in scaling up the process. The translation of high-performance RDE results into high-performance MEAs has been very challenging for all of the new catalyst systems. More work will be required to determine the suitability of the approach in fuel cell stacks.
- The project focused extremely well on the barriers and DOE targets. Notably, some of the targets were exceeded, and one was even exceeded by more than an order of magnitude.
- Accomplishments in the 2014 presentation, particularly the nanoframe concept, were outstanding. Compared with the 2014 presentation, it is hard to see significant progress in the 2015 presentation. There are several technical accomplishments throughout this project from 2009 to 2014: surface segregation of Pt alloy, ternary alloy, mesostructured thin film, and nanoframes. For the rest of the project term, it is suggested that the project investigate to show a ranking of these concepts for the project target, e.g., which concept is the most promising for the automotive fuel cell. Although the nanoframe catalyst shows a high performance at the low current density, it does not show a high performance at the higher current densities. Performance at the high current density is also important for increasing area-specific power density to

reduce the fuel cell cost. This could be out of the original scope of the project (maybe this could be another project). It is suggested that the project investigate the cause for the rest of this project term.

- Progress measured over the entire time of this project has been excellent, but it is unclear how much has been accomplished in the past year. The presentation said that this year's talk would concentrate on nanowires, but relatively little was said on this point other than removing the final anneal to prevent Au from coming to the surface and disrupting ORR, plus recent addition of a new component which could not be disclosed and for which no data were shown. It is good that Au's negative effects on ORR in the near-surface region are now being acknowledged by the project, not just the claimed improvements in durability. Nanoframes have now been tested in 5 cm^2 MEAs, but the discussion of this provided little beyond the fact that the basic nanoframe structure was maintained but that further loss of Ni was observed. The scale-up milestone was described as 80% done, but there were few clear data on scaled-up catalysts in the talk. It is not clear that a 5 cm^2 MEA is considered a scale-up. The mentioned, but not shown, very recent data showing a 30% improvement in MEA performance upon addition of an ionic liquid to an MEA indicate a start on determining whether ionic liquids could provide practical benefits in MEAs.
- Scale-up mass is still low. It was good to see the reporting of how much lower the catalyst activity goes with scale-up. The project should focus on why scale-up decreases activity. In situ mass activity measurements show that mass activity is still three times higher than the baseline. Fuel cell tests show that performance for the nanoframe catalysts at high current density is low. Despite the low Pt loading (0.035 mg/cm^2), the inflection of the polarization curve shows that mass transport losses begin to decrease performance around 0.4 A/cm^2. It may be interesting to see a polarization curve at higher Pt loading. Breakdown of performance losses is needed. The project also needs to share parameters related to the rest of the MEA (membrane thickness, anode catalyst loading, etc.). Although Ni leaching was detected, there should have been greater delivery with respect to addressing this, especially with another project at ANL addressing Ni leaching from dealloyed PtNi nanoparticles.
- The primary fiscal year (FY) 2015 accomplishments were on MEA testing with the nanoframes, in which considerable improvements in the kinetic region were observed over Pt/C. Higher currents resulted in poor performance. It was mentioned that transport limitations need to be overcome, but a curious inflection is obtained, indicating that other issues may be involved. The scale-up results with nanoframes are not particularly encouraging. This is a long way from commercial relevance.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The collaboration between the catalyst synthesis and the MEA fabrication and fuel cell testing was excellent. This approach needs to be duplicated for all promising catalysts first investigated by RDE measurements.
- A very strong team of the leading groups in academia (of ANL and Oak Ridge National Laboratory [ORNL]) and one of the leading companies (3M) was formed. The structure brought in the necessary proficiency without bringing in too many partners.
- Collaboration between the different divisions of ANL on this project now seems to be very good. There was not much discussion on outside collaborations within the presentation.
- With the exception of characterization (which is excellent), it appears that collaboration is mostly within ANL. A group with more MEA design experience could be beneficial at this stage in the catalyst development.
- There are only three partners, and they are all national laboratories. In the last year, a supplier or a developer would have added valuable collaboration, but this did not occur. ORNL has provided services with respect to imaging the catalysts. Los Alamos National Laboratory (LANL) provided fuel cell testing of the catalysts.
- No highly effective collaboration can be seen in this project expect atomic-scale microscopic analysis with ORNL. More effective collaboration is expected for durability (LANL) and cell fabrication and testing (ANL). In the cell fabrication area, collaboration with an industry partner is suggested.

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

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

- The relevance of this project is very high. A highly active catalyst could have the ability to considerably change the affordability of commercial fuel cell vehicles by decreasing the size of the stack and decreasing the overall amount of precious metals used in the stack. Surface-segregated PtNi with a Pt skin surface has been known for many years to be a highly active surface for oxygen reduction. This project seeks not only to make a nanoparticle version of this but also to do it with a novel morphology that can accommodate further design features in the catalyst layer. The project is committed to understanding whether activity shown ex situ can be confirmed in an operating fuel cell.
- Enhancement of ORR catalyst activity is imperative for the automotive fuel cell. This project is looking at atomic-level structure of the ORR catalyst to enhance the performance. The novelty of this approach is outstanding.
- The work to translate a significant portion of the thin film Pt3Ni(111) specific activity into a manufacturable and stable nanoparticulate catalyst is highly relevant to achieving the ultimate Pt loading targets for high-volume commercial fuel cells and meeting program targets.
- The relevance for automotive fuel cells is very high. The main barriers were successfully targeted. The results are getting even more relevant as the first two Asian companies launched the market introduction of fuel cell vehicles in 2014 and early 2015.
- This project historically has generated new paths towards higher activity and improved durability, which has influenced catalyst development throughout the industry. The fundamental work within this project has improved understanding of what factors are important to determining the activity and durability of a catalyst. It is not clear whether the new work this past year will be as influential as the earlier work, but the new efforts to control the negative effects of Au while maintaining Au's apparent durability benefits could prove fruitful.
- The relevance of the project is good. Much has been learned about how the microstructure and composition of Pt catalysts influence electrocatalyst activity. As for potential impact, that remains to be seen. After the disappointing performance witnessed by nanostructured thin film catalysts under real-world fuel cell conditions, judgments need to be withheld until extensive MEA optimization and fuel cell performance and durability testing are performed.
- The substantial number of presentations and high-visibility publications will have an effect on literature and citations. Less certain is that the efforts will have an impact on industry and commercial fuel cells.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- For the final year of the project, "alternative approaches to highly active and stable catalysts" would not likely be a task. The project already has much to settle with nanoframe performance in a fuel cell. Scale-up of the catalyst is needed, but it would be helpful to have a supplier involved. Perhaps this could be addressed in a later funding period. Catalyst stability does need to be addressed, but during both fabrication and operation. Further studies need to be done to understand the sources of voltage loss. Testing at higher Pt loading would also be helpful. It is good to see that the mesostructured thin films may be carried forward in a future funding period.
- It is absolutely imperative that the catalyst synthesis be scaled up to real-world quantities of materials (grams at least) and fuel cell MEA optimization be performed. Extensive testing of the materials in larger cells under DOE protocols is required.
- The future work is appropriate, but it is not clear whether the plans for MEA development are sufficient to fully realize the potential of these outstanding catalysts. Additional focus is also required to achieve scale-up of these catalysts.
- The plans to finish up the project, while not emphasized in the talk, seem appropriate.

- MEA development and testing need more emphasis.
- This project is ending in September 2015, and the remaining time is not enough to do something new.

Project strengths:

- The project has had a remarkable degree of success in past years, showing activity for PtNi nanoframes that is 35 times baseline catalysts and 15 times the DOE target. Investigators have extensive backgrounds and were involved in the original discovery of the PtNi(111) activity with a Pt skin surface. ANL and the other laboratories involved have considerable access to analytical capability.
- The outstanding capabilities of the project team have led to world-leading advancements in fuel cell catalyst design ability for performance and stability. The overall approach of structured, step-by-step improvement in understanding, as well as some serendipity in discoveries, has been highly effective.
- The fundamental studies of the factors leading to high ORR activity and durability under this project have been critical to developments throughout the field. ANL has one of the few laboratories in the world equipped to study single-crystal surfaces of alloy catalysts and the experience to interpret the results in a way that can provide unambiguous insights to the fundamentals of activity and durability.
- This is a world-class team in electrocatalyst synthesis in partnership with world-class MEA fabrication and fuel cell testing. The very novel synthesis approaches are used with excellent diagnostic and theoretical analysis. There is strong leveraging of BES and EERE capabilities.
- The strength of the project is based on its very basic scientific approach with a clear devotion to solving the issues of the ORR in view of cost reduction and lifetime enhancement. This also shows that longer-termed projects such as this one (over a five-year term) provide an opportunity for researchers to solve intricate problems in multistep approaches.
- The project has been very creative in developing new configurations and types of catalysts.
- The novelty of the atomic-level catalyst structure is a project strength.

Project weaknesses:

- The project is very strong, and no notable weaknesses can be identified. Minor issues should not be criticized just for the sake of completeness.
- There is very little MEA-level assessment and no optimization yet. Although the assessment at the MEA level needs to be done, care should be taken not to draw conclusions too quickly on the MEA performance. It is likely that much work will be required to realize the full potential of these catalysts at the MEA level.
- Lack of scale-up of materials synthesis thus far is a weakness. There is a need for extensive MEA performance optimization.
- Scale-up of the high-surface-area catalysts developed under this project has been very slow and raises questions of whether national laboratories should attempt such scale-up on their own rather than seeking experienced outside collaborators. Redirection of the project from its initial fundamental focus to greater attention to high-surface-area “practical” catalysts has diluted its impact on broader electrocatalyst development.
- The project lacks industrial collaboration. In the past year, the project was slow to produce fuel cell testing results. Results that have been reported have shown low performance without also exploring wide ranges of Pt loading or operating conditions. The synthesis scale reaches only milligram-size batches. The project still needs to explore why activity decreases with increases in fabrication scale.
- The project lacks proper collaboration, particularly in the fabrication of the cell area (transforming catalyst concept to real cell).
- The project has not been effectively focused on developing a product or technology that is useful for commercial fuel cells. It has been more of a BES-type of discovery project.

Recommendations for additions/deletions to project scope:

- Continued funding is needed to determine the viability of the novel electrocatalysts. The future research plan is well conceived and needs more years of EERE support.
- The project should restore the greater emphasis on fundamental work, including that on single crystals. Scale-up would likely be more efficient if undertaken with experienced outside suppliers rather than by

attempting it within ANL. National laboratory time is expensive and should be directed toward the unique capabilities of the laboratories rather than toward immediate commercialization.

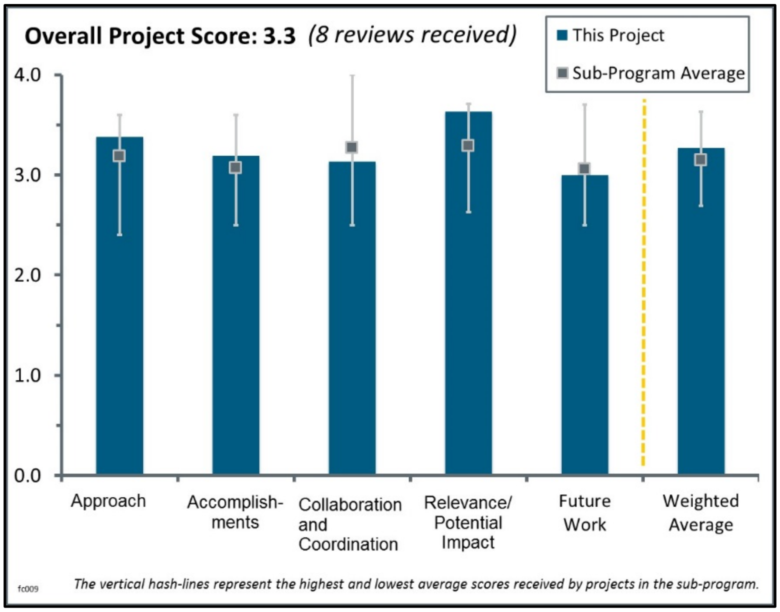
- Additions should include industrial partners (supplier and developer), an emphasis on gram-scale production, fuel cell testing that includes a range of Pt loading and operating conditions, and extensive in situ diagnostics to understand the sources of voltage loss. The remainder of the project should focus on fuel cell testing of PtNi nanoframes. At least for this project, there should be no further work on new catalysts.
- For the cell fabrication area, collaboration with an industry partner is suggested.

Project # FC-009: Contiguous Pt Monolayer Oxygen Reduction Electrocatalysts on High-Stability, Low-Cost Supports

Radoslav Adzic; Brookhaven National Laboratory

Brief Summary of Project:

The overall objective of this project is to synthesize a high-performance platinum monolayer (ML) on stable, inexpensive metal or alloy nanostructure electrocatalysts for the oxygen reduction reaction (ORR). For fiscal year (FY) 2015, Brookhaven National Laboratory (BNL) conducted electrodeposition of inexpensive refractory metal alloy nanoparticles on gas diffusion layers to fabricate electrodes of 5, 25, and 50 cm^2 and carried out membrane electrode assembly tests at BNL and General Motors (GM). BNL also further developed the nitriding method to stabilize cores and the stabilization method involving the addition of Au to cores. Finally, BNL sought to demonstrate the suitability of graphene as a support for Pt ML catalysts.



Question 1: Approach to performing the work

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

- Enhancing the ORR activity for the automotive fuel cell is imperative. The novelty of the approach (synthesizing a Pt ML) sets a trend for the ORR catalyst research, such as surface segregation and de-alloying.
- The approach for this project has been well thought out since the beginning: synthesizing a Pt ML on inexpensive support metals.
- This team continues its creative and productive development of new cathode catalysts. The primary challenge in the past has been lack of membrane electrode assembly (MEA) integration. The team has made much progress in this area, although the excellent half-cell performance of the materials does not translate all that well in MEAs. The team will need to address these sources of loss in MEAs.
- The approach is strongly focused on meeting U.S. Department of Energy (DOE) targets on Pt loading, activity, and durability
- The project pursues numerous synthesis approaches for developing improved catalysts. Each individual segment progresses at its own pace and will ultimately be tested in MEAs.
- The approach to catalyst development is good. However, it is not clear how the IrRuOx fits into the range of materials.
- In general, BNL's Pt ML approach provides an excellent building block to achieve maximum Pt utilization and, hence, shows the best opportunity for achieving both high oxygen reduction activity and high power performance with ultralow platinum group metal (PGM) electrodes. The project revisits on stabilization of the core with Au and nitride are encouraging. The focus on obtaining MEA data on new catalysts is welcome, y. Yet MEA fabrication appeared to be a weakness. Despite early promising MEA results on electrodeposited Pt/Pd/WNi, its MEA performance is still depressingly poor. Other MEA data with dispersed catalyst also look poor. It is important to determine whether these materials have an intrinsic problem or not. It is not clear if BNL has a plan and resources to investigate and improve upon these issues. The project also includes many other studies, some of which are questionable and perhaps even serve as

distractions. For example, the electrodeposited dendritic Pd is a huge waste of PGM and will create an electrode structure that floods readily and has poor O_2 transport. The PtPd dendritic catalyst is also susceptible to sintering and dissolution. Fe porphyrin/graphene is not particularly new and will cause severe membrane degradation. The study on graphene might be interesting, but as with any new support, oxygen transport in this layer can be an issue and requires proper MEA testing and analyses.

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

This project was rated **3.2** for its accomplishments and progress.

- The team has made very good progress toward the design of highly active and durable catalysts in electrochemical cells. Several novel and promising highly active catalysts (dendritic PtPd, PtML on nitride-stabilized cores, and Fe porhyrine supported on graphene) have been developed. Performance in the air still needs to be optimized.
- The project made excellent progress this year, with lots of MEA testing showing very promising results for PGM loading as low as 0.07 mg_{PGM}/cm^2. Although results indicate that air performance needs to be improved, ORR activity in MEA is close to the 2020 target.
- Overall, good progress has been made. Several candidates appear to yield mass activity approaching or exceeding DOE targets, and there appears to be a larger focus on MEA testing for evaluation of the electrocatalysts' activity and durability. Relevant MEA H_2/air performance is still substantially lower than state-of-the-art electrodes and needs increased focus.
- Catalyst stability using nitriding strategies is impressive, and the fact that the team has been moving much further toward MEA integration is good. Some of the other areas seem a bit tangential. It was not clear why the team moved to graphene-based supports, and their results in this area are not that impressive.
- The new syntheses (Pt ML on Pd/WNi/ gas diffusion layer) shows progress for durability. It is suggested that BNL show an effect of Pd or underpotential deposition Cu displacement. It seems to be a Pd effect. It keeps total PGM (including Pd) low. The PdNi core shows a possibility to reduce Pd content (lower cost). It is suggested to show the merit of graphene as a support (performance and durability), and determine which is more promising; FeP on graphene or reduced graphene oxide.
- The project accomplished high mass activity and good stability in the rotating disk electrode (RDE).
- MEA testing, which was lacking in this project, was accomplished with several catalysts. There is work ahead to achieve high performance catalyst layers. Regarding the MEA testing, results are reported in several instances for pressures, e.g., 150 kPa. Usually, kilopascal values are understood to be absolute pressures (e.g., 150 kPa is ~22 psia or ~7.4 psig). However, slide 8 reports results at 0 kPa, which obviously means that the kilopascal values are on top of atmospheric pressure. These pressures are significantly higher than typically inferred for data at 150 kPa.
- It was not clear if the project made any progress against DOE goals this year. Note that the project did not adhere closely with the DOE-recommended testing methods. Tricks such as pure O_2 and high pressure were used to show better-looking results.

Question 3: Collaboration and coordination with other institutions

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

- There is very strong collaboration among BNL, industry (GM and IRD), and other institutes. GM has demonstrated excellent work by testing these catalysts in MEAs. The H_2/O_2 and H_2/air tests in 50 cm^2 MEA are impressive. This is a significant leap from the last couple of years and is excellent progress compared to other projects on low-PGM catalysts. Toyota's active involvement is unclear. It looks like most of the MEA tests are done at BNL and GM.
- There is excellent coordination with industrial partners.
- Including industry partners adds a variety of technical approaches to fabricate the catalyst structure.
- This is a very well-coordinated effort between BNL and industry. Collaboration with theorists are indicated on slide 21, but none of the theoretical results are presented.
- Collaborations appear to be numerous and reasonably productive.

- The listed collaborators are excellent, but it is unclear what the work distribution is.
- It was not clear if there is any collaboration.

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

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

- The catalysts developed by the team demonstrate very high activity and durability at very low Pt loading, which aligns very well with Hydrogen and Fuel Cells Program objectives.
- Objectives of this project are very relevant to the Fuel Cell Technology Office and DOE research, development, and deployment objectives.
- It is imperative to enhance the ORR activity for the automotive fuel cell. Novelty of the approach (synthesizing Pt ML) sets a trend for the ORR catalyst research, such as surface segregation and de-alloying.
- If the Pt ML catalyst could be made stably, it could significantly reduce the stack cost and reliance on PGM, predominantly thanks to its high Pt utilization.
- The project is highly aligned with the key barriers of cost and durability. Relevance will be improved when high performance MEA electrodes can be demonstrated.
- Successfully implementing catalysts into low-loading, high-performance and durability MEAs would have a significant effect on the fuel cell industry.
- It was not clear if the complex chemistries used here will ever translate to industrial-scale implementation. The team has made a lot of progress toward MEA integration and larger amounts of material are being synthesized. There is much to be learned of fundamental importance here.
- The project matches the DOE objective of low PGM and high stability.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Future work is focused on the improvement of catalyst stability and durability in the fuel cell environment, which is critical for this sub-program. Novel strategies are proposed that could further improve catalyst durability. The number of novel systems needs to be reduced in order to have an opportunity for the complete optimization of at least for one system.
- Proposed future work on MEAs and stack tests is very good, but shedding light on what causes drops in performance in MEAs would be great. Also, avoiding adding Au for stabilizing the core would help to reduce the PGM cost.
- Synthesis, MEAs, and stack tests are reasonable, and moving toward incorporation of refractory elements is an area of interest for many. However, the effects of nitriding at high pressure and/or reactive spray deposition were unexplained.
- The stack tests with GM would be an important demonstration of the future viability of these catalysts.
- The focus on durability of core and support materials and performance enhancement is understandable.
- The project continues to focus on stabilization of core materials using multiple approaches. MEA development appears to be relying on a non-funded partner (i.e., GM). New catalyst developments also appear to require increasing amounts of MEA knowledge and resources going forward. It is not very clear if relying only on in-kind contributors will be an adequate approach.
- It would be good to see the evaluation of catalyst stability in full-size MEAs. Optimization of air performance is recommended as is developing an approach to material scale-up.
- It is recommended that for FY 2015 the project focus on electrode development to allow demonstration of the project electocatalysts' performance in relevant formats. Working with other groups with electrode expertise is warranted.

Project strengths:

- The team is very creative in formulating novel approaches for catalyst synthesis. The team standards are so high that extremely high activities obtained in electrochemical cells do not surprise anybody anymore.
- There is very strong collaboration among BNL, academia, and industry. Objectives and approaches are very well thought out. There is lots of MEA testing, and nearing stack testing indicates closeness to commercialization
- The knowledgeable team, state-of-the-art nanoparticle characterization capability, practicality, and product-oriented culture are all project strengths.
- A project strength is the high degree of sophistication in synthesis.
- The team appears to be making progress on many fronts.
- The project has demonstrated electrocatalysts with high activity and durability in RDE.
- The novelty of the Pt ML concept and the inclusion of industry collaborators are project strengths.

Project weaknesses:

- Industry needs to be more involved in order to help the team with optimization of catalyst layers. The project covers too many novel systems instead of focusing on the full optimization of just a few of them.
- The team does not have a complete understanding of degradation in MEA and its countermeasures.
- It is questionable whether the strategies here are viable in mass production.
- MEA knowledge and resources are lacking. It is recommended that the project align to DOE-suggested methods.
- Perhaps the project is too disjointed. It is not clear what the value is of yet another catalyst that performs well in KOH or of Ru/Ir oxygen evolution catalysts or of graphene supports.
- The performance in MEA electrodes is poor.

Recommendations for additions/deletions to project scope:

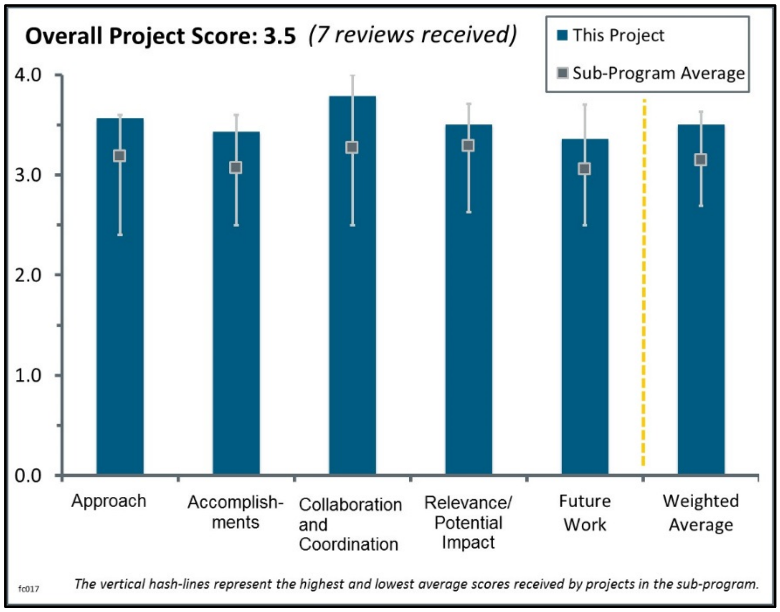
- The team should focus on the two systems that look the most promising and perform their complete analysis and optimization. One of the systems that looks the most promising is the nitride-stabilized cores.
- It is suggested that BNL show the merit of graphene as a support (performance and durability), and determine which is more promising; FeP on graphene or reduced graphene oxide.
- Prioritizing the approaches is recommended.

Project # FC-017: Fuel Cells Systems Analysis

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop a validated system model and use it to assess design-point, part-load, and dynamic performance of automotive and stationary fuel cell systems. Argonne National Laboratory (ANL) will support the U.S. Department of Energy (DOE) in (1) setting technical targets and directing component development, (2) establishing metrics for gauging progress of research and development (R&D) projects, and (3) providing data and specifications to DOE projects on high-volume manufacturing cost estimation.



Question 1: Approach to performing the work

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

- This project stands alone as the most comprehensive fuel cell system model in the public domain. The investigators are actively refining their work using input from key stakeholders. The model represents the current state of the art. In terms of approach, it does at least seem as if it would be difficult for someone outside the project to exercise the model. It is not clear whether the model will be disseminated as a user tool.
- The project addresses system-level operation with a projection for cost. This is a very useful methodology for cascading developments in components and stack configurations to the commercialization targets for fuel cell systems.
- Overall, the project appears aligned with the industry direction and is capturing the developments of new materials (nanostructured thin film [NSTF]) that make this very relevant as a tool for industry. Working closely with industry to try to achieve adoption of the model within automotive fuel cell development community is encouraged.
- The linkage of GCTool and Automomie models is an effective approach to analyze performance of the fuel cell system. The model has a dynamic performance capability. Technical assumptions rely on discussion with the U.S. DRIVE Partnership Technical Teams to leverage up-to-date industry perspectives. The project leverages Strategic Analysis, Inc.'s (SA's) cost analysis for optimization of the system architecture.
- The approach is appropriate for the objectives outlined. The teaming is appropriate, as are the objectives. The specific high-level technical tasks fit the objectives, leading to solid contributions.
- Some modification may be appropriate for the actual technical evaluations.
- The project has a very logical breakdown of efforts covering stack, air, water, fuel, and thermal subsystems.
- The approach and goals are well organized and carefully adapted to the needs of fuel cell researchers and developers. The model and approach, based on publicly available materials and components that are considered to be state-of-the-art, are becoming more realistic and in line with industry expectations every year. The use of the outcomes for cost analysis (FC-018) is therefore valuable. However, ANL should analyze the sensibility of fuel cell system architecture itself. Original equipment manufacturer (OEM) systems are not unique.
- The underlying task of this project is to create a computer-based simulation (a "model") of a hypothetical polymer electrolyte membrane (PEM) fuel cell system, given detailed and authoritative data on the behavior of its many components. This is a fine approach for gaining insight into the emergent behavior of the system as a whole and for the stated purposes of the project, which include gaining insight into

attainable technical targets and how the overall performance and cost of the system is affected by its individual parts—i.e., a sensitivity analysis. This can guide DOE toward focusing efforts on improving certain components in ways that could have the largest impact. Overall, the approach of the project, which assimilates large amounts of component-level data in an organized, thoughtful, and meaningful way, is well grounded.

- However, at various points, the presentation refers to the resultant model as "validated." The author may believe the model is "validated" because of the rigor in which the component-level data is vetted. Nonetheless, there is little or no evidence that the system model itself is "validated", i.e., that predictions of the model are tested against real-world data that are separate and independent of the data from which the model is built. While it is always difficult to know how accurate model predictions might be, the lack of "validation" in this sense means that it is even more difficult to judge how much weight (trust) one might ascribe to the many detailed estimates and predictions that are the outputs of the model here.

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

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

- The project has made excellent progress on investigations related to the NSTF catalyst, and the focus on cell-to-cell performance variability is excellent. Comparisons between PtNi and Pt provide valuable insights to the industry and the principal investigator (PI) is encouraged to begin making a broader assessment of additional catalyst materials, including variation of the supports where data is available.
- Very good progress has been made. ANL has demonstrated a significant amount of work looking at electrode variabilities, NSTF degradation, and Roots air supply system. Representative and best-in-class results have been introduced this year. NSTF degradation testing has been linked to fluoride emission rate (FER). Deeper understanding of mechanisms may be needed, and, in particular, the impact of the temperature should be studied.
- As presented, the results and progress are consistent with expectations for the project funding and overall magnitude of the project scope. The number of components, subsystems, and their interactions is overwhelming. The team did a good job prioritizing the evaluations.
- The project added an alternate catalyst (de-alloyed PtNi dispersed on carbon support) to the NSTF catalyst membrane electrode assembly [MEA]).
- The correlation between performance degradation and fluoride release rate (membrane degradation) was identified.
- The PI reported accomplishments over the past year, including analyses of stack performances with different catalyst systems, air management (compressors and expanders), water flow, and waste heat management. These all seem to be of genuine interest to collaborators and important to the Fuel Cells R&D sub-program overall. In each case, the project stands out as being "data driven," with many quantitative results (e.g., graphs). Nonetheless, these results may be most useful as qualitative comparisons among alternatives, rather than rigorous predictions of quantitative outcomes. \Tthe lack of explicit validation and a general lack of uncertainty analysis—i.e., propagating uncertainties from the underlying data through to the predictions of the model—is noted.
- There is good progress toward the end-of-life (EOL) analysis. This should continue to be the main focus; there is still a lot of work to be done. The investigators must not only consider EOL performance data from idealized experiments but also consider issues associated with system integration. Perhaps data from the National Renewable Energy Laboratory (NREL) contamination studies could be considered.
- In reference to slide 7, work on cell degradation and cell-to-cell performance variability could benefit from system-level experiments that use actual stacks to measure cell flow variations with manifold water accumulation. In reference to slide 17, it is not clear how much effort should be applied to studying NSTF when it appears this electrode approach is still far from meeting DOE targets. In reference to slides 18 and 19, it is not clear how much effort should be applied to studying the Roots compressor/expander because it appears this air management approach is still far from meeting DOE targets.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The collaboration among ANL, SA, component suppliers, OEMs, and laboratories is of high quality and enables ANL to build the model and provide key feedback to the partners. The coordination of the project also appears to be very good.
- The level of collaboration is good and well thought out with respect to the collaborators expertise. The feedback from the U.S. DRIVE Technical Teams and the partnerships with MEA suppliers is critical to the success of generating valuable data. The appropriate teams have been engaged to generate relevant data.
- This project is highly collaborative, both in the sourcing of component-level data for the model and in the demands for system-level analyses of varying alternatives. Slide 21 is representative.
- There is clearly a high degree of collaboration with other groups based on the data being fed into the project from the collaborators. However, the PI is encouraged to ensure that the process for the model is not to be a “simulation house” and to actively work on achieving adoption of the simulation software within the collaborator institutions. The collaborations include a cross-section of fuel cell stack level developers and fuel cell material/component developers, which provided an excellent backdrop for the applicability of the work in the project.
- This project leverages various collaborations and is supported by many in-kind works. Effective collaboration has been seen with the U.S. DRIVE Technical Teams.
- There is very strong collaboration with OEM partners. It is not clear if there are opportunities for incorporating the down-the-channel stack model being developed by Lawrence Berkeley National Laboratory.

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

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

- The impact of system modeling is potentially huge, and modeling has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives. The impact will be even greater when the model includes different components and different architectures. The dissemination of the modeling tools may also increase the impact, as it would allow developers to evaluate their new materials, components, or system architectures at an early stage. Validation of the model on a real system (e.g., using data from TV-001) would definitively enhance its impact.
- The model/simulation package will provide a very useful tool in evaluating a projected system cost for new materials and operational modes. This is a very important part of reaching the DOE targets from the perspective of down-selecting or targeting the efforts of other R&D projects. The use of this tool on material development projects as a final stage assessment of impact toward overall cost/performance is encouraged.
- This project is important to identify a technology direction and technology selection for the goal of automotive fuel cell systems.
- This project will be very impactful because of the team’s close collaboration with industrial partners.
- The impact of this project will be improved by describing the EOL performance of a fully integrated system.
- The PI’s tests and ultimate data collection and analyses are absolutely relevant. In particular, the degradation mechanisms and their impact on system performance and lifetime are highly relevant. However, it is not clear if there is a comprehensive understanding of the makeup of the MEA so that clear performance differences can be ascertained during performance testing and if using the test conditions with MEAs with different ionomer loadings or the like would potentially impact the “sweet spot” of performance for that given MEA. It is unclear if the gas diffusion layer (GDL) is the same in all tests or if there is a microporous layer. It is also unclear if the catalyst layer membrane interface is the same. Although these are details, they can impact performance and failure mode behavior. The percentage of polytetrafluoroethylene (PTFE) in the GDL is another issue. The humidity tests would be impacted by the

GDL and the microporous layer's PTFE content, as would the plate flow-field used. The FER tests are important and insightful. From prior published results, is it clear that all perfluorosulfonic acid membranes evolve F^- ions over the first 100 hours or so. It was not clear that any pre-preparatory or pre-operation period took place before measuring the F^- ion release rates. J. McElroy presented work in this area. Furthermore, if an ionomer is used in the electrode layer, it is not clear if F^- ions are released from this component. A long-hold at a specific V is not a degradation mechanism; it facilitates a degradation mechanism. The chemical or electrochemical degradation mechanism would be helpful to understand as a function of V. There appeared to be no data relative to stationary applications and/or operating conditions. They are different. Still, the tests on the various new catalyst systems are good and helpful to evaluate many aspects of their viability.

- Even with all the uncertainties, the system cost variability data are insightful.
- The relevance of this project arises from its ability to demonstrate a system-level impact of component-level changes. While this is a very useful, and indeed necessary capability to have within the DOE Hydrogen & Fuel Cell Program (the Program), it needs be understood that the model only provides estimates, not actual real-world results. Models are useful in that they allow alternatives to be explored without the time and expense of building physical systems, but ultimately physical systems need to be constructed to bear out the predictions of the model, and to refine it. Also, while analytical models may illuminate areas where technology innovations would be most needed or are the most successful, in and of themselves they do not create new innovations.

Question 5: Proposed future work

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

- The proposed future work (slide 22) seems appropriate and well balanced, although the reviewer offers a caution. The future work includes analyses of both system performance and manufacturing costs. This project has, as its strength, the ability to model system performance. Other projects (e.g., FC-018) are perhaps better optimized for modelling manufacturing costs. Therefore, the future work should be more heavily weighted toward performance analyses.
- The proposed work is in line with the objectives of the project. It is important not to focus on a given MEA and instead introduce alternate MEAs with advanced alloy catalysts. Introduction of bipolar plates and flow fields for low-pressure drops, uniform air/fuel distribution, and low cell-to-stack performance differentials are appreciated. Predictive degradation models might be introduced to reduce experimental testing.
- The future plans seem reasonable, but it is not clear how much of this project's activities should be coupled to NSTF electrode development and Eaton's Roots compressor/expander.
- The future work is appropriate as long as there are inputs from the partners. Further refinement of the tests without changing the relevance or direction will provide valuable data overall. The tests on the catalysts and related performance should remain a high priority.
- The proposed work addressed a wide cross-section of important areas. However, it may be too aggressive depending on the resources in the project.

Project strengths:

- The model appears quite complete and takes into account many mechanisms involved in the operation of a fuel cell system. The parallel cost estimation with SA is appreciated. Another strength is the high level of collaboration with other institutions and various suppliers, which facilitate the study of each subsystem/material performance and cost.
- The validated fuel cell system model and collaboration of Autonomie, cost model, and U.S. DRIVE Technical Teams are all project strengths. The availability of data from the DOE project and industry partners (in-kind) bases is another strength.
- Comprehensive tools and analyses on relevant components and test hardware are in place and being utilized. The team's qualifications are a project strength. It sounds like there is a good level of communication with the partners.

- The project has excellent collaboration activities and a highly relevant system-level analysis from an industry perspective. The focus on trade-offs and new material ensures the project is aligned with the current research direction and system-level configuration needs.
- The strength of this project arises from its ability to demonstrate a system-level impact of component-level changes. This helps enable the Program to keep an eye on the big picture, rather than just a lot of technical minutia.
- The project has great collaboration and a relevant model.
- The modeling represents the latest developments in application-scale technology.

Project weaknesses:

- This is a project with a broad scope and with many variables to take into consideration. This is not a weakness, but it adds to the difficulty of testing the appropriate components, conditions, etc. to yield valuable data. The team needs to stay focused and closely aligned with its partners to keep such an effort from turning into a "weakness" by testing scenarios unrelated to the primary task.
- The team may be devoting too much effort to understanding the performance of components that are not fully vetted at the subsystem level.
- The model relies on performance and durability validation data that lack consensus. It is recommended that these validation datasets be cross-checked with literature and other OEMs. In some cases, the electrodes being used are not optimized. Additionally, system-level mitigation strategies should be incorporated in the durability experiments. In many cases, the patent literature is a good source for determining these methods.
- The team relies too much on the GCTool fuel cell system model. The recent fuel cell stack and system shows higher performance by improving stack architecture, including flow field configurations. It is beyond a non-dimensional model.
- The main weakness of this project is the lack of experimental validation on a real stack or system. As mentioned during the presentation, the investigated system does not exist today, even if it were to be assembled. The data on performance and durability rely on 50 cm^2 single cell testing.
- It is hard to know the actual predictive power of the model (the GCTool), i.e., the uncertainties of its predictions. It is recommended that the team not refer to the model as "validated" unless systematic validation efforts are added to the project.
- The project is considering the durability considerations in system analysis, and it is not clear what mechanisms of durability are included in the model. More effort should be made to provide a high-level overview of the included physics (transport and kinetic) and the required data inputs for the model to allow a more detailed assessment of what is "under the hood."
- The statistical variation of the component properties is also an area of discussion that was not addressed in the cell-to-cell performance variability. Both operational and material sensitivities are important from a cell-to-cell variability perspective, and it would be ideal to understand the impact of both, especially given the fact that the project scope includes future work on assessing implications of high-volume manufacturing.

Recommendations for additions/deletions to project scope:

- Continue to focus on EOL and system-level tradeoffs.
- Consider scaling back NSTF and Eaton collaborations until these components are closer to meeting their individual targets.
- The model should be validated against stack data and system data. As it may be difficult due to intellectual property issues, one option might be to use a system design from the first car generation in TV-001 and to compare the results from the model and the "on the road" driving data assessed by NREL. Regarding stacks, some representative automotive stacks are "available" (see FC-021) for characterization.
- It is suggested that the team input the benchmark information of the latest high-performance automotive fuel cell system, such as Toyota's Mirai fuel cell electric vehicle.
- It could be a time to reconsider the use of GCTool for fuel cell system model. It is basically a non-dimensional model and does not simulate performance and operating conditions with the fuel cell stack architecture (flow field design, etc.). Toyota's latest fuel cell system in the vehicle showed significantly higher performance at the high current density region that leads to a cost reduction. Also, it has no

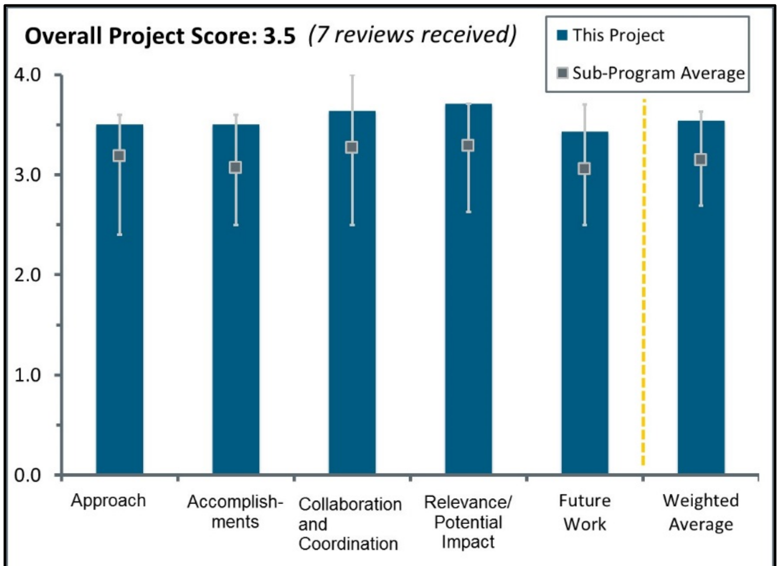
humidifier. Consider the alternate fuel cell model, e.g., the stack model to cover the implication of stack architecture.
- Use of de-alloyed PtNi needs a system mitigation strategy in the fuel cell system, because the instability of catalyst material (support) at the high half-cell potential.

Project # FC-018: Fuel Cell Vehicle and Bus Cost Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:

The objectives of this project are to (1) project a future cost of automotive and bus fuel cell systems at high manufacturing rates, (2) identify low-cost pathways to achieve the U.S. Department of Energy (DOE) 2020 goal of \$40/kW_{net} (automotive) at 500,000 systems per year, (3) focus on low-volume production (1,000–5,000 systems/year) and near-term applications, and (4) identify fuel cell system cost drivers to facilitate Fuel Cell Technologies Office programmatic decisions.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

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

- The overall purpose of this project is to develop the knowledge base from which to derive rigorous and detailed cost estimates for the production (manufacturing) of fuel cell systems. This bridges the gap from the understanding of what is technically possible to the understanding of what is economically feasible—that is, what has a realistic chance of being adopted in the marketplace. This approach is vital for maintaining the relevance of the fuel cell research program. More specific to the project itself, its approach is to review technological advances and to map their production steps into a Design for Manufacturing and Assembly (DFMA) framework. This is a fine approach to achieve the goals.
- This is one of the most focused projects in the portfolio. The cost analysis is based on current cell and stack data and system analyses. Very frequent input from stakeholders keeps the approach fresh and timely.
- This approach has been vetted over a number of years and is as good as it has been in the past.
- The analysis methods used are good, and the principal investigator (PI) is responsive to good suggestions.
- The design of the study is very methodical and is valuable for being such a detailed study. However, it would help if there were some guidance or interpretation on taking the findings and applying them. In particular, publications from the project seem to analyze a specific system design. Guidelines for determining costs for other, perhaps similar, systems would be helpful to the community. For example, for the design of an 80 kW system, there should be a discussion of the applicable vehicle platforms and how the costs (at the vehicle level in particular) may vary for vehicle classes that are larger or smaller. The system-level discussion is also particularly useful to elucidate the linearity or nonlinearity of variation in and between the components.

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

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

- The project's technical accomplishments this year were focused on new analyses of alternative catalyst systems, air handling systems (compressors and/or expanders), and various manufacturing approaches for bipolar plates.

- This cost analysis is based on recent data and analysis and guides DOE efforts to reduce cost. The cost analysis is frequently updated to incorporate the latest findings. The 2015 analysis covered lower production volumes.
- The project has completed the cost estimate for the current year of technology status.
- The accomplishments for this year focused heavily on crossover points at which one manufacturing technology becomes favorable over another. This was helpful to demonstrating the limitations of various options, but it also left open significant questions about which options may be more likely, especially when disparities were large at low volumes but not as large at high volumes. Perhaps further industry collaboration, particularly receiving feedback related to these messages, will provide value to the project and help solidify the total system cost projections.
- Additional areas for potentially lowering manufacturing costs have been identified. Feedback from the 2014 review was incorporated to include lower-volume projections. Some potential cost improvement is shown, but progress toward DOE goals is limited.
- Good progress has been made this past year, but even more could have been done. Also, it is not clear why most, if not all, of the future work shown on slide 21 could not have already been done, as the project has plenty of funding relative to the schedule (i.e., there is a question about why the pace of the work is not faster).

Question 3: Collaboration and coordination with other institutions

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

- There is significant collaboration across DOE, the national laboratories, and industry. The project is also seeking to include Toyota. This work also links to other DOE work, including Los Alamos National Laboratory's polyaniline research.
- The list of collaborators is long and broad. In addition to ongoing baseline system cost analysis, Strategic Analysis, Inc. (SA) provides cost analysis for PIs working on specific components such as compressors or bipolar plates.
- This project is highly collaborative, particularly in the development of detailed manufacturing data.
- This project makes good use of relationships and information provided by industry suppliers.
- SA does seek out industry input when it takes on modeling a new process, which helps make the results reasonably realistic.
- There seems to be heavy industry collaboration to verify the assumed costs, processes, and so forth, but the collaboration did not seem to receive as much attention as expected. Also, the list of collaborators seemed to be limited to only those directly involved in this year's accomplishments. While there is logic in that, it would have been helpful also to provide a more comprehensive list to discuss the collaborations for all system components. Additionally, it would be useful for the study to reach out to policymakers to help determine additional useful outputs that this study could provide. It is clearly a wealth of information, but it does not seem yet to be presented or disseminated in ways that will directly address challenges faced by policymakers.

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

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

- The Fuel Cells sub-program needs to set cost targets for stack systems that are competitive with internal combustion engines. This project provides an analytical framework to determine where and how cost reductions might be achieved and to demonstrate program progress with respect to the cost targets. This project provides ongoing insight into where high costs are, helping DOE apply resources logically and intelligently.
- This project is key to helping the DOE sub-program prioritize what should be done to further reduce costs. It is also the type of project that can be done only with DOE funding (i.e., industry is unlikely to share cost modeling results publicly).

- Results show slow advancement to lower automotive production cost. The analysis of cost breakout at differing volumes is useful to both DOE and industry.
- The volume of production appears to be higher than would be realistic in any relevant time frame. Manufacturing volumes of up to 500,000 units per year per original equipment manufacturer (OEM) is unreasonably high. More focus should be made in regard to the reasonable expected volume of production per OEM, for example, by looking at the market share of each major OEM and project volumes of sales as a fraction of common product lines. Perhaps volume data could be extracted from the Polk database*)*. This effort of analysis is done to help guide research and development targets and development. In communicating with OEMs, it is important to ask directly what areas of technology need improvement in the public domain.
- The point made during the presentation that this work helps elucidate the areas in which research may be needed to meet DOE cost targets was particularly effective. It would be helpful for the research to identify or at least suggest options for getting the current-status $43/kW down to the DOE $40/kW goal. This could have been a valuable output that was not presented.

Question 5: Proposed future work

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

- The future work seems well aligned with Hydrogen and Fuel Cells Program needs, including further analysis of low-volume production costs, further analysis of emerging component technologies, and further analysis of a bus fuel cell system.
- All of the work listed on slide 21 is good.
- The project will perform a cost comparison of catalyst preparation methods. Several cell, stack, and/or system components will be costed.
- Buses remain a large potential future market, and the limited modeling systems may inhibit the value of this work to the market.
- It is particularly curious that hydrogen storage is left out of the project, unless it was implied in the general balance of plant (although it did not appear in the sub-bullets). Having an entirely complete analysis of the entire fuel cell electric vehicle's (FCEV's) system and components will be much more valuable than an analysis that covers 95% of the vehicle's systems. Also, a look into how these costs might change based on vehicle platform (which may be implied by the baseline sensitivity analysis) would be extremely valuable.

Project strengths:

- The detailed and methodical analysis utilized at all levels of the analysis is exemplary. It clearly requires varied expertise and significant coordination with manufacturers and other researchers to pull this information together in a way that it can all be informative within a single framework. This is a major accomplishment and possibly the project's greatest strength. Additionally, the project does seem to be appropriately responsive to new developments, looking to provide answers for projected costs of some technologies that are much newer and may be more difficult to analyze.
- The project provides a systematic and effective framework for providing cost projections and for analysis of how costs can be reduced.
- This project incorporates learning and feedback into future work and is very focused on finding the lowest-cost components and assessing more state-of-the-art options. Incorporating the impact of manufacturing volumes is valuable.
- In addition to cost analysis, SA evaluates manufacturing approaches for applicability to fuel cell components.
- Including a more detailed analysis of low-volume cost projections is an excellent addition.

Project weaknesses:

- As with all modeling projects, there is always a risk that the model will diverge from reality in ways that are not readily apparent. Therefore, validation against known systems should be an important part of the project. The PI indicated intent to perform a comparison with the ENE FARM Panasonic stationary fuel cell systems and to do some benchmarking against the Toyota Mirai. This is to be encouraged.

- It will be difficult to accomplish the program objective with feedback and input from only one automotive OEM.
- The weakness of the project really lies in its transferability. It is not immediately clear how others outside DOE could best take advantage of the results of this study. The value for the DOE is clear, in determining progress to targets and potential paths. However, the wealth of information developed by this project likely has much broader application if it is appropriately brought to bear on other questions, such as the likely costs of fleets of varied vehicles (state or national), costs of implementation of policies and regulations, and so forth. This does seem a little outside the project's stated scope, but it seems close enough and a great opportunity to make the best use of the work.
- The biggest weakness of this project is that it does not have any benchmarking with current prices of actual fuel cells. This study seems to be operating in a parallel universe, and although it is rigorously grounded in its calculations, there has never been any kind of a reality check. Such a benchmarking would greatly enhance the believability of the project's results.
- The model does not seem to account for improvements in performance and potential reduction and/or increase in weight. If a component is taken out of the system, weight would be reduced, and the car would need less power, less hydrogen storage, and so on. Compounding effects like that can have major impacts.
- The project does not address how early-market PEM fuel cell products (e.g., forklift trucks and telecommunications power) may affect costs for road vehicles in low volumes (i.e., initial introduction of FCEVs).

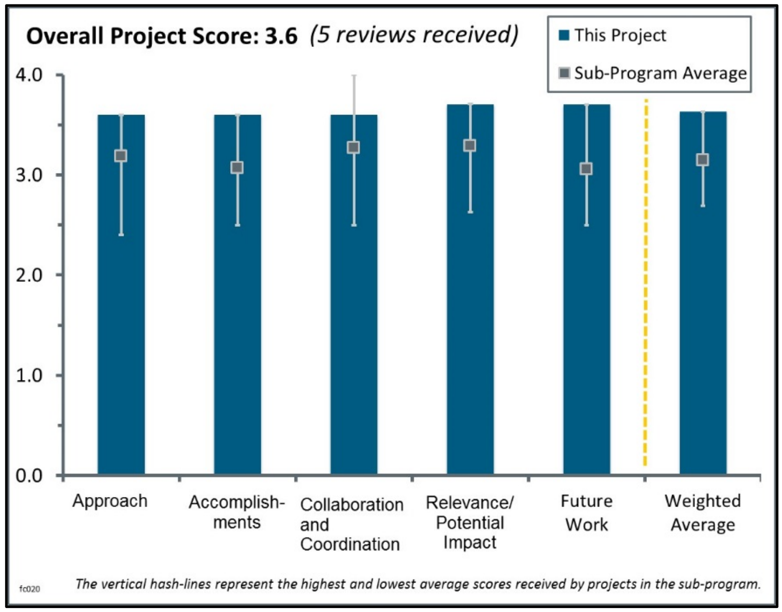
Recommendations for additions/deletions to project scope:

- Non-platinum-group-metal cost modeling should include the impact of the total kilowatts required for a vehicle that must utilize two stacks instead of just one. In other words, the system will need >80 kW to have performance equivalent to an 80 kW system that is significantly smaller and lighter. A cost analysis should be conducted using an estimation of what the early FCEVs are actually doing, as was shown on slides 16 and 17. This exercise could be an excellent verification of SA's low-volume cost projections. It would also be interesting to evaluate how the cost of these early FCEVs could be affected by various changes in key parameters (e.g., what the impact is of limiting peak temperature to 80°C). In addition, it may motivate changes in the current model constraints (e.g., it is not clear why the heat gain per temperature change ($Q/\Delta T$) is being held at 1.45 if a value of 2 is preferable for cost).
- The project should consider analyzing the known production supply chain. For example, if there are one or two suppliers of gas diffusion layers (GDLs), GDL cost could be estimated based off the total volume of that production. On the other hand, stack plates may be produced in one OEM per production line, yielding lower volume or production for that part of the fuel cell system.
- Now that Plug Power is manufacturing thousands of units, it would be nice to have some comparison of what this project's model suggests (hundreds of dollars per kilowatt) and what real fuel cell systems are selling for (thousands of dollars per kilowatt), with some explanation of the differences. It is difficult to understand why this has not already been done.
- Generalization of the results would be a good addition to the project scope. Instead of stating the analyzed base system and its cost, the project should, additionally, discuss what kind of vehicle this system likely represents, how the system and costs are likely to change for other vehicle classes and/or platforms (even if just in a representative sense for the class), or perhaps how the component and system costs vary with major design decisions (such as power output or degree of hybridization).
- It would be nice to be able to run costs as a function of platinum cost, understanding that platinum cost is variable.
- Toyota and/or other automotive OEMs should be added to make sure this work is aligned with industry, not behind it.

Project # FC-020: Characterization of Fuel Cell Materials

Karren More; Oak Ridge National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) identify, develop, and optimize novel high-resolution imaging and compositional/chemical analysis techniques and unique specimen preparation methodologies for the micro- to Angstrom-scale characterization of materials composing fuel cell membrane electrode assemblies (MEAs); (2) understand fundamental relationships between MEA material constituents and correlate these data with stability and performance as per guidance/input from the broad fuel cell community; and (3) integrate microstructural characterization within other U.S. Department of Energy (DOE) projects.

Question 1: Approach to performing the work

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

- The principal investigator's project and approach is to develop and apply state-of-the-art electron microscopy techniques in the service of the Hydrogen and Fuel Cells Program (the Program). In other words, the approach of this project is to establish unique expertise in using electron microscopy to measure and characterize what is happening in fuel cell components at the atomic level. The work is outstanding and well integrated into the Program as demonstrated, in part, by the fact that both the Program Director and the Team Leader for the Fuel Cell Technologies Office's (FCTO's) Fuel Cells sub-program drew from the accomplishments of this project in their plenary talks.
- This is a critical capability for the development of fuel cells because the microstructural characterization of catalysts layers and critical interfaces allow a true scientific understanding of the real problems that still need to be solved in these devices. Because of this, it enables the fuel cell community to develop more durable and more highly performing devices. The project is very well integrated into the portfolio of DOE projects.
- The project implementation and development of microscopy is excellent.
- The proposed approach is appropriate because it is collaborative with numerous partners and aims to benefit the entire fuel cell community by providing a better understanding of materials evolution in the MEA components. This ongoing characterization project without milestones is also appropriate—as long as the work is following the community's needs—because it supports other DOE projects and provides the fuel cell community with access to state-of-the-art microscopic capabilities.
- The project's characterization really helps the fuel cell community in general. It is encouraged to work with more partners to explore more innovative ideas outside national laboratories.

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

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

- This was a very productive year, which focused on catalysts, catalyst supports, and ionomer thin films. For example, the project demonstrated that electron microscopy can map ionomer distribution by using the fluorine on the ionomer to provide contrast, and thus clearly diagnose the dispersion of ionomer in relationship to the microscopic particles of catalyst.
- The Oak Ridge National Laboratory microscopy team continues to develop critical morphological information for all partners. As usual, a huge amount of data has been collected and disseminated to partners using state-of-the-art transmission electron microscopy (TEM) techniques.
- The project remains as productive as in the previous years. The team has made excellent progress with characterizing the ionomer layer while overcoming some practical limitations related to sample preparation and characterization of operating conditions. This progress has been used to investigate deeper into the ionomer distribution and how its degradation depends on the catalyst layers. Still, some uncertainties arise:
    - It is not clear whether there is any explanation for these agglomerate formations depending on given conditions (e.g., carbon support nature). The importance of the ink preparation process in avoiding it is also unclear.
    - It is not clear whether these observations were enough to build a bridge between the ionomer distribution and the associated performance or the active area.
    - It is not clear whether the unchanged ionomer distribution on Pt/low surface area carbon catalyst layer is reproducible or whether it is linked to the given materials and the investigated testing conditions.
    - In the case in which there is strong carbon corrosion, it is not clear whether the catalyst layer becomes compact and stops working. The added value of looking at the ionomer is not clear.
    - Regarding slide 16, it is not clear whether the protocol of ink preparation with graphene is well mastered or whether it needs to be improved.
- The microscopic characterization indeed helps to understand the catalyst, support, and ionomer degradation. The team may need to further correlate other surface properties to its microscopic morphology characterization.
- While this project has gone a long way to answer many questions, it has done so using a very specialized set of tools. There should be more tie-in to more sample averaged techniques, such as x-ray diffraction (XRD) for particle sizes, porosities for pore sizes, nuclear magnetic resonance (NMR) or others for Nafion particle sizes, etc.

Question 3: Collaboration and coordination with other institutions

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

- This project is highly collaborative, with service to the fuel cell community being one of its missions. The collaboration enables it to more quickly meet the project targets. International collaboration is very positive. As an example, the work with the French Alternative Energies and Atomic Energy Commission on energy-dispersive X-ray spectroscopy map microscopic analysis on ionomer dispersion has been widely used this year.
- The project has an excellent set of collaborators, including universities, national laboratories, industrial laboratories, component manufacturers, and original equipment manufacturers. The facility is open to additional collaborations, so this area of the project also continues to improve.
- This project is inherently collaborative in that its purpose is to develop analytic capability while relying on other researchers to provide material samples for testing and study. The many partners and collaborators with this project are summarized on slide 2 and slide 5.
- It has collaborated with many partners. It should work with them deeply.

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

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

- Understanding fundamental relationships between microstructure over the range scales and performance is of the highest importance to making any progress in the commercialization of fuel cells.
- This is an extremely relevant project and is critical to advancing technology toward the goals of the FCTO Multi-Year Research, Demonstration, and Development Plan.
- In order to improve fuel cell durability, it is necessary to first understand the behavior and durability of the components at a microscopic (indeed, atomic) level. This project brings such diagnostics into the Program.
- If the DOE goals are dissemination of expertise, there should be some mechanism to transfer the techniques to the community at large (e.g., protocols of samples preparation).
- The project has good relevance but just needs to have more impact.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- The future work is right on the money. The fuel cell community absolutely needs more information about where the ionomer is in the catalyst layer, and more work on non-platinum-group-metal (PGM) catalysts and hetero-atom substituted carbons that could help the community understand how these emerging materials will work is always going to be important.
- The proposed future work, as outlined on slide 21, is an appropriate blend of follow-up to previous work (e.g., continuing development of tomographic techniques) and new research with new collaborations (e.g., improving the understanding of non-PGM catalysts).
- The proposed future work is appropriate. Studies on ionomer distribution and degradation should continue with an emphasis on understanding the correlation between ionomer and MEA performances. Close collaboration with FC-127 (Borup) is encouraged. These observations should be performed on different materials (e.g., carbon support, catalyst supplier, and ink preparation protocol) in order to differentiate what is general from what is specific to a given electrode.
- Electron tomography development and application are a good way to reveal catalysts, ionomers, and their interfaces.

Project strengths:

- The project has good national and international collaborations and provides a valuable and continuous service to the fuel cell community. The project offers excellent characterization capabilities and expertise in the fuel cell materials.
- This project is a stable source of technical excellence and helps to buttress many aspects of the Program.
- Cutting-edge development and implementation of electron microscopy to MEAs are project strengths.
- Projects strengths include the state-of-the-art microscopy applied to real problems in fuel cell science and engineering.
- The team has very strong characterization skills.

Project weaknesses:

- This project has no particular weaknesses.
- No weaknesses were specifically identified.
- There should be more tie-in to more sample-averaged techniques, such as XRD for particle sizes, porosimetry for pore sizes, and NMR or others for Nafion particle sizes. Also, a user-accessible database for distributing the data would be helpful.
- The team does not have enough understanding of the impacts of the surface property changes on performance.

Recommendations for additions/deletions to project scope:

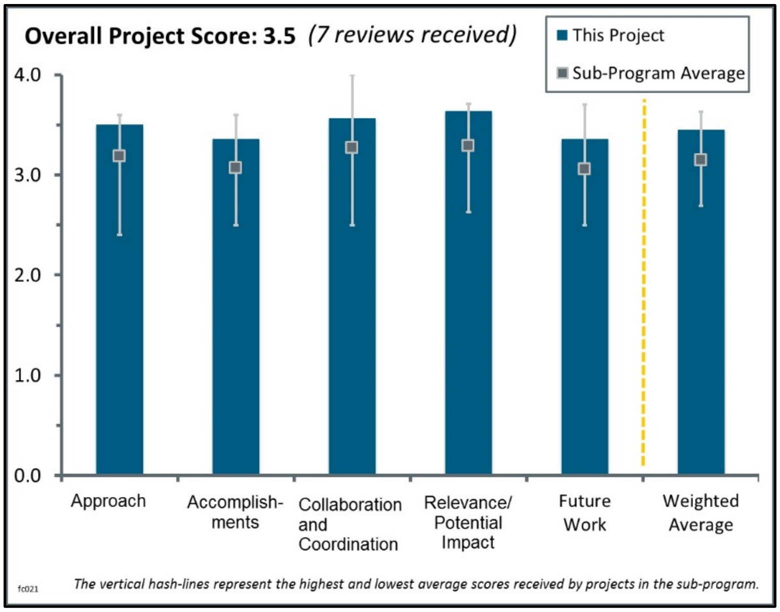
- There should be more tie-in to more sample-averaged techniques, such as XRD for particle sizes, porosimetry for pore sizes, and NMR or others for Nafion particle sizes. Perhaps a set of “representative” MEA samples can be analyzed to address MEA manufacturer comments on the structure of the MEA used in Nafion analysis.
- More in situ characterization of catalysts is recommended.

Project # FC-021: Neutron Imaging Study of the Water Transport in Operating Fuel Cells

Muhammad Arif; National Institute of Standards and Technology

Brief Summary of Project:

The objectives of this project are to (1) study water transport in single cells and stacks, (2) enable the fuel cell community to study water transport phenomena, (3) tailor neutron imaging to the needs of the fuel cell community, and (4) improve the spatial resolution to provide more detail of the water content in commercial membrane electrode assemblies (MEAs).



Question 1: Approach to performing the work

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

- The National Institute of Standards and Technology (NIST) project for neutron imaging studies of water transport addresses a key performance issue for fuel cells—water management. Water management also has a large impact on cost and durability. The approach (i.e., to maintain a national user facility, develop and maintain fuel cell testing infrastructure, and pursue improvements in resolution) is effective, and the project is sharply focused on addressing fuel cell issues. The project is cost effective for the U.S. Department of Energy (DOE), with a large portion of funding coming from NIST and industry; in addition, the project is leveraging work at the National Aeronautics and Space Administration (NASA) on Wolter optics. The new mail-in service should prove useful for groups that do not have the time or resources to send someone to NIST to run experiments.
- For low-temperature polymer electrolyte membrane fuel cells (PEMFCs), the management of liquid water remains one of the primary areas of concern on the cell and stack levels from the perspectives of both performance and durability. This project is sufficiently focused on providing the tools necessary for industry and academia to understand the distribution and amount of liquid phase present in an operating fuel cell. The approach to continually improve the spatial resolution is directly in line with the needs of the research community, given that an understanding of the water content in the membranes, catalyst layers, and microporous layers is critical for future progress.
- The NIST team has had, throughout the duration of the project, an excellent approach to providing and improving upon a valuable tool for the fuel cell community. As is expected for a characterization project, it is well integrated with the material and cell development and characterization efforts within the Fuel Cell R&D sub-program. The team’s approach of continually attempting to improve the resolution of the technique is excellent. In addition, their approach of making this valuable tool more accessible to the community by adding a sample mail-in service demonstrates their commitment to having an impact on the sub-program.
- Neutron imaging of fuel cells and components is a promising approach to image water in fuel cells in situ. This project is taking an excellent approach in developing fuel cells and understanding water transportation in single cells and stacks.
- The mail-in service will certainly save a lot of money and time for users. Continuing improvement in spatial resolution is great, too. The approach taken to try to address the current challenges in fuel cells, such as water and thermal management, is very effective.
- The approach is good and one of the primary pathways through which water in PEMFCs can be identified.
- The overall approach is good because neutron imaging is a key technique for fuel cell water visualization. The use of multiple techniques is a good direction, but it is not clear how much information will be gained

by the combined X-ray studies for cell studies; perhaps information will be gained for component ones, but that does not seem to be the focus.

- The need for better resolution is critical. The mail-in service is a nice idea, although not enough details are given, and it is not clear how much beamtime is dedicated to this service, who will run the actual experiments, and what type of real-time feedback is available.

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

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

- With the improvement in spatial resolution, actual stack size cells can be accommodated for imaging. The study of the thickness effect of non-platinum group metal (PGM) catalysts to understand er management is very helpful and insightful. The stack imaging experiment with Commissariat à l'énergie atomique was interesting.
- The mail-in service is a very good approach for users because it minimizes the time they spend at NIST. The work related to the non-PGM cathode thickness effects is very good and relevant. Also, the work related to water imaging in a stack is relevant and important. The work related to the neutron lens based on Wolter optics features a very good approach.
- NIST has added a sample mail-in service this year, which is a great benefit to the community and also reduces the cost to the Hydrogen and Fuel Cells Program of this capability, making an impact on fuel cell system development. NIST also added electrochemical impedance spectroscopy (EIS) and an environmental chamber this year, which are excellent added capabilities. Efforts this year in technique development focused on achieving less than 1 µ resolution, and excellent progress has been made. NIST is also adding capability of X-ray imaging.
- The new accomplishments, such as evaluating a full-size cell, are a step forward in approaching real systems.
- The addition of a large-scale test stand should prove beneficial. The first open user experiments to image a stack have been performed. Progress on the new high-resolution cold neutron imaging instrument, which would provide the ability to differentiate between water and ice, is good, and the facility is expected to be operational in July. Resolution improvements to 10 micron are expected by the end of 2017 and to 1 micron by the end of 2018. Acquisition time has been improved using high-resolution image intensifiers. Initial resolution was less than expected, but the vendor is working to correct the issue. The progress on increasing resolution using slit imaging is good, with improved gratings being prepared.
- Interesting work is presented, looking at the differences in water content using the NPGM cathode and the thickness effect. It would have been interesting to see these data with a baseline PGM cathode of similar thickness as a side-by-side comparison. The extraction of the thermal conductivity should be aligned with more detailed and fundamental approaches to ensure the methodology gives consistent results. It would be ideal to report on the progress of the path toward improved spatial resolution with a Gantt chart or a visual of the time frame expected for completion.
- It is tough to determine what is new in a lot of the presented work. Although this presentation is more for the facilities and technique, it would be good to see some aggregated data from the studies or findings that were enabled by the data.

Question 3: Collaboration and coordination with other institutions

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

- The collaborations are very good. Collaborations with NASA on the Wolter optics and Pusan National University in South Korea on preparing gratings have been essential for improving the resolution. Collaborations with General Motors, Los Alamos National Laboratory, and other users are apparent.
- The project features outstanding collaboration with NASA and the Massachusetts Institute of Technology to utilize their lens capabilities for the neutron microscope optics. Also, collaboration with colleagues in South Korea for improved gratings is noted. NIST continued its collaborative efforts with users in the fuel cell community.

- The project seems well coordinated and has excellent cooperation with relevant industrial partners, universities, and national laboratories.
- The project features excellent collaboration with academia, laboratories, and industry. The new mail-in service can be valuable.
- The project features excellent collaborations. NIST is a user facility. It would be good to see how collaborations impacted the findings.
- It would be good to include information regarding the proposal process for access to the facility and the tests that are planned or are in queue. Overall, the project has an extensive list of collaborators, and the focus is primarily on a “service-based” user facility model.
- An unusual number of partners were listed in the presentation. It is hard to gauge what each partner contributed.

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

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

- This project is critical to the Hydrogen and Fuel Cells Program (the Program) and has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives. Water management issues are key, and this facility is essential for providing in situ measurements to determine where the water is during fuel cell operation.
- Using neutron imaging to understand the water management and localized thermal conductivity can be impactful in designing or optimizing catalyst layers. Identifying the effect of channel geometry on thermal transport from cathode to anode is very insightful.
- The project is targeting the main challenges in fuel cell development: improving performance and durability and identifying water transport in single cells and stacks. Simultaneous in situ neutron/ X-ray analysis is unique -20 keV–90 keV is also a good area for water imaging.
- Water management is highly relevant, especially with the new issues experienced with high-activity, low-loaded catalysts that suffer from additional losses at high current densities.
- The relevance and impact of this work are excellent, based on the impact this characterization capability has on the Program and the fuel cell community.
- Neutron imaging is a critical technique for use in the fuel cell community. The impact of the actual studies is a bit hard to judge.

Question 5: Proposed future work

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

- The proposed future work to increase resolution is appropriate and will help to differentiate boundaries between the gas diffusion layer, catalyst layer, and membrane. Improved resolution will also allow greater resolution in time and provide more accurate determination of how changes in operating conditions affect water distribution. The proposed addition of simultaneous X-ray imaging should prove beneficial in correlating local aging and degradation with water content.
- The addition of EIS will be pretty helpful, and the proposed combined X-ray and neutron imaging will be very interesting because both the porous catalyst layers and water management can be studied simultaneously.
- Improving the resolution is an excellent idea and will lead to greater understanding of water management and identification of local water transport issues.
- Regarding the new high-resolution cold neutron imaging instrument: the goal to achieve a resolution of 1 micron by the end of 2018—but with extremely long exposure times (20 min for 1 micron resolution)—is only suitable for stationary phenomena, but it would still be unique.
- The impact of neutron imaging techniques on the Program is dependent on the resolution of the technique. NIST continues to work toward improving the resolution, and this is an important goal for all future work in this project.

- There is a need for higher spatial and temporal resolution. It seems that this is progressing, but the slides are quite similar to what has been presented before, and it is tough to see if the progress is on track. There are a lot of ways to improve the techniques.
- Information on the status of work completed related the new detectors should be included.

Project strengths:

- The ability to resolve ice and water will present significant value to automotive research and development activities. NIST facilities represent a significant focal point for diagnostics related to *in situ* water content analysis, and the use of the facilities by a broad cross-section of groups ensures a high impact of the work on the detectors and technique capability.
- Neutron imaging is a key technique for the community. Being able to measure water is important in understanding operating fuel cells..
- The project's strengths include its approach, NIST's expertise, its collaborations, and that 50 cm^2—stack-size cells can be accommodated.
- The project features a unique technique for identifying water in PEMFCs. It can be applied to full-scale platforms. Cells can now be mailed in.
- The project's strengths include the excellent research and good cooperation with industrial and institutional partners overseen by the project team.
- Strengths include the unique capabilities of NIST's neutron source and the leveraging of funds from NIST and work at NASA.

Project weaknesses:

- In actual fuel cell operation, water management issues are specific to a given flow field, which is typically proprietary. Although general water management can be understood, specifics for a real stack and a real cell cannot be extrapolated based on these data in subscale cells.
- The project should include a strategic plan on what the use of a higher resolution detector will allow from a fuel cell design activity and what type of processes could be quantified with the higher resolution capability.
- A target of 10 s exposure time with 10 microns resolution (to be achieved by 2017) is not short enough for really dynamic processes.
- The impact to the field is dependent on getting collaborations and key samples, as well as the results of the identified experiments.

Recommendations for additions/deletions to project scope:

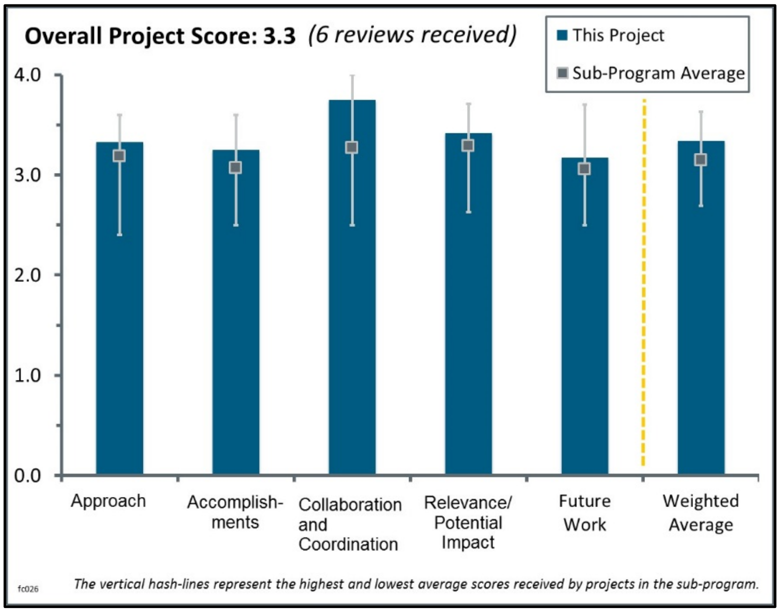
- The project should include a translation from water thickness into a value of local saturation within the MEA; this would make the data more translatable for use in analyses and provide better correlation to performance.
- It would be interesting to see the effect of MEA durability cycling on water management. Also, it would be interesting to compare neutron imaging to X-ray tomography of MEAs.
- At the given resolution, the need to image ice versus water is not required. It would be good to see more progress in size and time resolution.

Project # FC-026: Fuel Cell Fundamentals at Low and Subzero Temperatures

Adam Weber; Lawrence Berkeley National Laboratory

Brief Summary of Project:

The overall objectives of this project are to understand transport phenomena and water and thermal management at low and subzero temperatures using state-of-the-art materials and to elucidate the associated degradation mechanisms due to cold and cool operation. Lawrence Berkeley National Laboratory (LBNL) will (1) examine water management with thin-film catalyst layers, (2) examine water management and key phenomena in the various fuel cell components, and (3) enable optimization strategies to be developed to overcome observed bottlenecks.



Question 1: Approach to performing the work

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

- The approach is sharply focused on resolving durability and performance issues in polymer electrolyte membrane fuel cells employing very thin-film catalyst layers. The approach is well designed because it combines modeling tools and experimental validation in order to understand and mitigate degradation mechanisms caused by cold start and water management at low temperatures.
- The approach is good, and the work plan is thoughtfully distributed among the partners. State-of-the-art materials such as catalysts, ionomers, and gas diffusion layers (GDLs) are used for the study.
- The approach is well structured and includes analytical and modeling techniques that are well developed by this project and previous researchers to develop a thorough understanding of the phenomena. The work plan clearly identifies responsibilities of the organizations but does not identify the task that pulls all of the information together to explain the results of the experimental and modeling efforts. The deliverable should be identified.
- Transport-related barriers are clearly being addressed in a manner that is organized by a state-of-the-art model. However, durability is listed, and it was not apparent how this is being addressed or integrated in the model.
- The general approach of applying ex situ and in situ diagnostics to develop inputs for a cell model that is then applied to explain trends observed in operando is sound. However, there is risk in using conventional serpentine flow fields to develop fundamental data for modeling (e.g., slide 14). At high inlet relative humidity the channel U-bends will likely accumulate water, resulting in "short-circuiting" the flow through the GDL. A pure counter-flow flow field, such as that used by General Motors (GM) and Los Alamos National Laboratory (LANL), would be more appropriate for these experiments and more relevant to transport processes in automotive fuel cell hardware.
- Using adiabatic cell model for freeze start-up is not a practical way to model the cell in a stack. While the middle cell may be approximated as adiabatic when there is no coolant flow, the cells at the end are not adiabatic and are highly relevant for freeze starts. The approach should have contrasted the two extremes for a freeze start.

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

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

- Very good progress has been made toward understanding low-temperature performance of nanostructured thin film (NSTF), including catalyst layer resistances and ionomer mass-transport resistances at low loadings.
- The team has made solid progress on understanding the impact of various GDL/membrane properties on the performance of NSTF electrodes.
- The integration of GDL properties into the model and detailed evaluation of NSTF is very good.
- Great progress on several important issues was reported. However, the project has not yet revealed insights regarding NSTF electrodes during cold start. A fundamental description of limitations will enable developers to evaluate the feasibility of applied solutions. The team should continue to focus on interfaces.
- The accomplishments identify the methodologies to be used, and these methodologies have sufficient track records to lead to a successful project. The early modeling results suggest improvements in characterizing observed behaviors. There was no indication that wetting properties or contact angles of water droplets with GDL were considered. If it is assumed that the GDLs are completely wettable, this may not be a valid assumption at the anode. Measurements of catalyst uptake in thick catalyst layer by neutron imaging may not adequately describe the thin catalyst layer water uptake because of differences in porosity and pore size distribution. It is not clear how this is explained. Local catalyst layer resistance increases with lower Pt loading, which could be due to changes in the wettability of the catalyst layer. Pt is more wettable than carbon. If carbon does not have an oxide surface, it is not clear how wettable carbon is. There was no discussion from this perspective; the approach emphasizes electrochemical engineering but does not discuss chemical properties of the materials, unless it was somehow hidden in the analysis. For NSTF catalyst layers in which no carbon is present, it is not clear whether increased resistance would be due to limited “connected” paths in the catalyst layer. It is not clear whether this has this been considered. For a project that started in 2009, a more detailed analysis is expected.
- In regard to slide 14, there are concerns with using serpentine flow field segmented cell data for an along-the-channel model, especially for conditions with significant liquid water. Also, it is not clear whether any effort has been made to compare this model to that developed by the GM-led project that ended in 2014. The GM-led project also developed a publicly available database that could provide additional validation data. In regard to slide 16, it should be emphasized that the presentation of the data points is not indicative of the neutron imaging system’s effective spatial resolution but is based on the physical pixel size in the imaging hardware.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- There is strong collaboration. This project also organizes the transport working group, where a diverse group of stakeholders share their perspectives. This project has been very quick to integrate research needs identified by the working group.
- There is a very well-coordinated effort among LBNL, LANL, 3M, and the United Technologies Research Center.
- The project has a strong and diverse group, which now includes more involvement from automotive original equipment manufacturers to enhance the applicability of the research outcomes.
- An extremely strong team has been organized with expertise in most, if not all, of the critical areas that would lead to an understanding of water distribution in the cell.
- Collaboration among the team members is excellent and evident from the results.
- There is a very broad spectrum of collaborators. It is unclear what the major contribution of each team is.

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

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

- This work is excellent and pushing the envelope in understanding fuel cell transport processes. Also, it is very pleasing to see that a technology transfer activity has been included.
- The careful analysis of the contribution of different components to water management issues can help researchers develop mitigation strategies and avoid failures during NSTF operation at low temperatures.
- Understanding the water transport phenomena and water and thermal management at low and subzero temperatures is of prime importance. Different GDLs and ionomers are being used, but the NSTF catalyst system is being studied the most.
- If successful, the project should explain properties of the NSTF catalyst, but it is unclear whether this catalyst is characteristic of real-world catalysts.
- This project seems to be taking on all transport-related issues in fuel cell research. If the investigators continue to integrate current material advancements and fundamental understanding in their model, it will remain highly relevant. However, as the scope continues to increase, there is concern that too much is being attempted with limited resources. The quality of validation will define the lasting impact of this project, and good validation experiments are very tedious. It seems that most of the validation is represented by only a single experimental data set, and this is not sufficient.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Continued NSTF work is important, but shifting even more of the resources toward low-Pt electrodes of conventional design is encouraged.
- Investigation of traditional catalyst layer resistances at low catalyst loadings needs to be complemented by investigation of NSTF resistances.
- The proposed future work addresses the addition of traditional catalysts. Use of the model to determine critical parameters to guide the material development make more sense.
- The "Path Forward" slide identifies problems for NSTF compared to Pt/C systems. It is not clear what the mean pore diameter of the NSTF catalyst layers is.
- Understanding the cold and freeze start performance is critical to enabling the NSTF electrode. However, it is unclear from the proposed work whether the performance gap between conventional and NSTF electrodes can be closed. The team should at least exercise the model to define the parameter space wherein the low-temperature (<20°C) performance of NSTF electrodes are comparable to the traditional carbon-supported electrodes.
- Although it is difficult in a transport/modeling project, the investigators should attempt to define more specific metrics. Much of the future work is simply carried over from last year.

Project strengths:

- This project has a strong team that seeks input from the key stakeholders to remain relevant. The team is continuing to develop collaborations and sharing knowledge in the public domain.
- Project strengths include the very efficient combination of modeling tools, advanced materials diagnostics, and consultations with industry.
- This world-class team is clearly pushing the envelope on the fundamental understanding of fuel cell transport processes.
- Project strengths include the strong team and well-thought-out work plan. The project started focusing on the low-platinum-group-metal catalyst layer.
- Project strengths include the solid modeling and experimental team.
- The project has a strong team and is well funded.

Project weaknesses:

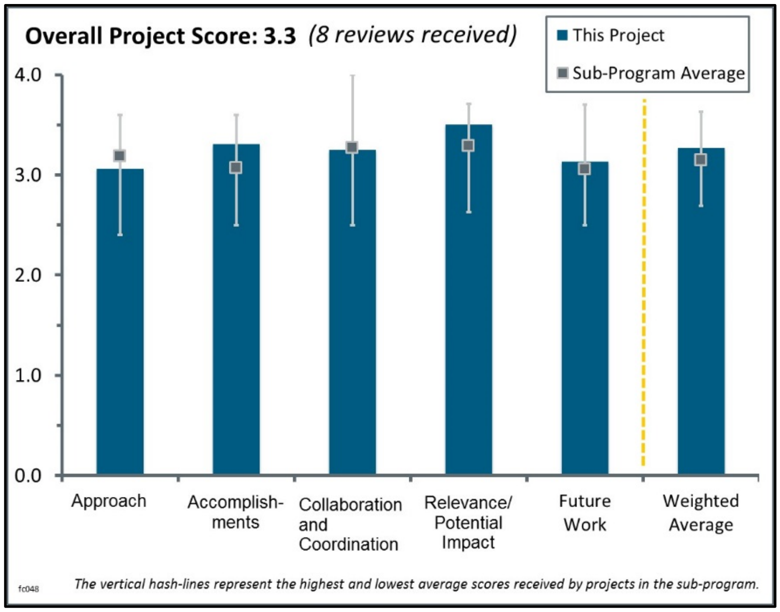
- The project should move away from conventional serpentine flow fields for experiments intended to resolve spatially varying phenomena.
- The project is focused mostly on NSTF. Other catalyst systems were not studied. The catalyst layer resistance is shown to increase with loading, which is expected, and for thinner catalyst layers, resistance increases a lot. However, nothing was mentioned regarding different supports/carbons in a catalyst layer with similar thicknesses. In addition, most of the state-of-the-art low-loading membrane electrode assemblies (MEAs) are shooting for 0.1 mg/cm^2 loading. It would be nice if the team could add this, too.
- The dependence on NSTF is a weakness. While the title says "Fuel Cell Fundamentals at Low and Subzero Temperatures," the work is focused on NSTF.
- The modeling lacks predictive capability.
- It seems that transport in the catalyst layer is the Achilles' heel for a robust model. Lack of validation methods may limit progress. Additionally, this project needs more focus on cell-level validation through parametric studies.
- After several years, there is no indication that the NSTF flooding issues are understood and can be resolved.

Recommendations for additions/deletions to project scope:

- The effect of loading on the catalyst layer is studied, but most of the state-of-the art low-loading MEAs are shooting for 0.1 mg/cm^2 loading. It would be nice if the team could add this, too. Also, it would be great if the team can perform similar studies for catalysts with different Pt weight percentages but similar Pt loading in MEA in mg/cm^2. Hence, Pt loading in MEA would be similar, but catalyst layer thickness would be different.
- The team should avoid work with thick catalyst layers; the results bring more questions than answers.
- The project should scale back more on the NSTF-focused work.

Project # FC-048: Effect of System Contaminants on Polymer Electrolyte Membrane Fuel Cell Performance and Durability

Huyen Dinh; National Renewable Energy Laboratory



Brief Summary of Project:

The objectives of this project are to (1) understand the extent to which fuel cell performance and durability are impacted by materials used in system balance of plant (BOP) components, (2) identify and quantify contaminants derived from BOP materials, (3) develop an understanding of fundamental degradation mechanisms and performance recoverability resulting from the presence of these system contaminants, and (4) be a resource to the fuel cell community by disseminating findings.

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The project followed through on the approach outlined in the previous year's future work to quantify leachates, study the effect of leaching parameters, perform mechanistic studies using organic and anionic compounds, and study the effect of both isolated and mixed contaminants. The approach establishes patterns and practices for future contaminant studies.
- One of the objectives of the work is to provide guidance to system developers for BOP material selection. This is solid and relevant work—the current Pt loadings in advanced fuel cell stacks have decreased significantly, so the impact of system contaminants needs to be studied. The selection of caprolactam and sulfate as two model compounds derived from structural plastics is a good approach because the insights obtained from fundamental studies involving these model compounds may be generalized to other compounds with similar functional groups.
- The proposed approach follows a well-thought-out, logical progression from developing identification/quantification procedures for organic contaminants to identifying the degradation products of common fuel cell system components and finally the effect of those degradation components on fuel cell performance and its ability to recover. The establishment and curation of a fuel cell contaminant database at the National Renewable Energy Laboratory (NREL) is an extremely useful tool for the fuel cell community at large. The types of materials and contaminants studied were down-selected with the help of General Motors (GM); however, it would be very useful to look at a broader range of plastics and materials, as well as at greases or sealing compounds commonly found in piping and fabrication, to identify other organic/inorganic materials that could have an impact. This project is slightly different than others that are directly aiming for specific U.S. Department of Energy (DOE) performance targets. For this project, the barriers listed are durability and cost, and technically these are not directly addressed. The results presented, however, will aid future informed/intelligent design of fuel cell components, leading to improved stack durability and lower cost.
- The strengths of the approach include the following: (1) the use of actual cell testing where possible; (2) the identification of model compounds that can represent numerous possible structural materials, assembly aids, or lubricants; (3) the decision to disseminate data on a website that is easy for development teams to use; (4) the consistent reporting of data with standard metrics (delta V1 and delta V2) that are comparable; (5) the use of low relative humidity (RH) operating conditions so that contaminant species are not easily washed away, creating "false positives"; and (6) the standard screening for which contaminants cause

recoverable losses and which cause non-recoverable losses. The use of leachant solutions to determine the appropriate concentration of model contaminants was appropriate. The use of an integral cell (based on stoich) allowed the researchers to encapsulate contamination at both high and low reactant concentrations at inlet and outlet of the cell, respectively, and it also allowed for the detection of mass transport losses. It may be interesting to take 1–2 contaminants and determine whether different cell temperatures would have a profound effect, or whether different gas concentration (hydrogen or oxygen) would also have an effect. The reported data for this year appear to be on 0.4 mgPt/cm^2 cathode catalyst layer loadings. Lower loadings would be preferred (lower loadings were used in past years, but not this past year). While 0.1 mgPt/cm^2 may be aggressive (close to target), a loading on the order of 0.2–0.3 mgPt/cm^2 would be preferred as a baseline versus 0.4 mgPt/cm^2. Pt loading needs to appear in the fuel cell performance plots shown on the NREL website.

- The approach is a survey of the effect on fuel cell performance of leachants from practical structural materials. The project features a direct study of fuel cell performance as well as other characterizations, such as voltammetry, rotating disk electrode (RDE) polarization curves, and quartz crystal microbalance and chromatographic techniques, to develop an understanding of both time dependence (exposure time and reversibility when exposure is removed in time) and the mechanism of leachant effects. Such an understanding is needed, mainly under conditions of normal use for fuel cells, but also during storage (at least 150°C as for batteries). The team may want to think more about extreme conditions to try to learn the effects of heat (e.g., on leaching rate and decomposition products from otherwise benign materials) and environmental conditions such as automotive exhaust, salt spray, etc. Developing a website on contaminants is a good idea.
- The approach is a good start at identifying contaminants that could impact performance. The assumption that standard original equipment manufacturer (OEM) plastics can be used with fuel cell power plants should be reevaluated. Furthermore, if a leachate is identified and shown to impact the performance, it is unclear why there is a need to study the degradation mechanism. The team should spend the time finding more suitable materials. The Japanese combined heat and power units have significant lifetime results. It would be good to know what materials they use. The value of the approach is good. Identifying potential chemical species in any of the subsystems is valuable. Setting up a fast screening approach would be invaluable. The team should not hold the current density at 0.2 A/cm^2—that is too low. The team should use 0.4 A/cm^2 or higher.
- The approach to identify leachate from materials used in fuel cell systems, and then dose them to an operating fuel cell, is good and showed a clear response from the fuel cell. However, it is a very slow and labor-intensive approach, and thus only two materials were studied. In reality, the number of materials that need to be examined is large and impractical to analyze using this approach. Perhaps a more rapid screening approach could be envisioned.
- The approach in pursuing the influence of contaminants on fuel cell performance is appropriate and is capable of addressing the main goals in this project. The choice of analytical techniques is adequate and is properly utilized throughout the project.

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

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

- One output from this project is the user-friendly and interactive website that contains a database of the contaminants studied by the team. The website provides a material screening tool that is a very good resource for system developers. The gas chromatography mass spectrometry (GCMS) method that the team developed to quantify the concentration of contaminants in the leachates allowed the team to obtain a range of concentrations that would serve as more realistic doses for future infusion experiments. More realistic doses of contaminants will provide more relevant information to system developers. The team has identified the major species in the two structural plastics—polyamide (PA) and polyphthalamide (PPA)—that have commercial relevance to automotive applications. This is good progress because the researchers have found that the less expensive material (i.e., PA) leaches out more contaminants. Without this kind of knowledge, system developers would almost certainly use the cheaper plastics in order to lower costs.

- This project is very well focused and executed to overcome major obstacles in fuel cell performance coming from the impurities that could be found in real systems. The principal investigator has demonstrated significant progress in identifying the contaminants that could be present and has made impressive effort in quantifying the correlation between impurities and performance. This project has a very important role in addressing the DOE mission, and findings from this report are a valuable asset for the stakeholders from industry and research institutions.
- To this point, this project has successfully accomplished many of its objectives, including development of an identification/quantification procedure for system component degradation products and their impact on fuel cell performance. Half-cell was used in combination with electrochemical quartz crystal microbalance (EQCM) to identify the specific adsorption of degradation components of plastics and ionomers. No specific interaction of the sulfonate component of perfluorosulfonic acid (PFSA) ionomer and membranes was found on Pt; this result is in contrast with much of the literature, and an explanation for this should be presented. Accomplishments to date are well in line with project goals.
- The results were clear—the causes and effects were directly noted in a meaningful way; for example, the effect of impurities on the main fuel cell reactions, hydrogen oxidation and oxygen reduction, was measured as a function of impurity concentration and exposure time, both in a fuel cell and using ex situ techniques such as RDE.
- The project did a very good job of distinguishing whether contamination was associated with high-frequency resistance increases, which is intended to be indicative of membrane contamination. For PPA, PA, and caprolactam, there did not appear to be a loss of more than 6 mV (or less) at 0.2 A/cm^2. The project was responsive to prior feedback that low contamination at low cell RH should be studied. This should have prevented washout of contaminants. The lack of voltage loss with exposure of 10 mM H_2SO_4 prompted considerable discussion. The project team used methods that relied on a liquid carrier (infusion or EQCM), and some suggestions were made that more harmful contaminants would not be water soluble. That said, the project team did attempt to observe contamination from longer chain molecules that contain sulfonic acid groups. EQCM showed little effect by a chain with a sulfonic acid group alone, but it showed an additive effect of the sulfonic acid group when combined with a carboxylic acid group in the same molecule.
- The project team identified major organics in leachates and developed GCMS methods to quantify concentrations, demonstrating that solid phase micro-extraction can be used to observe trace species. There was speculation that caprolactam was contaminating the ionomer; it would have been nice to see more concrete evidence via model x-ray photoelectron spectroscopy (XPS) studies or similar methods. The team showed interactions between individual leachates, with the surprise finding that the presence of sulfate actually reduces the deleterious effects of caprolactam. It was not entirely clear why membrane degradation compounds were being studied—the project seemed focused on contaminants originating from the BOP.
- The overall progress and accomplishments are good, especially the ability to identify the leachates. The ability to see the impact on an electrode is good. Identifying chemical species is challenging. Knowing the percentage of leachates not identified but present would also be of value. Contributing to the NREL website is very positive. It is not clear whether PFSA is the membrane or the ionomer, or both. The impact of fluoride ion or fluorine-containing polymer fragments on electrode performance is also unclear. Few (side chain) sulfonic acid degradation issues were seen.
- Only two materials were studied from two suppliers. The same materials from other suppliers could have different impacts on the fuel cell system.

Question 3: Collaboration and coordination with other institutions

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

- The project is one of the better projects in the DOE portfolio for reflecting a spirit of collaboration. First of all, the project team collaborated with an automotive OEM (GM) in order to obtain an understanding of which materials are relevant, and, therefore, which contaminants are relevant. Second, the project has been highly responsive to reviewer feedback, particularly feedback to study sulfates and sulfonic acid groups and to use low RH conditions. The collaboration with the Colorado School of Mines (CSM) was seen from the EQCM data. These data showed the effect of membrane degradation products that were difficult to analyze under fuel cell conditions. This collaboration assisted with understanding why sulfuric acid did not have an effect on cell performance, but other membrane degradation products would, especially some containing sulfonic acid groups. 3M provided membrane degradation products for the CSM collaboration. Some added background would be useful to help reviewers understand whether these degradation products would be the ones expected under GM drive cycle conditions.

- The involvement of GM ensures that the contaminants being investigated are relevant to automotive fuel cells. GM's involvement also makes the contaminant concentrations used in the infusion experiments relevant and reliable.
- Collaboration with partners, including GM and 3M, has been integral to the successful progression of the project to this point.
- Collaborations in this project are well executed and coordinated between GM, CSM, and NREL.
- The collaboration and coordination is consistent with the magnitude of the effort. Teaming with GM is a positive.
- The team leverages academia, such as Ryan Richards of CSM; materials suppliers, such as 3M, for samples; and end users, such as GM, for advice. There was more information about these collaborations in the archived slides than in the oral presentation, but it is clear there are adequate inputs about contaminants from many points of view.
- There is good engagement with current partners, including industrial partners at 3M and GM. The project would benefit from increased interaction with other industrial partners and OEMs.
- The presenters only assumed the parts per million (ppm) level of contamination introduced into the fuel cell. In the spirit of collaboration with GM, the authors should analyze the inlet of a real fuel cell system using the suspect materials and see what the ppm level of contamination is in a real fuel cell system.

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

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

- This project is very important because the performance gains obtained in other DOE-funded projects, such as low Pt loading and advanced Pt alloy catalysts, may be negated if system contaminants degrade fuel cell performance and durability significantly. With the findings from this project, performance degradation due to contaminants may be avoided.
- The team is focused on meeting the needs of the Hydrogen and Fuel Cells Program (the Program) and will advance progress by avoiding materials that can lead to poor performance of fuel cells. It will also avoid diversions in making progress on performance development. "Real" performance can be masked, since real-world fuel cell performance is dominated by the effects of contaminants leaching either from structural materials or from the environment.
- Attempts to achieve system-level specific power targets prompt the investigation of lightweight materials that may not be compatible with the fuel cell stack. The same is true with respect to meeting system cost targets. Results of the predecessor project (funded from 2009 to 2013) have yielded a website that has become useful to developers and has helped to reduce the time needed to research answers to material selection questions. While contamination-related lifetime limitations are rarely addressed publicly, because of competitive concerns (unlike matters such as carbon corrosion, Pt dissolution, etc.), the practical reality is that these limitations can be encountered within a vehicle program, and having a general resource available to address contamination can be helpful in ways that DOE may never consider.
- This work is extremely relevant. It is important in clearly understanding long life objectives, cost, performance, etc.
- The goals and results of this work align well with the objectives of DOE and the Program. With the majority of research and development focusing on membrane electrode assembly (MEA) and stack development, little effort is focused on addressing the impact and interaction with the components that make up the balance of systems. Identification of the detrimental effects of some of the compounds that make up those components is of critical importance for addressing the longevity of the polymer electrolyte membrane (PEM) fuel cell. What is missing is a more comprehensive survey of potential balance of systems components and development of strategies to either remove or mitigate their impact on fuel cell performance.

- This project already made progress toward the DOE goals by listing accomplishments that provide important guidelines for developers in addressing the DOE technical targets.
- Over the course of the project, a variety of contaminants have been studied and information has been disseminated via the website. This year, advanced methodologies were introduced for identifying and quantifying organic and anionic contaminants that could be utilized by the broader community. Ongoing use and development of the website should be tracked and reported in future reviews.
- The relationship to actual operating fuel cell systems is not clear. As shown on slide 8, it is not clear that exposing 1 ml of deionized (DI) water to 1.5 cm^2 of sample material for 1,000 hours at 90°C has a reliably known relationship to the dosing level of contaminant used during fuel cell tests. For example, in a real system using the studied material, in 1,000 hours, it could be that 10,000 ml of DI water passed the 1.5 cm^2 surface of the sample material, not 1 ml. Therefore, the contamination level in the actual fuel cell inlet could be 10,000 times less than the presenter used in the dosing level for the fuel cell tests. The authors should measure the real ppm level of air inlet contamination in an operating fuel cell system when using the evaluated materials; one suspects it could be much, much lower than the authors used in the dosing experiments. It is not clear how long this level of contamination exists in a real fuel cell, and whether it is confined to the first 100 hours of life. The relationship of where the material is used in the system and the resulting level of contamination is missing. Instead of reporting the cell voltage response to contaminants, the authors should present power output reduction at a fixed cell voltage.

Question 5: Proposed future work

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

- The proposed future work is well aligned with the progress made in this fiscal year and will continue to make progress toward DOE goals.
- Understanding the underlying mechanisms of how the contaminants impact fuel cell performance, particularly possible contaminant-ionomer interactions, is of high importance.
- Lower Pt loading is mentioned in the future work, which is needed. The direction with advanced catalysts is consistent with developments in the rest of the DOE portfolio. To be further consistent with the portfolio, it may be helpful to include 3M polyfluoroimid acid (PFIA) fragments, as well as contaminant effects on PFIA. The directions to look at the effects on ionomer in catalyst layers, and to look at volatiles that evolve from structural materials, are good. Because species such as PtNi likely affect catalyst layer ionomer, it would be wise not to neglect this effect.. Volatiles may come from materials other than structural materials as well. More emphasis on operating conditions may be useful, particularly with respect to temperature and reactant gas concentrations. More studies varying RH are also recommended. High current density and mass transport losses due to contamination appear to have been deemphasized in this year's presentation. Some attention should still be paid to contaminants that might limit performance by changing the surface energy of porous media in the cell.
- Performing mechanistic studies on mixtures of model compounds is a good extension of the work done this fiscal year. In the actual fuel cell system, the contaminants will be mixtures of different species, so findings and insights from these studies will be more relevant to OEMs and system developers. Studying the effect of contaminants on low Pt loading electrodes and advanced alloy catalysts is also a natural extension of the work because these catalysts may be more susceptible to organic contaminants. Also, because it is known that OEMs are actively working on low Pt loadings for their next-generation fuel cell stacks (~0.1 to 0.2 mg/cm^2 Pt), these types of studies would provide timely and relevant information.
- The proposed future work appears sufficient and addresses the interaction of different compounds as well as their effect on loading-optimized MEAs and catalyst layer ionomer. Expanded survey of materials and potential leachates, as well as the impact of water quality, would be helpful. It would also be useful to provide some insight into the development of contaminant mitigation and recovery strategies.
- Overall the future plans are good, but before worrying mixtures, the team may want to consider the effects of extreme conditions to try to learn the effects of heat (on leaching rate and decomposition products from otherwise benign materials) and environmental conditions such as automotive exhaust, salt spray, etc.
- The proposed work is good. The team should consider focusing more on the identification process and the impact on performance than the mechanistic studies.

- A more direct relationship between materials used and their impact in a real fuel cell system should be included. For example, even for the materials studied in this project, it is not clear whether these materials could be used in the fuel cell system at different locations where the impact could be much less or none.

Project strengths:

- The project is responsive to reviewer feedback—it addressed low RH conditions and the possible role of sulfonic acid group or sulfate poisoning, and it used diagnostic techniques such as electrochemical impedance spectroscopy to distinguish ohmic losses from kinetic losses. The project uses consistent metrics (delta V1 and delta V2) to derive consistent comparisons between contaminants for both the time period during which contamination occurs and during recovery. The project has disseminated data in a fashion that is immediately useful to developers. The website can be accessed quickly and is user friendly.
- The dissemination of research findings via NREL's updated website is excellent. This will help system developers in designing BOP components and avoiding fuel cell performance degradation. Insights obtained from the team's fundamental studies may be generalized to other plastics/components with similar functional groups.
- The project successfully developed highly sensitive and quantitative analytical tools for the identification of potential contaminants as well as their direct impact on PEM fuel cell performance. Another project strength is the development and curation of the contaminants database, which is a very useful resource for the fuel cell community at large.
- Project strengths include the well-balanced approach, well-chosen and efficient team work, and systematic evaluation of contaminants.
- The project has done well in developing methods and tools for studying and quantifying BOP contaminants that can be utilized in future studies.
- The project features good teaming and a good methodology for studying the effects of contaminants, and it is systematic.
- The project features a good team, and there is excellent analytical equipment available.
- The project features good analytical tools and analyses. The team is good, including the partners. The team has good electrochemical knowledge. Focusing on the "model" compounds is a good start from a process perspective. It may become a weakness, however, if a broader approach is not taken. Leachates should be identified and tested, but not over-studied.

Project weaknesses:

- The baseline cathode catalyst layer loading of 0.4 mg Pt/cm^2 is still too high. Although the project attempts to use ex situ means with model compounds to address contaminants that may not be water soluble, there is still an open question about what water-insoluble contaminants might be able to do to a fuel cell if there was some way that they would enter the cell. Assignment of contaminant effects on cyclic voltammetry features are often attributed to the contaminant, but there may be some possibility that the contaminant could itself degrade or cause other materials to degrade, which would then lead to the features noted. The project could use greater emphasis on high current phenomena.
- Not a lot of consideration is given to environmental effects such as heat, ambient environment, etc. interacting with the system. For example, heating during storage of a fuel cell can decompose materials, accelerating leaching and even decomposing materials to make contaminants; some environmental materials, such as salt, can ion exchange with membranes, causing a drop in conductivity and poisoning catalysts.
- The project has a limited scope that is focused on only two potential contamination compounds. It is unclear why sulfonate appears not to adsorb. Previous half-cell studies have shown very clear evidence for the adsorption of sulfonate from Nafion onto Pt.
- The project lacks specific mitigation strategies for dealing with contaminants. The focus has become too narrow, with only two contaminants used in this study.
- This could be a huge project with significant value. The team needs to focus on the right materials or the scope may become a weakness.
- The relationship to a real fuel cell system is missing,
- The list of contaminants could be expanded.

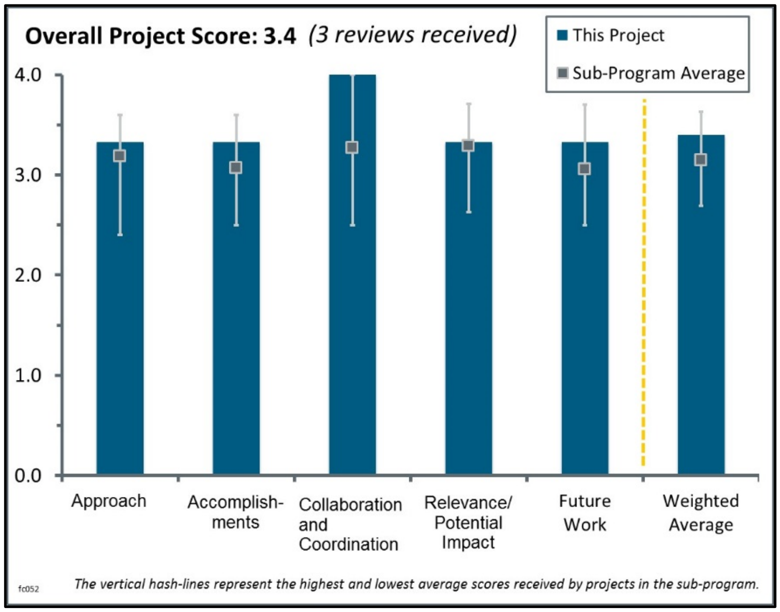
Recommendations for additions/deletions to project scope:

- The team should (1) increase its emphasis on high current phenomena; (2) use limiting current techniques to understand mass transport losses imposed by a contaminant; (3) study contamination effects on advanced catalysts; (4) study contamination effects derived from the breakdown of PFIA membranes or other advanced membranes from the portfolio; (5) study volatile or water-insoluble contaminants; and (6) study all contaminants at greater range of operating conditions, including temperature, reactant gas concentrations, and RH. The team should remove the 0.4 $mgPt/cm^2$ cathode catalyst layer loading and replace it with a lower baseline loading.
- Limiting current measurements in single cells should also be performed in order to determine the effect, if any, of the contaminants on the pressure-independent gas transport resistance, as reported in recent GM, Toyota, and Nissan papers on oxygen gas transport resistance in the cathode. The team should also investigate and report the effect of contaminants on the proton resistance in the cathode in the near future.
- The project team should mainly consider the interaction of the environment—such as heat, salt, etc.—on decomposing materials and leachants from these materials to make poisons that affect fuel cell performance. The team should look at the effect of free sulfate on the anode ($H_2 + H_2SO_4$ yields elemental sulfur, a poison to Pt catalysts).
- The researchers should determine the effect of different sources and qualities of water. They should expand analysis to include a larger library of materials and compounds. They should also develop contamination mitigation strategies and/or methodologies for faster and more complete recovery.
- Considering the project's relevance and systematic approach in addressing the barriers, it would be very useful to include chloride anions to the list of contaminants.
- Adding input from more fuel cell developers to the project would increase the range, depth, and overall impact of the work on the fuel cell community.
- The team should identify, analysis, test, develop a database for leachants, and then move on. The team should not over-study the "whys" in this specific project.
- The project's weaknesses could be mitigated by closer interaction with GM.

Project # FC-052: Technical Assistance to Developers

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:



Los Alamos National Laboratory (LANL) will test catalyst materials and participate in the further development and validation of single-cell design and test protocols. LANL will also provide technical assistance to working groups, the U.S. Council for Automotive Research (USCAR), and the USCAR/U.S. DRIVE Partnership Fuel Cell Technical Team.

Question 1: Approach to performing the work

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

- This work is an excellent initiative by the U.S. Department of Energy (DOE) and LANL that provides a mechanism where developers (e.g., start-up companies and academic laboratories) can take advantage of LANL's technical expertise and fuel cell research equipment/capabilities.
- The mechanism for applying for consideration is straightforward and involves submitting a formal request to DOE and LANL.
- A mechanism is in place to protect the confidential information/intellectual property of the organization seeking technical assistance.
- It is apparent that LANL used sound technical approaches in the tasks it executed in support of fuel cell developers.
- The issue of "Approach" is not relevant here in some respects because LANL essentially responds to the Fuel Cell Technologies Office's requests. However, LANL's approaches to each of the tasks assigned do seem appropriate.

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

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

- LANL was able to assist several developers with various studies. For example, institutions such as Pajarito Powder (a start-up company), Indiana University – Purdue University Indianapolis (IUPUI) (an academic institution), and Argonne National Laboratory (ANL) (a premier national laboratory working on advanced fuel cell catalysts) have sought assistance with membrane electrode assembly (MEA) testing of their materials. The project has also helped an original equipment manufacturer (Ford) in its efforts to sputter-deposit Pt onto powder substrates (using LANL's vacuum deposition system).
- Particularly noteworthy is the MEA testing of ANL's advanced PtNi nanoframe catalysts in this project, which shows the impact and usefulness of this technical assistance project. LANL has expertise in the fabrication and testing of MEAs, while ANL is known for its fundamental science and rotating disk electrode (RDE) testing expertise. Through this program, MEA data were generated using ANL's state-of-the-art nanoframe catalyst, an important step in validating the potential of these high-activity, novel catalysts.

- The team appears to have accomplished an impressive amount of work for the budget allocated. (Note: In collaborations with non-U.S. entities, it should be clearly stated that funding is also provided from these sources.)
- This is an extremely difficult project to assess on the basis of progress toward overall DOE goals. DOE made considerable investments at LANL over the past several years, and LANL has world-class facilities and capabilities. Using LANL in this technical support capacity is a great way of extracting further value from that investment. It is especially gratifying to see small businesses taking advantage of LANL’s capabilities in this project because it would otherwise be very difficult for them to do so.

Question 3: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- This project necessitates close collaboration and coordination with the institutions that require technical assistance, and from the quality and variety of results presented, it looks like there is good coordination between LANL and the organizations involved.
- This project, by definition, is collaborative in nature.

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

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

- This project may provide a way for organizations who are synthesizing high-activity, novel catalyst nanoparticles (e.g., shape-controlled octahedral alloy catalysts) to obtain reliable MEA performance data and not just rely on RDE testing. This project may also help entities who are actively working on new catalyst layer design/architecture using LANL’s x-ray tomography capabilities.
- LANL’s availability to assist, as needed, can have significant impact on certain projects.
- The potential impact is determined more by the impact of the projects that the program supports, rather than the program’s specific tasks. Assuming that LANL is supporting high-impact projects and is performing project-critical tasks, then the potential impact is high.

Question 5: Proposed future work

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

- LANL’s plans for currently defined efforts are sound.
- The future work is mostly extensions of the current collaborations. It would be good to see a report on the number of organizations that have formally requested assistance and the number of requests that were approved.

Project strengths:

- This work is an excellent initiative by DOE and LANL in providing a mechanism where developers (e.g., start-up companies and academic laboratories) can take advantage of LANL’s technical expertise and fuel cell research equipment/capabilities.
- This project leverages the world-class capabilities and facilities that have been established over several years of DOE investments.
- This project allows others to utilize and benefit significantly from LANL’s valuable capabilities.

Project weaknesses:

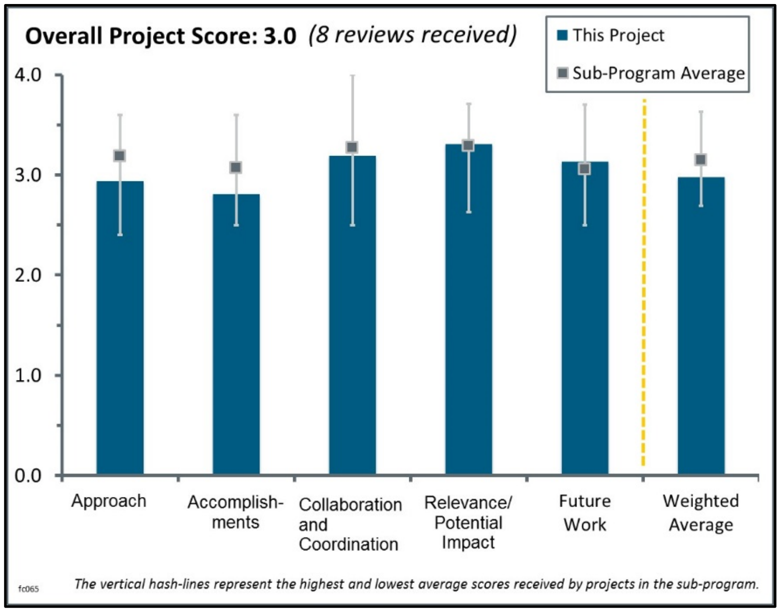
- *[No reviewers provided feedback.]*

Recommendations for additions/deletions to project scope:

- There are no recommendations from the technical side. From the managerial side, it might be a good idea to have the companies that receive LANL technical support complete a survey that assesses the quality of work performed by LANL and the value of this work to the recipient companies. Committing to this survey could be considered a prerequisite to obtaining the support. DOE (and LANL) should be tasked with working out the details of the survey (e.g., whether the survey should be designed and executed by DOE or LANL).
- The team should add Brookhaven National Laboratory's (BNL's) project (FC-126) to the list—to better understand why the air performance of its MEAs is poor.

Project # FC-065: The Effect of Airborne Contaminants on Fuel Cell Performance and Durability

Jean St-Pierre; Hawaii Natural Energy Institute



Brief Summary of Project:

The overall objectives of this project are (1) to identify and mitigate the airborne contaminants adversely impacting fuel cell system performance and durability and (2) to identify materials, design, operation, and maintenance recommendations to maximize performance. The FY15 project objective is to demonstrate mitigation for species that do not lead to a performance recovery by ceasing contaminant exposure.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The approach is well laid out; a Gantt chart describes the approach. The sequence of determining/characterizing the effect of various contaminants on the fuel cell performance, the long-term effects of the contaminant, and the effect of recovery methods (acidic or cleaning solution) is a reasonable approach to evaluate the poisoning effect. Furthermore, the coupling of contaminants (organic and cation) is very important because some effects may be magnifying while others may be dampening, and this will be key to understanding the real-world application scenarios.
- The approach, which uses a selection of contaminants based on probability of being in the air and the effect on membrane electrode assembly (MEA), is correct, particularly as it helps avoid overlap with air contaminants that have already been studied. The table indicating the rationale of the investigated species is appreciated. The systematic approach to identify and characterize potential airborne contaminants is correct. It will lead to an improved understanding of the types of poisoning and potential recovery methods. However, air contaminant mixtures should also have been investigated before the end of the project, as it is well known that not all effects are additive. Investigating the contamination effect on low Pt loading is appreciated. This effort shall guide not only MEA or system developers but also the development of advanced air filters.
- The approach in this project is well balanced with the milestones and effectively addresses fuel cell technical barriers and limitations that might originate from airborne contaminants.
- The approach is generally effective; the principal investigator (PI) is looking at the right class of materials. Nonetheless, it would be beneficial to see greater emphasis on the following:
    - Lower catalyst loadings relevant to current state-of-the-art and future directions (~0.1 mg/cm^2)
    - More focus on real-world contaminant levels (it is not clear if the mechanisms and recovery procedures are the same.)
    - Greater examination of contamination while under voltage cycling that is reflective of real-world operation.
- As a whole, the project has had an effective approach. However, the steps used to poison the MEA with Ca^{+2} are not comparable to how the MEA would be poisoned in real-world applications (especially utilizing a surfactant to help the Ca^{+2} ions penetrate the MEA and saturate the catalyst layer). This could have a large impact on where the Ca^{+2} ends up in the MEA and therefore on how the Ca^{+2} impacts performance. A method of exposure of the MEA to the impurity that is more similar to what would be expected in real-

world applications should be employed. Catalyst loadings have, for the most part, been high. More low-loading studies would be beneficial.

- The project focuses on studying air contaminants for fuel cells. This is clearly an area of merit but not one that has been critically limiting the technology to date, and therefore it is of limited impact. Additionally, the choice of eight specific contaminants has not been strongly justified, and in many cases, the proposed contaminants seem highly unlikely to be major concerns for fuel cell systems. The team also investigated recovery techniques that required difficult implementation (e.g., the addition of isopropanol) to be valuable in deployed systems. It is good to see a focus on low Pt loading.
- The approach used by the PI and his team is rather standard, following U.S. Department of Energy (DOE) and Fuel Cell Technical Team recommendations. Cells are subjected to individual contaminants, performance loss is determined, contaminant is removed, and finally the performance recovery and its degree are studied. While interesting from the point of view of determining performance loss under various conditions and proposing methods of (partial) performance recovery, the project falls short of providing understanding of the mechanism of processes behind the observed phenomena. That includes providing a convincing, science-based rationale for some of the recovery techniques used, e.g., the role of iso-propanol in the performance recovery after Ca^{+2} contamination.
- The work lacks depth and the deeper understanding of the mechanisms that the team is trying address. This may be due to the team trying to do too much or due to the team lacking the ability to draw deeper conclusions from its tests. The results shown do not indicate that a proper design of experiments was crafted or executed. Test parameters—such as acid concentration, time of exposure, and delivery point of exposure—had little to no variation, and no justification as to why the test parameters were chosen was given. In addition, little to no post mortem analysis was conducted to determine why the chosen techniques did not fully recover performance and what the mechanism behind the remaining unrecoverable losses was.

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

This project was rated **2.8** for its accomplishments and progress.

- The accomplishments made in this project are invaluable for further advancement of fuel cell technology. The project is very well executed with carefully chosen systems that complement previous projects related to contaminants. This funding cycle was particularly focused on the effect of contamination by Ca cations, and the problem was addressed by systematic evaluation of MEA performance with the addition of Ca, which was followed by acid wash and MEA performance recovery. In addition, long-term evaluation tests were performed in the presence of acetonitrile. The PI provided performance decay rates and contaminant tolerance limits that can serve as guidelines for fuel cell developers.
- This study has generally been effective in determining the effects of contaminants on fuel cell performance. The work is focused on two critical issues: durability and the ability to withstand environmental contaminants the fuel cells would come into contact with in the real world. Ionomer content could have an impact on how Ca^{+2} is distributed and its effect on performance. The effect of ionomer content in the catalyst layer on Ca^{+2} poisoning was not investigated. Mitigation strategies running under conditions where more water was being formed (rather than the relatively low current density operation point) would be of interest to see if Ca^{+2} is flushed out with operation. The PI looked at long-term tests with acetonitrile and showed decreased fluoride emission with acetonitrile present. Tests under voltage cycling conditions are of interest to compare with constant current measurements.
- There seemed to be less progress this year as compared to the previous; in part, this was due to recognized issues with dosing aqueous cation contaminants to the electrode/membrane. The project team did address some of previous year's reviewers' concerns (e.g., the 0.1 mg/cm^2 catalyst), but it still should get more emphasis.
- Some lead-in discussion of the cell hardware used in the project would be useful in understanding the relative levels of cell behavior. Based on the data and mechanism for Ca^{+2} poisoning, it would be ideal to present the transient data as the primary analysis rather than a "steady-state" curve, because it is not clear based on the data presented that the system has reached a "steady" behavior with the poisoning behavior. Essentially, it is unclear what the lower plateau level that the poisoned performance will reach is. The work

on acetonitrile is particularly interesting, and more work on the presence of additional Fenton's Reagent in the membrane would be relevant in the comment on radical scavenging.

- The team has performed well this year with its focus on the gas diffusion layer (GDL) effect on the Ca^{+2} effect and has made several guidelines and discoveries that will benefit the fuel cell community as a whole. However, the PI should have explained why there was a focus on Ca cation and if this species could be seen as a reference for cation contamination similar to how CO is seen to have a “Canary effect” on H_2 fuel quality. Regarding the GDL effect on Ca^{+2}, it is not clear if it is only a GDL effect or if the microporous layer is also involved. Perhaps the effect would be the same with catalyst-coated backing MEAs. Acidic flushing has some positive effect. Nevertheless, it might be difficult to implement it in a real system. Long-term contamination testing on a low Pt loading MEA is interesting if the investigated MEA is representative. The used MEA shows a huge degradation rate in reference conditions and, therefore, creates doubt regarding the reliability of the acetonitrile impact. The team should contact MEA producers providing state-of-the-art low Pt loading MEAs.
- The number of contaminants studied in the past year has been quite modest. Most of the attention has been focused on Ca^{+2} as an important contaminant of the ionomer. The role of acetonitrile in ionomer degradation has been the other focus area, as fewer data have been reported. The mitigation strategies used after the cation contamination have led to recovery of only partial performance.
- Efforts in past year were highly focused on Ca^{+2} and acetonitrile. Ca^{+2} as a divalent ion that could show up as a road deicer has some value, but specific tests did not give meaningful new insight into ionic contamination. Earlier work by Greszler et al., Kienitz et al., Mikkola et al., and/or Weber et al. (including models) exhibited much clearer fundamental understanding of ionic contamination and more detailed experimental studies delineating loss mechanisms and recovery. Acetonitrile has very limited interest in fuel cell systems as a contaminant because no data have been presented that suggests it is likely to be a specific exposure concern to fuel cell systems.
- Comments from last year’s reviewers have not been adequately addressed. The mechanisms are not fully understood. A quick check on fuelcelletc.com shows that MEAs with Pt loadings down to 0.03 mg/cm^2 are readily available for purchase. Only one approach for recovery of foreign cations was tried (adding sulfuric acid to the inlet stream). Although this showed some success at recovering fuel cell performance, this test is likely not a feasible option in functioning fuel cell electric vehicles (FCEVs). No other alternatives were suggested or attempted.

Question 3: Collaboration and coordination with other institutions

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

- Collaboration with project partners and with University of Connecticut (UConn) has been good. The Hawaii Natural Energy Institute has done a good job of collaborating with the fuel cell community as a whole to determine which contaminants to investigate.
- This project involves several collaborators outside the team of four organizations that are under the DOE contract. The “other collaborators” have well defined roles that benefit the research in the project and enhance its relevance to original equipment manufacturers (OEMs) and the fuel cell community in general.
- Collaborations are well coordinated and executed among the participants in this project.
- There are many organizations involved in this project, but the collaboration seems very good. Partners are well coordinated with the leading PI. In addition to OEMs, air filter manufacturers should be included in the project team.
- Collaboration with other groups is significant, and it is recommended that the team consider a few directed case studies based on upstream analysis and testing for a few selected collaborators and their field-based systems.
- The funded subcontractors are limited, with only UConn having a clearly defined role in the project as presented. The industrial consultants’ roles were not clearly defined. The team has been in the area of contaminant testing for some time and has external connections highlighted on the collaborators slide that do provide added value.
- It seems that most of the work described in this presentation was conducted by UConn, which is the team responsible for foreign cation research. There needs to be a better description of what parts of the team did what work over the last year.

- The team perhaps still needs more input from OEMs for recommendations on specific contaminants (and concentration levels) to focus efforts on. It is suggested that the team canvass the OEMs, if it has not already done so. The team may also need more input from fuel and fueling station suppliers.

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

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

- DOE technical targets would be effectively achieved by the findings and recommendations from this this project. Airborne contaminants are recognized as one of the major obstacles in fuel cell technology, considering the constant exposure of cathodes to the air. This project does not only quantify the effect of contaminants but also offers plausible solutions to overcome the suppressing effects on fuel cell performance.
- This project is in line with Fuel Cell Technologies Office (FCTO) goals as described in the FCTO Multi-Year Research, Demonstration, and Development Plan. The effect of airborne contaminants on fuel cell systems could potentially be a huge issue with the rollout of a fuel cell fleet with different contaminant effects depending on the location. It is at least as critical as fuel quality. The role of impurities in electrocatalysis is important and will be more important because the catalyst loading has to decrease to meet cost targets.
- The goal of understanding contamination effects on fuel cell performance and developing mitigation and recovery strategies is very important to the success of commercial FCEVs. The most important part of this project has been identifying which contaminants cause recoverable versus unrecoverable performance loss.
- Implementation of fuel cell power plants (automotive or stationary) will be subject to the local jurisdiction’s air quality, and the effect of the air quality will be a critical piece of the final market viability for the fuel cell system.
- The project is relevant and addresses DOE Hydrogen and Fuel Cells Program needs. Impurities studied are relevant and have been suggested by fuel cell industry representatives.
- Airborne contaminants are of significant relevance to enabling low-loaded, durable cathode catalysts and membranes. Understanding mechanisms, acceptable contamination levels (for filter requirements/design), mechanisms, and potential mitigation strategies is vital for competitive fuel cell commercialization.
- This research is relevant to DOE goals because it addresses one of the main challenges facing polymer electrolyte fuel cells for automotive applications. The impact has been moderate to date; proposed mitigation techniques seem to be either impractical (e.g., ex situ and take a very long time), partially effective, or both.
- Air contaminants (particularly those investigated in this project) have not been demonstrated as limiting elements to fuel cell deployment through cost, performance, or durability. The experimental results add incrementally to the knowledge base of the community in the area of contaminants. The project is rightfully focusing on low loadings capable of meeting DOE’s future targets but has not demonstrated any specific progress toward meeting any specific target.

Question 5: Proposed future work

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

- The project is approaching the end date. The proposed future work is appropriate to complete the project.
- Future work would continue to effectively address performance limitations that originate from airborne contaminants.
- The proposal to demonstrate successful mitigation of the impact of important airborne contaminants is a reasonable goal. The team has identified some experiments it is likely to try, but it does not have any backup plans if those approaches do not work. The team also needs a better and more thorough design of experiments to know what techniques will be most useful and that the techniques have been optimized to some degree.

- The amount and scope of proposed future work is adequate given the time left until the project's completion in December 2015.
- The mitigation strategies to be investigated have to be realistic regarding an embedded fuel cell system. Determining the impact of contaminant mixtures on low Pt loading cathode sounds good if the investigated mixtures are representative of severe environmental conditions. A rationale for that should be presented.
- The PI generally lays out the proper future work (lower platinum group metal loadings, contaminant concentrations, and mechanisms).
- The proposed future work is limited, as would be expected for a project nearing completion. The focus on the four "most important" air contaminants seems reasonable, but it is not clear what these are or the specific criteria used to determine them. It appears these four will be a subset of the eight presented, and these eight are not of the highest interest of different contaminants for consideration, because contamination concerns are a function of both the impact of a contaminant and its likelihood (and type of) exposure to the fuel cell. This project is reaching a logical endpoint in its study.
- A significant focus of the path forward should be mitigation strategies on the system or the MEA level. This work should be done directly in collaboration with an automotive application developer and a catalyst/MEA material developer. This focus will take the large amount of effort and data generated into this project and ensure that it culminates into a strategy to enhance the wider adoption of fuel cells in various applications.

Project strengths:

- The main strength is the approach to testing fuel cell performance with selected contaminants in a way that is complementary with already studied species. Other strengths include the following:
  - The obtained database of contaminants
  - The identification of electrochemical and chemical reaction pathways
  - The short-term publication of the results for the community
- Project strengths include the team's strong background in contaminants, history of performing related work, connections within the contaminants community, and the ability to bring in the U.S. Department of Defense to this specific area, as many of its concerns would be greater than DOE's concerns.
- Project strengths include good collaborations and a good effort to get industry input regarding which contaminants should be investigated.
- Project strengths include a well-balanced approach, a well-chosen and efficient team, and the systematic evaluation of contaminants.
- A large amount of data seems to have been collected. Tests provide a preliminary indication of which contaminants cause recoverable versus unrecoverable performance loss.
- The project is well laid out and systematic. The data collection covers a broad range of contaminants that are directly relevant to potential application locations. The data should be put out in a contamination guide or review paper as a go-to resource.
- The PI has a strong background in the subject. Ballard can supply the OEM perspective.

Project weaknesses:

- The team should work to extract kinetics and mechanisms so that the data are translatable into either system or MEA/unit cell level models. This would allow for projections, impacts, and trade-off analyses to be completed and would enable a better understanding of the cost of recovery procedures.
- The team needs access to consistent, reliable low-loaded state-of-the-art catalysts. The team needs greater input from the other OEMs regarding which contaminants are of greatest priority.
- A more thorough focus on the correlation between the oxygen reduction reaction (ORR) kinetics and contaminants is needed.
- Contaminants contained in this study have relatively low interest/relevance for primary fuel cell target applications. Fundamental understanding and insight gained from the work to date have not been as strong or complete as was desired/expected.
- Insufficient attention to the mechanism of performance loss and performance recovery is the main weakness of this project. That applies in particular to the impact of certain mitigation strategies, such as the

impact of acetonitrile, a known strong poison of Pt active sites through chemisorption, on the electrode kinetics.

- The project still needs to complete testing at low Pt loading on the cathode and, therefore, to link with other DOE projects. An investigation of the impact of contaminant mixtures is lacking, but will be integrated into the ongoing work. The mitigation strategies do not appear very realistic for implementation into a real system. First mitigation strategies may be validated in short stacks. There is no link with air filter manufacturers to relax the MEA constraints and to quantify the cast balance between robust MEAs and advanced air filters.
- Project weaknesses include a lack of deeper understanding, a lack of statistical analysis of results, and a lack of thoroughness and creativity in experimental techniques.

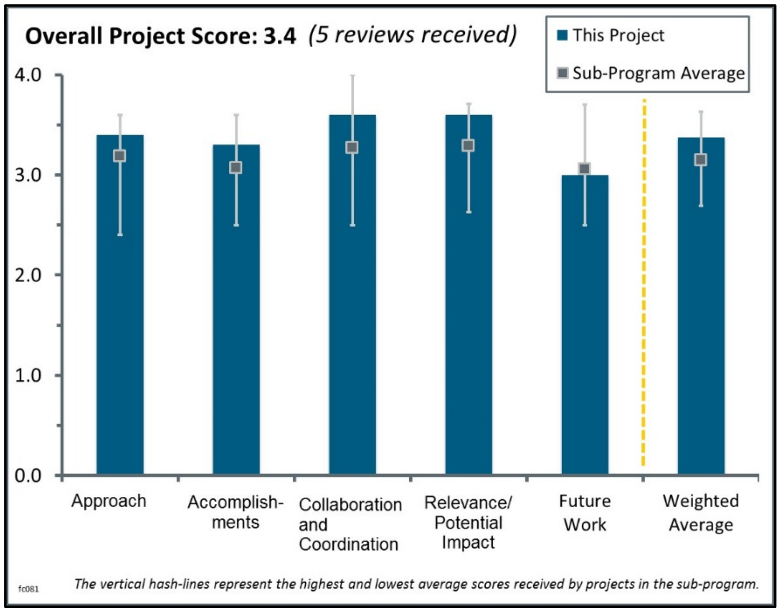
Recommendations for additions/deletions to project scope:

- The project is scheduled to end at the end of the calendar year; it is a logical place to end this specific effort.
- The PI could expand their evaluation of the impact that contaminants have on the ORR kinetics as well as the mechanism.
- It would be interesting to investigate if or how air contamination affects anode performance and durability. If it does, it is not clear what impact it might have on the fuel quality specification. Discussions between these two research groups on possible cross effects of air/fuel contaminants are encouraged.
- The team should add collaborations to system modeling design groups and unit cell/MEA level modeling groups. Additional focus on mechanisms and the extraction of exchange, reaction rates (kinetics), etc. would make the data and work more translatable for further work and use by other groups.
- More fundamental insight into the contamination mechanisms and, especially, into the recovery mechanism is strongly recommended. For example, there seems to be no understanding as to why acid treatment fails to result in full performance recovery after Ca^{+2} contamination. The catalyst performance loss in the presence of acetonitrile, which is entirely neglected in research to date, should be determined and weighed against the gains brought about by the reduction in the rate of polymer degradation.
- There should be less focus on cation work, which has been adequately covered in the existing literature.
- Studies into mitigation strategies need to be more thorough. Pre-test and post-mortem analysis of likely mechanisms of performance loss needs to be carried out. This should include measuring cell characteristics (such as exchange current density, Pt utilization, high frequency resistance, hydrogen crossover, and limiting current) before testing, after contamination, and after the recovery effort. In addition, these tests should be run at multiple fuel cell operating conditions because some fuel cells may operate differently under hot or cold and dry or wet conditions.

Project # FC-081: Fuel Cell Technology Status: Degradation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:



The fiscal year 2015 objectives of this project are to (1) receive and analyze new laboratory fuel cell durability data and (2) update and publish the durability results. The National Renewable Energy Laboratory will provide an independent assessment and status of state of the art in fuel cell durability for different applications by uniformly applying analysis methods to developers' voluntarily supplied data from laboratory testing.

Question 1: Approach to performing the work

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

- This project makes use of excellent statistical analysis to report what would otherwise be a scattered number of data reported by original equipment manufacturers (OEMs) in other non-technical forums. The project has found creative ways to deal with typical problems on how to report degradation, which is not an easy task, given the variety of definitions and design parameters currently present in the industry.
- The voluntary component is hampering the thoroughness of the analysis, though this is no fault of the principal investigators. It does, however, influence the impact of this project within the grand scheme of things. Good correlation between lab tests (time to 10% loss) and real-life durability lifetime is lacking. Long-term trend analysis may be able to project durability improvements to fuel cell systems over the years, perhaps even predicting near-future performance, which would be of benefit for investors in the fuel cell industry (including the U.S. Department of Energy [DOE]). On an individual level, the partners who voluntarily supply their data are rewarded with a good analysis of where they fit in the current competitive field, thereby stimulating industry participation.
- Though the generation of results has been dependent on voluntary OEM participation, there have been sufficient data generated for analysis. The only means of improving the approach appears to be if vehicle or test rig data were available for the DOE reference stack/system.
- This analysis is not so useful unless the performance and durability statistics are shown with technical information such as fuel cell system design/materials/system architectures. Getting meaningful technical information from fuel cell developers on a voluntary basis seems to be a limitation.

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

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

- In general, the project does not solve any particular material or design problem, but it does provide guidance as to whether the industry is on track and how far the industry is from the overall targets. This is key to DOE's understanding of where to direct money for specific projects that address degradation problems.
- The project supports progress toward project and general DOE goals—it speaks to status vs. targets and to general technology progression over the past few years.
- With the resources available, the project is effective.

- No significant updates have been seen since the last review (2013).

Question 3: Collaboration and coordination with other institutions

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

- There is very good collaboration with other institutions, as is evident in the data that are available only from external sources. The project is entirely dependent on external collaborations and data from other institutions.
- Asking OEMs for this type of data is no easy task, and the team was successful in convincing them to provide enough information to have a representative body of data.
- Within the limitation of access to technical information, this project seems to have good relationships with the fuel cell system developers providing information.
- The voluntary participation model may hamper the thoroughness of the evaluation and may even skew the results slightly if either the over- or under-performing systems are omitted.

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

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

- Long-term trend analysis may be able to project durability improvements to fuel cell systems over the years, perhaps even predicting near-future performance, which would be of benefit for investors in the fuel cell industry (including DOE). On an individual level, the (industrial?) partners who voluntarily supply their data are rewarded with a good analysis of where they fit in the current competitive field, thereby stimulating industry participation.
- Technical benchmarking is very important for commercialization of automotive fuel cells.
- Status against DOE targets is tracked with in-service data. Project assumptions for high volume are unrealistic based on the current state of the market and market growth.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Electrolyzer data will be very useful now that the focus in the fuel cell field has shifted to include the supply of hydrogen.
- Regarding the proposed future work listed by the principal investigator, it is not clear that the plan to "alternate between durability and cost/price" is necessary unless (1) the work load to get both types of data is too much for the current funding or (2) there is not enough information. Yearly updates are interesting in both areas. In addition, publishing a report on the cost analysis method is recommended.
- As the project relies on external data, future work is dependent on further developing collaborations, which may limit the scope of future work.

Project strengths:

- There is a neutral approach to collecting and publishing data that would otherwise be confidential and not accessible. The project also has a great statistical methodology.
- Valuable data analysis gives investors (industry partners and DOE) a good picture of the status in fuel cell durability. It seems this would be very helpful to the partners in evaluating their own positions within this field.
- The project provides real-world data, collecting information about the progress of the technology and providing overall progress guidance for DOE projects.
- The project analyzes the state of the fuel cell industry against the DOE targets for fuel cell technology from data provided by external collaborations.

- The relationship with fuel cell developers to receive technical information is good.

Project weaknesses:

- The data are grouped by application but not by technology. Information is not provided about the progress of each technology to meet the application needs. This is very important for DOE and commercial clients in technology selection.
- There is limited ability to receive technically meaningful information for performance and durability analysis. Any analysis of this kind without technical information about design/materials/system architecture is not useful.
- The fact that the data sharing is voluntary, combined with the fear of misplacement of confidential data, may lead to omission of valuable segments of the industry, which in turn may lead to inaccurate trends.
- Providing the data is voluntary, which limits the quantification of the results.

Recommendations for additions/deletions to project scope:

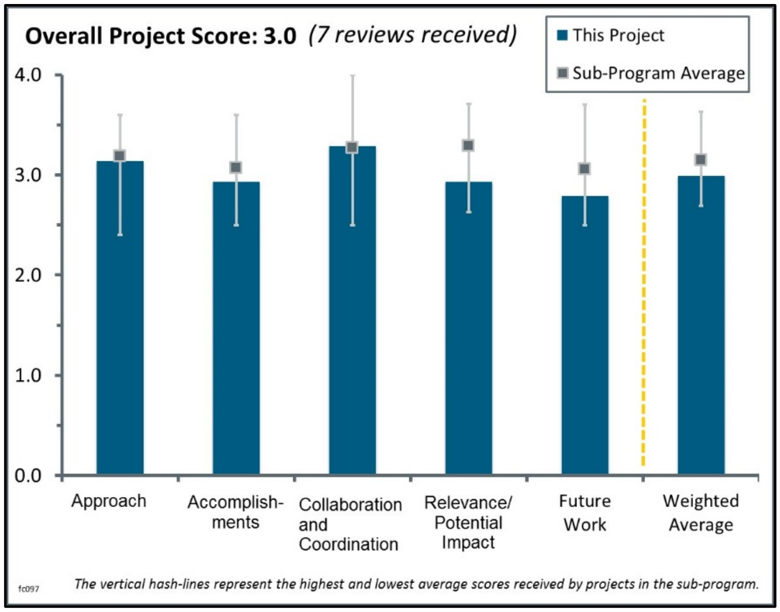
- The need for benchmarking is high. However, any analysis of performance and durability without technical information about design/materials/system architecture is not useful. Data acquisition on a voluntary basis shows critical limitations. It is suggested that this project change to a benchmarking project. Recently, two fuel cell vehicles were released to the market, and another fuel cell vehicle is supposed to be released shortly. Actual benchmarking on these vehicles would be able to show performance and durability with detailed technical information. Collaboration with U.S. DRIVE Partnership Technical Team is expected.
- Incentives (maybe even financial incentives) must be created so that OEMs will publish more data.
- Adding electrolyzers and reformate fuel cells to the analysis would be helpful.
- The project should break down the data into technologies for each application.

Project # FC-097: Stationary and Emerging Market Fuel Cell System Cost Analysis—Primary Power and Combined Heat and Power Applications

Vincent Contini; Battelle

Brief Summary of Project:

The overall objective of this project is to assist the U.S. Department of Energy (DOE) in developing fuel cell systems for stationary and emerging markets by developing independent model and cost estimates. The project goals are to (1) identify major contributors to fuel cell system cost; (2) quantify potential cost reduction based on technological improvements; (3) identify major contributors to fuel cell system manufacturing cost; (4) identify areas for manufacturing research and development (R&D) to improve quality and/or throughput; and (5) provide a basis for consideration of transition from other industries.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The researchers did a good job of addressing the makeup of many of the costs and attempted to project into the future based on the design for manufacture and assembly (DFMA) models. It is difficult to assess the overall accuracy of the DFMA model for out-year projections, and it would have been useful to see a discussion on how these were determined. Perhaps there is a comparable industry that has validated the cost reductions of volume manufacturing. It would have been good to see the cost of the catalyst backed out of the overall polymer electrolyte membrane (PEM) membrane electrode assembly (MEA) cost and an estimate of the value of platinum recovery added as a credit to see its impact on MEA cost. It is believed that more than 95% of platinum can be recovered. On a different topic, an essential element of customer acceptance is the cost after sales support and how quickly a unit can be repaired. An estimate is needed for mean time between failures and mean time to repair, as well as what the repair mode is (e.g., repair by replacement). Also needed is an estimate of how much the manufacturer cost for field tech support will be. This can be a huge cost. For example, a field call to commission an electrolyzer can cost more than $20,000. The project needs to include the hourly rate, cost of air travel, and per diem. It adds up fast. The key to overcoming this is to have a robust product that has been extensively tested before it is shipped. The project needs to allocate a significant warranty budget, especially for products that are early in their product cycles, as well as a budget for spare parts. The trend today, it seems, is to lay the cost of spare parts on the customer rather than the vendor. Manufacturers do not want a large spare parts inventory on their shelves. The penalty for the customer is long lead times for spare parts—the wait can be up to six weeks—which means the customer's system is out of action.
- Project barriers are well identified; project goals based off those barriers are feasible and use information and data from other participants.
- The conservative approach to production volumes is more realistic. The analysis includes operating costs in addition to manufacturing costs, and both grid-connected and grid-independent operation. It is not clear why the researchers designed their own system rather than operating and measuring the performance of existing commercial systems of various technologies and capacities.
- The project has a thorough and systematic organization of the manufacturing cost analysis from early evaluation of markets to development of system design, cost modeling, and analysis. A limitation could be

system design because Battelle has limited experience in the design of fuel cell systems and is dependent on original equipment manufacturers.

- The following is a list of items that stand out:
    - Batteries are used only in cases of black-start capability and off-grid operation. Those are rather exotic applications, especially for urban markets. The majority of urban markets are rather unlikely to have such systems and would not justify the expense.
    - The preferential oxidation (PROX) blower is unnecessary. Slipstream from the cathode can be taken to supply a PROX catalyst.
    - Combined heat and power (CHP) efficiency for low-temperature (LT)-PEM is unrealistic for U.S. market hydronic systems. U.S. systems operate with high-temperature loops, which do not lend themselves to high recovery of low-quality heat.
    - CHP heat utilization looks optimistic. Considering seasonal requirements as well as daily fluctuations in demand, numbers can be as low as ~12% of actual utilization. It is often economically unjustifiable to install heat recovery for LT-PEM or solid oxide electrolyzer cell systems. Hence, Bloom Energy does not even make an attempt to recover waste heat, even though the company sells systems outside California as well.
    - 0.4 A/cm^2 for PEM is very low, even for stationary systems. For longevity, such systems are operated at higher current densities to allow lower voltage of operation and reduce carbon corrosion.
    - Both PEM systems and solid oxide fuel cell (SOFC) systems are highly sensitive to complete shutdowns for both thermal and atmospheric cycling. A shutdown reformer unit “inhales” exhaust oxygen as gasses in it cool down and contract. In this process, the atmosphere changes from a reducing environment to an oxidizing environment, causing a myriad of material issues. Thermal cycling itself also causes differential thermal expansion of oxidation layers versus metal layers and thus flaking of metal components and catalysts. Catalysts themselves also go through an oxidation/reduction cycle during each shutdown, which is really not desirable.
    - It was unclear whether the project used any thermodynamic process modeling. If not, there is plenty to tap into, and these models are absolutely necessary for component sizing. It is also very important to model interaction with hydronic systems and estimate the realistic heat recovery from different systems. If the project has not done this, it should not be done at this point. Doing it right is a very involved process, and the information can be seen from previous studies. The information should, however, be examined to determine realistic heat recoveries. The project should not just “take someone’s word for it.”
- The approach includes market assessment, system design, cost modeling, and sensitivity and life cycle cost analysis. Incumbent and potential processes are analyzed for applicability.
- The project aligns with DOE’s objectives for current cost status, per the project’s assumptions.

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

This project was rated **2.9** for its accomplishments and progress.

- Project accomplishments so far have been informative and provided useful data. It would be good to include additional LT-PEM stack developer parameters. The progress to date and the process developed is sound, but loading other parameters for various technologies could provide an additional layer of detail that many would find useful.
- Various PEM and SOFC systems and production levels have been analyzed. Dominant cost items have been identified, and an attractive value proposition has been established under certain (utility rate) conditions.
- The team members have made good progress on what they have selected to evaluate, but they should consider other areas to ensure they are looking at a complete picture of what it takes to make a product viable. They have a major hole in the customer acceptance objective. Customers will not accept products that are not robust and that are difficult and expensive to repair. While the team has focused on a technical systems design to identify major technical components, they should consider conducting a total product

systems requirements analysis that looks at all aspects of what it takes to launch a robust product into the market.

- Overall efficiency of 80% for LT-PEM seems excessive. The low-quality heat from the PEM system makes thermal recovery limited. Even as a preheater for hot water, this would require a close proximity to the water heater. It is unclear whether Battelle did the analysis for heat transfer or whether it accepted inputs from LT-PEM producers. The use of silicone seals is questionable for most PEM systems. It is unclear how dependent the PEM life cycle cost analysis is on the CHP or what the life cycle cost would be for the PEM system if CHP were eliminated. It is also unclear why annual operations and maintenance costs are the same for PEM and SOFC systems. Because there are fewer parts in the SOFC, there should be fewer maintenance requirements.
- Analysis results show that SOFC CHP is substantially cheaper to manufacture than PEM CHP—much of industry has already arrived at this conclusion. Reviewer comments from 2014 were appropriately incorporated. Analyzing large-scale PEM may not drive toward meeting DOE efficiency and performance targets.
- It is unclear how this analysis is leading toward cost reduction and customer acceptance. The results are valuable, but the connection was not made toward addressing those barriers.

Question 3: Collaboration and coordination with other institutions

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

- Using real data to conduct analyses shows that there is excellent collaboration. The opportunity to run the analysis multiple times with various parameters adjusted could be very useful.
- The project shows strong collaboration across research and industry. The inclusion of fuel cell system manufacturers with more efficient technology may have changed the direction of this program.
- The team includes fuel cell technology (cells and balance of plant [BOP]) developers, manufacturers, and integrators, as well as systems analysis organizations.
- Battelle has established high-quality collaborators.
- The collaborations are representative of the systems analyzed.
- The project has some excellent collaboration partners but can get more out of them. Panasonic would provide excellent input on what it takes to launch a product into the marketplace, which would help to address the customer acceptance issues. Ballard should also be able to provide input from the point of view of supporting stacks and BOP. Johnson-Matthey Fuel Cells Inc. can provide input on platinum recovery economics.
- The collaboration companies list could be improved. People in the United States are not making small CHP systems, but there are plenty of “consulting” folks who were in the trenches during the early 2000s building such systems. They should be consulted for lessons learned. Until a couple of years ago, for example, Plug Power was making LT-PEM CHP and high-temperature (HT) PEM CHP systems. Plug Power is still around and has in-house staff who should be asked to review and provide input on such models.

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

This project was rated **2.9** for its relevance/potential impact.

- The results of the analysis provide valuable input to DOE funding decisions (focus and level) based on Technology Readiness Levels and low-volume cost estimates.
- The project is doing great at identifying cost drivers and break-even times for “average” system architectures.
- The project identifies where cost issues exist and can be used for decisions on funding support.
- It would be good to see a greater effort on specific areas upon which the DOE Fuel Cell Technologies Office can focus its future R&D. To say that electronics and power conversion dominate system cost is too general. The team should investigate which components, specifically, need to be addressed. After spending three years examining these systems, the project should have a good feel for what needs to be fixed. For

example, there is broad consensus that inverters and converters need to be much more robust and cheaper. The project should engage with US Hybrid, a collaborator and an expert in this field, for input. Panasonic and Ballard can be much more specific as to where the effort should be applied.

- The results of this project show a substantial cost differential for SOFC and HT PEM and have the potential to inform DOE about direction of future stationary CHP Fuel Cell Technologies Office (FCTO) funding. Under the current DOE structure, without a focus on stationary systems, and with SOFC in the Office of Fossil Energy, it is unclear where this information will be used.
- The results are valuable for status reporting. How the analysis contributes to cost reduction and customer acceptance is not clear.
- This is an excellent effort and excellent work, but it has been done many times. The benefit is unclear. While Japan shows progress in CHP/residential systems, that work is largely backed up with policy/ subsidies.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The future work seems aligned with the project cycles so far. It would be good to see how it fits with the legacy budget period work and other similar DOE-funded projects.
- While there is benefit in all of the cases being run through the process, running specific cases with real performance data would be more useful.
- The proposed future work slide was too high-level and not specific enough. Some more thought could have been put into future work instead of “more of the same but bigger.” The future work plan needs to be developed to address issues and recommendations identified by reviewers, in addition to evaluating the larger systems.
- A 2014 reviewer comment objected to HT-PEM, and Battelle agreed. HT-PEM “did not make the cut for this year’s CHP and Primary Power analysis.” However, HT-PEM seems to show up on the proposed future work slide, so the status is unclear.
- The project has identified a pathway to complete the cost analysis for several applications. The project should explain why there has not been a greater acceptance of fuel cell systems, given the two-year payback identified.
- The plan for large-scale primary power PEM evaluation seems disconnected from the most efficient and cost-effective stationary systems (e.g., SOFC, molten-carbonate fuel cell, and phosphoric acid fuel cell). This begs the question of whether this evaluation may be taking place simply because Ballard is a collaborator, rather than because the technology with the greatest potential to meet DOE targets was selected.

Project strengths:

- The following are project strengths: good technical systems analysis, good identification of current cost elements, good use of modeling programs, and good industry participation at the technical level.
- The process and details put into the analysis are comprehensive. The amount of data and the cost breakdowns are also useful.
- The project has a good team and a good approach to the cost analysis.
- This project shows the benefits of SOFCs and demonstrates the value of this technology to the FCTO.
- The details in the results are a strength.

Project weaknesses:

- The project does not adequately identify specific areas for future R&D investment, nor does it address real-world customer acceptance issues and associated costs, including after-sales product support.
- It is not clear how other industry organizations will use the information resulting from this project because they are already manufacturing at low volumes and have hundreds/thousands of systems in the field.
- Feeding more relevant information into the process could provide more useful data.

- The project does not clearly show how the analysis results are addressing the barriers.
- System design and the use of low-quality heat water for CHP should be revisited.

Recommendations for additions/deletions to project scope:

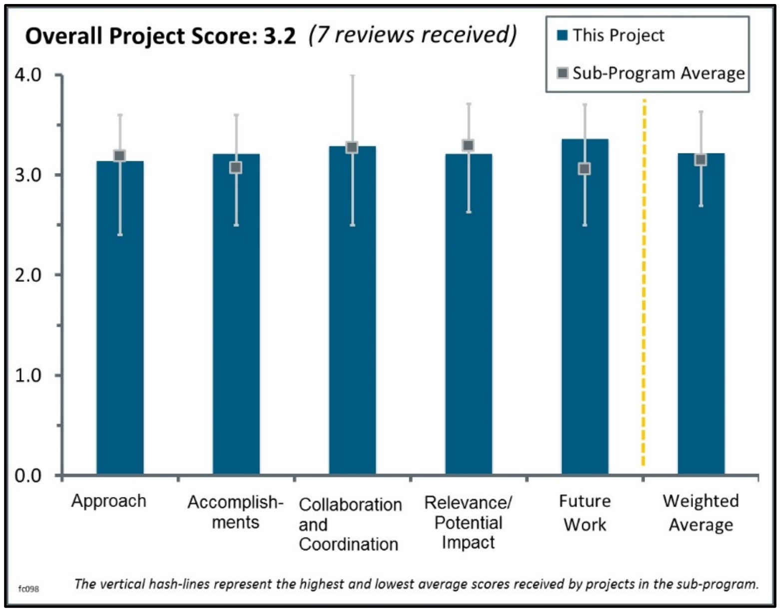
- It would be good to see this work tied into the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility—systems were evaluated in the field, but there may be synergy with the NREL center. Measurement of existing systems and reporting on their success could be more useful to drive deployment than modeling systems (similar to the data collection program).
- Perhaps using the operational data received from the fast food restaurant with real fuel cell performance data could show how technical advances accelerate the return on investment.
- The project should develop a total system requirements model that includes after-sales product support.
- Takeaway messages on the slides would be helpful, as well as what impact this analysis has had.
- The project should revisit low-quality heat for PEM CHP.

Project # FC-098: A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications

Max Wei; Lawrence Berkeley National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop a total cost of ownership (TCO) modeling tool for design and manufacturing of fuel cells in stationary and materials handling systems in emerging markets. Lawrence Berkeley National Laboratory (LBNL) will expand the modeling framework to include life cycle analysis and possible ancillary financial benefits, including carbon credits, health/environmental externalities, end-of-life recycling, and reduced costs for building operation.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The work is good and does a reasonable job of walking along the footprints of previous analysis methodology.
    - It is not clear whether there is thermal modeling behind the figure on slide 15. It seems that there is not; in addition, there has not been research on published piping and instrumentation diagrams.
    - It is not clear why there is not a fuel blower—in residential systems, the fuel supply is only ~4–30 inches of water pressure.
    - It is not clear how the anode exhaust is entering the fuel pre-treatment. The pressure in the pre-treatment unit would be higher than the pressure of the anode exhaust because of the dynamic pressure drop of the process. A three-way valve is not the right unit operation there.
    - Burner exhaust would have lower mass flow than fresh air (because oxygen is removed in the cathode). In the "react. air heat exchanger," lower temperature differential on the cold stream than on the hot stream is to be expected, yet the cold stream changes by 550 K while the hot stream changes by 440 K. There is a bit of heat capacity differential due to the temperature of the stream, but it looks wrong.
    - In greenhouse gas (GHG) emissions off-set, the project team should consider not grid-mix but removing the generation equipment with most "pressure" against it—coal. If grid equipment is being displaced based on GHG reduction pressure, combined cycle plants would not be shut down—at least, not at first.
- The work is focused on the cost barriers and benefits of fuel cell combined heat and power (CHP) technology. This type of study can be very helpful in guiding research to address the main cost drivers and identify the appropriate markets and locations so initial introductions of the technology are successful and show the technology's benefits. The addition of life cycle impact for environmental and health externalities to the cost model is important because these benefits are often ignored. It is not clear how locations for the TCO model were chosen. The cities mentioned are all large cities and appear to fall mostly in the two extremes for expected heating requirements. Some indication of how the locations are selected would be beneficial.
- The "Total Cost of Ownership Model" as presented on slide 6 is a good overall approach and is supported in more detail on slides 7, 8, and 9. However, there should be equal detail for the "Other Costs" elements. These could be presented in a separate slide or added to slide 9. As it stands now, the "Other Costs"

element appears to have been forgotten or not attributed the priority it deserves. Customer acceptance is critical to a successful product cycle, and expensive maintenance and after-sales support is not going to foster that acceptance.

- The analysis outputs are directly supporting the U.S. Department of Energy's (DOE's) goal for understanding fuel cell costs for targeted and impactful direction on lower-cost research.
- It is not clear how the focus on 10 kW and 50 kW was established. It would have been useful to start with a market analysis to understand what size systems have the greatest addressable market. The expanded life cycle assessment is valuable and commercially relevant, although there are existing benchmarks and standards that could have been used, such as those from the California Air Resources Board, Itron reports, etc. The TCO values electricity but not natural gas, so there is divergence between a predicted market with high electricity costs and the actual market evolving, in which there are high electricity costs and low natural gas costs.
- LBNL costs should be compared to Battelle and Strategic Analysis, Inc. (SA) estimates as they become available. It would be good to include environmental costs, but that seldom plays into a buy decision except in very localized areas. Therefore, it would be useful to isolate the realized (out-of-pocket) cost from the total cost including environmental externalities.

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

This project was rated **3.2** for its accomplishments and progress.

- This is a good analysis that is on track to meeting project goals. The work confirms other cost evaluations that have found that the balance of plant (BOP) is key to cost reduction, and power electronics are a major component of BOP.
- The solid oxide fuel cell (SOFC) CHP direct cost model was completed, along with the TCO model for the high-temperature (HT) polymer electrolyte membrane (PEM) CHP system. The addition of regions in the TCO model for the HT-PEM CHP case is valuable.
- This project demonstrates that the SOFC system is close to meeting DOE goals. The inclusion of an incentive review can help DOE look at target costs that are reasonable for the markets.
- The results for TCO will be highly dependent on the system performance. The principal investigator (PI) has validated fuel cell performance against current systems. The PI's comparison of real learning curves from the Japanese micro-CHP fuel cell experience to the model cost reductions with increasing scales is commendable. Some sensitivity analysis to performance parameters may be beneficial (similar to the SA sensitivity study on power density). The PI's assertion that Chicago and Minneapolis are "regions with higher-carbon-intensity electricity" was surprising. Illinois (including the Chicago region) has a substantial amount of nuclear energy production and, according to the U.S. Energy Information Administration, was in the top third for lowest CO_2 intensity of energy supply (kilograms of energy-related CO_2/million Btu). Illinois and Minnesota were both below the national average for CO_2 intensity of their energy supplies. (In 2011, the average for the United States was 55.3 kg/MBtu; Illinois was 50.9 kg/MBtu and Minnesota was 52.9 kg/MBtu. Illinois was only slightly above California, at 49.5 kg CO_2/MBtu.) Kentucky, West Virginia, Wyoming, Indiana, and Utah were the highest (81, 76, 75, 72, and 72 kg CO_2/MBtu, respectively). The data can be found at www.eia.gov/environment/emissions/state/analysis/. The PI should check and provide a reference for his CO_2 intensity and emissions data. Case studies from a high-CO_2-intensity region (e.g., Kentucky, West Virginia, Wyoming, Indiana, or Utah), a state with "average" CO_2 intensity, and a state with low CO_2 intensity would be beneficial (versus two case studies from regions with similar CO_2 intensity). If Chicago and Minneapolis are below average in terms of CO_2 intensity (as the 2000–2011 data show), this means fuel cell CHP will be beneficial for much more of the nation than if they are high-CO_2-intensity regions. The conclusion that fuel cell CHP is most favorable in regions with higher carbon intensity electricity seems counterintuitive. It seems that the cost of electricity, or more accurately, spark spread, would be more important than carbon intensity in determining whether fuel cell CHP is favorable, and areas of high-carbon intensity (with cheap local coal) would be less favorable. Carbon intensity appears, financially, to have a minor impact because savings from GHG credits appear to be much lower than electricity costs on a dollar/kilowatt-hour basis.

- Most of the work to date seems to have been focused on the "Manufacturing Cost Model." This has been detailed and thorough. The "Lifecycle Cost Model" to date seems to have been focused on fuel and electricity costs. What is missing is "Other Costs," such as product maintenance and warranty costs. It appears the project plans to address these elements in its last year. This seems a bit late because the project was started in 2011, and it would be useful to get some advance insight into what these costs might be. For example, on slide 12, it is interesting to note that the reformer and compressor/blower's projected lives are only 10 years. This means there must be a replacement. The project should determine how big an effort is required to change out these components and how much this adds to the life cycle cost. Perhaps this indicates the opportunity to conduct cost trade-offs for designing these components to last for the system life of the fuel cell stacks. The components have the potential to pose a big "hassle factor" and cost for the customer.

Question 3: Collaboration and coordination with other institutions

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

- Additional partners have been added, creating a strong and diverse set of partners.
- There is a broad range of collaborators, including industry representatives.
- The collaboration with SA is good. Feedback from industry for the SOFC (from VersaPower and SOFC Power) and PEM fuel cell models is taking place (Ballard, Altergy, and Panasonic were mentioned last year). Some interactions with the technology validation projects at the National Renewable Energy Laboratory and Pacific Northwest National Laboratory may be beneficial for providing additional input/validation for fuel cell performance assumptions. Some basic assumptions, such as Pt price, should be coordinated between all the cost modeling projects.
- The project has some excellent collaboration partners but can get more out of them. To address the customer acceptance issues that have been raised, the Japanese fuel cell micro-CHP and Italian programs could provide excellent input on what it takes to launch a product into the marketplace. To address some of the BOP issues, the project should engage US Hybrid.
- Additional partners who are working on related areas could be included and parameters shared. Much of this analysis has already been completed by stationary fuel cell companies and third parties. The California Public Utilities Commission recently released an Itron report on the 2013 impact of the Self-Generation Incentive Program. It measures environmental impacts and GHG reductions of fuel cell systems, as well as system performance and capacity factor. These criteria and calculations could be benchmarked for this analysis. Most of the new partners and collaborators are academic, not from industry.
- There should be more collaboration with companies that actually build systems in-house.

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

This project was rated **3.2** for its relevance/potential impact.

- The project is relevant and aligns with DOE Fuel Cell Technologies Office goals and objectives for micro-CHP and medium-scale CHP fuel cell systems. The project helps determine where the costs are in current systems and where the opportunities for cost reductions are, as well as helps identify how these systems would compete in the market and where deployments may make economic sense now. These studies help initial technology validation and market transformation work target the appropriate applications and locations.
- The project advances the DOE goals by valuing the environmental, societal, and financial benefits of fuel cells. The connection to policy is important—it can inform policy initiatives and the direction of DOE support.
- This project confirms findings of other cost-estimating groups and adds the impact of environmental factors. However, environmental factors are not typically part of the buy decision, so a TCO without those factors needs to be included as part of the results. Environmental costs are also controversial, so a bit more attention to that aspect would be appreciated.

- These are values that are used for the status and breakdown of costs, with the specified assumptions on volume.
- Greater effort is recommended on identifying very specific areas upon which the Fuel Cell Technologies Office can focus its future research and development (R&D). On slide 6, a key output is the identification of specific areas in which R&D investment needs to be applied, for example, system components such as compressors and reformers that match the system life of the fuel cells. On slide 26, “Answers to 2014 Reviewer Comments” under BOP opportunities, the project needs to be much more specific, and it is worth a slide on its own to identify the specifics. The project should consult with US Hybrid on this aspect and get its input.
- This exercise can be done by building more on old evaluations and examining technology changes instead of fully reworking the analysis. Efforts may be better spent in tackling technological problems encountered by past “waves” of fuel cell companies. It is well understood already what the roadblocks have been and what performance targets need to be to achieve market penetration.

Question 5: Proposed future work

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

- The planned scenario/sensitivity analysis including energy prices and incentives will be very useful. Future work should include a plan for dissemination of results.
- The proposed future work is appropriate. Investigating systems including absorption chillers is a good idea because much of the United States has low space-heating demands and high cooling demands. Case studies of key cost reduction opportunities in BOP are appropriate because BOP costs are high.
- The future work is consistent with the project cycles and continuation.
- The project has a good plan but needs to enhance the end-user product acceptance barriers. If the issues and recommendations raised in the previous evaluation areas are accepted as having merit, then the future work plan needs to be developed to address these issues.
- The project should leverage existing models, such as the FC Power model for TCO/life cycle engineering modeling. Much work went into getting such models through peer review with DOE, and they should be used for consistency and efficiency of analysis.

Project strengths:

- Project strengths are the manufacturing cost model, CHP system designs and functional specifications, and the broad group of collaborators and reviewers.
- It is important to review the TCO of fuel cell systems to account for their additional environmental and societal benefits.
- The inclusion of environmental and health savings is a strength and has not been done in most other similar efforts.
- The project involves a thorough cost analysis with significant relevance to deployment of CHP systems.

Project weaknesses:

- The project should be cautious about trying to do too much on design for manufacture and assembly (DFMA). Others (e.g., Battelle and SA) are doing that in significant detail. Therefore, LBNL can back off of that aspect by taking advantage of others’ work. That will allow LBNL to focus more on its specific strengths: life cycle cost modeling and valuing environmental externalities. Additional discussion of how the environmental externalities are valued would be helpful. This is a controversial area, and some discussion of the “error bars” associated with how environmental costs are counted would be useful. There was some mention of different values for environmental costs but very little backup or explanation—this could be stronger.
- Recognition of the need to address “Other Costs” needs to be translated into specific action; more emphasis is needed on identifying specific areas for additional R&D. Expertise on what it takes to launch and sustain a product into the marketplace needs to be included.

- Rather than following a no-go decision and a redirection of funds, the project continues to analyze HT-PEM because the work was already planned.

Recommendations for additions/deletions to project scope:

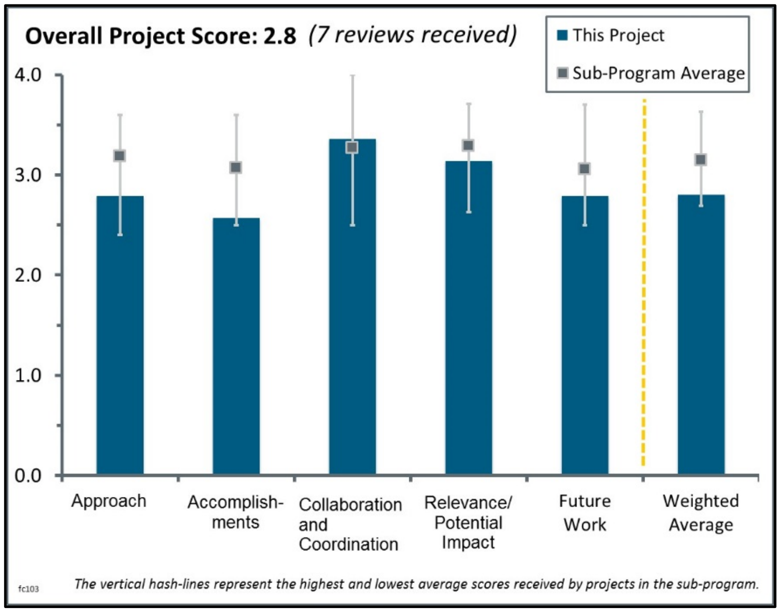
- Overall, this is well-executed and very interesting work.
- It would be good to see the material condensed with takeaways on the slides for simpler interpretation. Every detail of the work is not needed to demonstrate the work and progress. It is not clear how this information can be used for targeted R&D or submitted to fuel cell manufacturers for product improvements and cost reduction.
- The project should address the areas raised in the evaluation, including business issues. US Hybrid should be engaged to assist on BOP issues.
- Because the project is nearing completion, it would be difficult to make significant changes at this point.

Project # FC-103: Roots Air Management System with Integrated Expander

Dale Stretch; Eaton Corporation

Brief Summary of Project:

The primary objective of this project is to demonstrate key improvements to compressor/expander efficiency, including (1) compressor/expander efficiency at 25% flow of >65/70% by 2017, (2) combined motor/controller efficiency at 100% flow of >90% by 2017, and (3) compressor/expander input power at 100% flow of <8/14 kW by 2017. Secondary objectives include conducting a cost reduction analysis and developing fully tested and validated air management system hardware capable of meeting 2017 project targets.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The approach is good. It will leverage the broad efficiency map of Eaton's Twin Vortices Series (TVS™) compressor to improve the overall drive-cycle fuel economy and integrate the expander, compressor, and motor to reduce system cost and increase system efficiency (this is a new approach, similar to a traditional turbocharger).
- Eaton has leveraged its automotive supplier production expertise in this project—this is a project strength. While the team members have cited most of the key issues, it is unclear whether they have addressed—or plan to address—them all, including potential fuel cell contamination and the impact of high relative humidity (RH) and liquid water on expander durability.
- The approach is appropriate for the project objective and provides a clear path to solve a real-world problem. More information on the testing for validation would be helpful.
- The approach follows a reasonable product development cycle: modeling/computational fluid dynamics (CFD) to subsystem development/validation to full 80 kW module validation. Although progress has clearly been made, the compressor/expander efficiencies are far from the targets, as is the cost.
- The project employs straightforward design analysis and engineering. This should have revealed the unlikely single-shaft design. The project seems to focus on beating the incumbent centrifugal compressor instead of meeting U.S. Department of Energy (DOE) targets.
- The approach of using a plastic expander has not been successful. It is not clear which barriers can be overcome by continuing to focus on this approach. The project approach does not include the motor/controller, which has the largest potential impact on cost reduction of the air handling system.

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

This project was rated **2.6** for its accomplishments and progress.

- The project has made significant progress toward completing its deliverables and milestones.
- The project team moved the bar forward on a number of the metrics compared to the 2011 "baseline" (e.g., compressor-only power, cost, and idle to mid-range power performance). However, the project also fell behind on a few elements, including noise and full power compressor plus expander power, which has an

impact on fuel cell system cost to recover the deficit. The ability to achieve higher compression ratios, especially with the expander, has not yet been demonstrated. System durability, including exposure of the expander to liquid water, and the potential impact of contaminants has also not been demonstrated.
- There has been steady improvement in mid-range power consumption for the compressor/expander, but there is a performance deficit at full power. All performance metrics for the compressor/expander appear to be far from the 2017 targets.
- Several meaningful improvements over incumbent technology were realized, but not all DOE targets were met. The Eaton cost at 500,000 units is higher than that of the incumbent technology (slide 14).
- While moderate progress has been made over the past year, there are still huge gaps to be addressed to meet the critical cost and efficiency targets.
- Only 5 of the 21 targets have been met since 2011.

Question 3: Collaboration and coordination with other institutions

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

- External partnerships with Ballard and Strategic Analysis, Inc. (SA) are useful and will generate meaningful data and relevant cost information, respectively. Other partnerships appear to be providing relevant simulation data that have been incorporated into project results and progress toward achieving targets.
- Collaboration on this project is excellent and provides an appropriate mix of academia, national laboratories, and industry.
- The collaborations with Argonne National Laboratory and SA on system and cost modeling have been productive. Ballard will be doing some validation testing, but it is unclear whether these tests will include the expander. (The slides stating that Ballard testing will include the expander contradict answers during the session discussion.)
- The following summarizes the collaborations:
    - Ballard is an industry subcontractor within the DOE Hydrogen and Fuel Cells Program (the Program). Ballard's responsibilities for this project are to (1) provide fuel cell original equipment manufacturer (OEM) input into the design and specifications of the air management system, and (2) integrate, test, and validate the Eaton compressor/expander with a 75 kW Ballard HD6 stack.
    - Kettering University is a university subcontractor within the Program. Kettering's responsibilities are to provide critical analytical support, including expander CFD analysis, critical speed analysis of compressor/expander design, and critical speed analysis iterations of Eaton's compressor only.
    - Electricore, Inc. is an industry subcontractor within the Program. Electricore is providing administrative project management.
    - Argonne National Laboratory (ANL) is a federal laboratory subcontractor outside the Program. ANL is responsible for providing critical simulation and modeling support of the fuel cell system to assist in optimizing the roots air system with the Ballard HD6 module.
    - SA is an industry subcontractor outside the Program. The company is developing fuel cell system cost, utilizing the manufacturing cost of a roots-based air management system.
- A fuel cell integrator was properly incorporated at all stages, from initial component specifications to the final test. Use of CFD was demonstrated in the early stages of compressor design. From the performance, it appears the project supplier is more than competent, but this cannot be fully evaluated without knowing the source or the design's potential for large-scale manufacturability.
- Collaborators are working on cost analysis, CFD analysis, system analysis, and system testing.
- The partnerships appear to be strong, but the project should include a motor/controller partner because these components seem to be the primary barriers to meeting the cost target.

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

This project was rated **3.1** for its relevance/potential impact.

- The project addresses a clear need related to fuel cell systems and, if successful, can improve the overall balance of plant (BOP). The BOP contributes to a significant portion of the overall system cost and represents a significant problem in system reliability.
- A fully tested and validated (Technology Readiness Level [TRL] 6) air management system hardware capable of meeting 2017 project targets by project conclusion supports Program goals.
- Development of low-cost air handling equipment is one of the biggest enablers of meeting automotive fuel cell cost targets.
- Compressor cost is a key contributor to overall fuel cell system cost and thus is of great relevance to the Program's goals.
- More focus is needed on the motor/controller to achieve the efficiency and cost targets; it is stated that these components account for 71% of cost. Although the work on low-cost plastic components is important, last year's presentation stated that the total cost impact of plastic versus aluminum is small. Therefore, it is not clear that the seemingly significant effort applied to developing plastic rotors is justified.
- BOP component development is not one of DOE's top priorities.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is good, but better-defined validation testing could make this excellent. More definition on addressing the noise of the current system would also be useful.
- Performance and validation testing with Ballard is critical to determining both the technology's viability and whether DOE should invest further to get efficiency and cost closer to fuel cell system targets.
- Integration and testing with fuel cell systems is the key next step, as proposed. However, it appeared from the question-and-answer session that the expander was not incorporated in the unit to be tested with the Ballard fuel cell system. If so, this is not acceptable. The complete compressor/expander needs to be tested in-system. (The presenter's answer may have been misinterpreted.) The following were both mentioned in the Technology Advancement slide but were not listed as future work:
    - Should demonstrate 3.0 PR compressor.
    - Should demonstrate an expander (PR ~2.3–2.6) consistent with the above 3.0 PR compressor and material compatible with its environment (deionized water). It is not clear whether a plastic part can do this.
- The future work should include an emphasis on noise reduction, which should align well with focusing on improving efficiency. Future test validation at Ballard is planned for an 80 kW system, which is good. Unfortunately, the unit being tested at Ballard apparently does not include the expander, so it is unclear what the validation plan is for the full "roots air management system with integrated expander."
- Performance and durability testing on Ballard stacks is planned.
- The critical speed may be too low with overhung expander rotors. Integration with polymer electrolyte membrane fuel cells may not go as well as hoped. Direct coupling of the expander to the compressor may result in fuel cell stack pressure and flow rate control issues. The system might not operate at optimal conditions.
- The project will complete testing to objectives; however, it does not appear that project targets will be met.

Project strengths:

- This is the only DOE project on air handling equipment. There are strong collaborations with modeling and cost projection teams. There is a plan for validation at TRL 7, so the unit should be readily commercialized if it meets requirements.
- Eaton's considerable experience with roots machines and large-scale manufacture is a plus, as is the company's integration with a fuel cell system manufacturer.
- The strengths of the project include the project team and the relevance of the problem being attacked.
- The project is conducting full-scale validation with a strong OEM partner.
- Broad relevant collaborations are a project strength.

Project weaknesses:

- The chosen (roots) technology will inherently be noisier and more bulky than a dynamic (centrifugal) air machine. Issues with potential bearing contamination also remain.
- The project is still far from performance metrics, with no clear path for closing the gaps. The significant cost of the motor/controller (beyond the scope of this project) is a serious concern.
- There is no clear path to the project meeting cost and durability targets.
- There does not appear to be a path for significant reductions in motor and controller costs.
- Eaton may never completely meet the targets.
- Better definition of the testing would help in understanding the true impact.

Recommendations for additions/deletions to project scope:

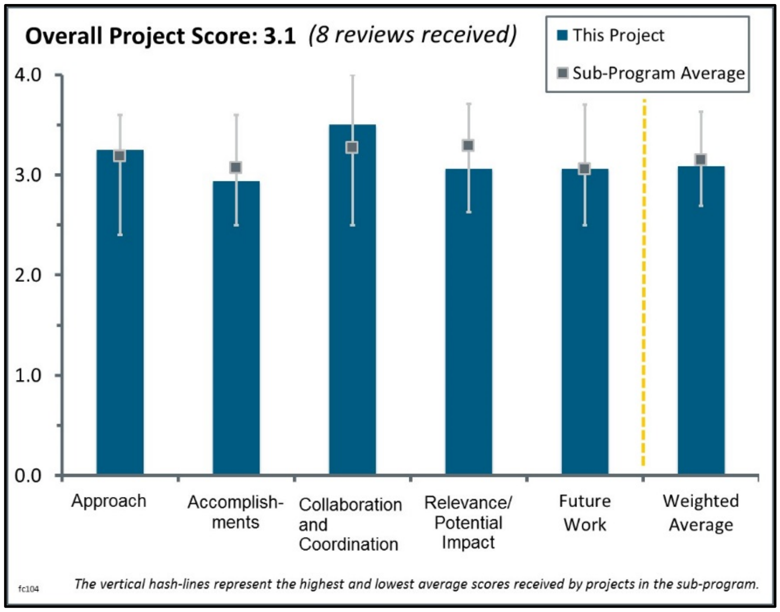
- The focus in the remaining six months should be on:
  - Integrated testing with the Ballard fuel cell system (including the expander).
  - Demonstrating expander compatibility with deionized liquid water.
  - Demonstrating the bearing technology's compatibility with fuel cell systems (analyzing for contaminants and perhaps consulting with the National Renewable Energy Laboratory and Hawaii Natural Energy Institute contaminant programs).
  - Demonstrating the viability of a low-cost plastic expander at PR >2–2.5.
  - Demonstrating a compressor capable of PR~3.
- A focus on cost reduction should be included, as should system testing on the full compressor-expander module, including the expander.
- The project should minimize effort on plastic component fabrication and focus more on closing performance gaps.

Project # FC-104: High-Performance, Durable, Low-Cost Membrane Electrode Assemblies for Transportation Applications

Andrew Steinbach; 3M

Brief Summary of Project:

The overall objective of this project is to develop a durable, low-cost, robust, high-performance membrane electrode assembly (MEA) for transportation applications that is able to meet or exceed U.S. Department of Energy 2020 MEA targets. The objectives for fiscal year (FY) 2015 are to (1) improve MEA robustness for cold start-up and local transient via materials optimization, characterization, and modeling; (2) evaluate candidate MEA and component durability to identify gaps; (3) improve activity, durability, and rated power capability of Pt_3Ni_7/nanostructured thin-film (NSTF) cathodes via post-process optimization and characterization; and (4) integrate MEAs with high activity, rated power, and durability with reduced cost.



Question 1: Approach to performing the work

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

- The project structure is robust. The initial work focuses on developing components (e.g., catalysts, gas diffusion layers [GDLs], and membranes) until they reach durability, performance, and cost thresholds. The components are then assembled into MEAs of various configurations. Best-of-class MEAs are then selected for building a short stack.
- This year's work was incremental but along tightly focused lines, addressing problems that have arisen in attempts to make NSTF workable for automotive systems. The project now attempts to use best-of-class MEAs to address all issues simultaneously, although efforts to address the durability of transient response will not occur until integration of the more durable Type B interlayer or some other solution. A large amount of data was presented in an unusually clear and comprehensible form.
- The approach is at the level of the complexity it addresses. The integration of anode and cathode 3M catalysts with membrane, GDL, and interlayer is planned adequately; leaching of Ni is not.
- This is a very well-developed approach for testing fuel cell operation under realistic conditions; however, this is something that 3M has been doing for decades. There is no meaningful improvement over previous efforts. It was also really difficult to see any systematic approach—too many parameters are being changed simultaneously (e.g., temperature and the nature of the catalyst) to really develop meaningful insights. The suggestion would be to simply pick the best catalyst and then systematically change the variables to develop a more mechanistic picture of what is happening. For example, the effect of temperature is obviously very important; however, it is difficult to determine what temperature is affecting—kinetics, stability, or something else entirely. It is positive that 3M is using modeling to better understand water management, but the researchers are encouraged to spend more time with real experiments rather than rely too heavily on modeling.
- This project is focused on (1) developing durable, low-cost, high-performance MEAs and (2) improving operational robustness for transportation applications by optimizing and improving 3M's low-platinum-group-metal (PGM) NSTF oxygen reduction reaction (ORR) cathode catalysts. Although this is an MEA-oriented project (not a catalyst project), it would still be best to make the best use of 3M's NSTF catalysts.

However, researchers have relied heavily on the use of interlayers and anode GDLs to overcome fundamental challenges faced by NSTF catalysts, which leads to other critical issues. In particular, the interlayer is of limited implications and would bring additional cost and technical issues.

- The approach has been consistent throughout the project—namely, using the same three methods to address the outstanding issues with NSTF MEAs: (1) small changes in the alloy composition, (2) changes in the GDLs, and (3) addition of an "interlayer." Unfortunately, the approach has not included any major changes to the catalyst layer design or composition, which should also be included because this is the layer that is limiting the performance.
- The approach is focused on 2020 targets on MEA cost, performance, and durability. The weakness of the approach is in incorporation of the interfacial diffusion layer and using the leaching catalyst, as was indicated in last year's review.

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

This project was rated **2.9** for its accomplishments and progress.

- The team has done much work, and the number of cells tested by 3M during this project is truly impressive. There has been significant progress in some respects, such as shown in the graphic on slide 17. However, the rejection of the reviewers' comments on slide 17 is puzzling because the limited approaches being used are still falling short of the targets and also have some obvious weaknesses. For example, the addition of an interlayer also adds many concerns, including added complexity and increased PGM (loading); the durability of this layer that includes carbon is also a concern (one of the original major advantages of an NSTF electrode was that it did not include carbon and would therefore be inherently more durable). It seems very likely that the interlayer is degrading because, as shown on slide 10, the load transient performance is substantially degraded after accelerated stress testing, and the interlayer is the component primarily responsible for the improved transient performance, as shown on slide 9.
- Best-of-class MEAs exhibit promising results, with targets for PGM content (0.118 mg/cm^2) and Q/ΔT (1.45 kW/°C) achieved. However, the performances are still 10%–15% below the 2020 DOE targets. The work on improved robustness (GDL and interlayer) would require deeper effort to understand the failures at both electrocatalyst and support cycles (after 10,000 and 10 hours, respectively) and present an MEA of operational robustness. There is little commentary on the work on cold start modeling with the integration of Michigan Technological University's (MTU's) GDL pore network model and Lawrence Berkeley National Laboratory's (LBNL's) MEA model, and the documentation does not clearly explain how this effort is used (e.g., perhaps the project seeks improvements to the model or a back loop to the new GDL/MEA).
- Very good progress and a good deal of work have been accomplished in the last year. Key procedures to improve the MEA performance, integration of the catalysts, and incorporation of an interlayer apparently promise that, in subsequent research efforts, most of the performances will be at 2020 levels. However, several problems with this catalyst are not completely solved: the necessity of using an interlayer with the thickness of another catalytic layer, the dealloying procedure, and the problem with Ni leaching due to the Kirkendall effect. The third point has not been considered at all.
- Progress was made toward addressing the major problems that have arisen in attempts to integrate NSTF into automotive systems, although it is unlikely NSTF stacks will ever be a simple drop-in replacement for stacks made with conventional dispersed catalysts that have shown superior robustness over a range of important operating conditions. The performance of NSTF MEAs in air has gotten closer to that of state-of-the-art MEAs made with conventional supported catalysts, although NSTF still falls short. NSTF now appears to have been made compatible with reinforced 3M advanced membrane materials through modification of the membrane. Modification of anode GDLs has improved operational robustness for cold start, but it still falls short of that of conventional MEAs. Use of interlayers has improved robustness against cold start and transient operation but has introduced a new sensitivity to voltage cycling. The new Type B interlayers may provide at least a partial solution to the durability problem, but it is unlikely that the thin NSTF electrodes will ever fully match the operational robustness of conventional electrodes.
- While there have been some improvements in high-rated power performance and stable temperature range, the operational robustness does not appear sufficient. Furthermore, some of the improved performance

results shown in FY 2015 should be validated in the short stack testing. The modeling efforts by MTU and LBNL look promising.
- Progress has been made toward durability and performance targets owing to the synthesis of more durable and more conductive membranes and more durable interfacial layers. However, this new membrane is still not durable enough, and contamination problems are not solved. The more durable catalyst is still not durable enough.
- Based on the history of 3M in this space, more results were expected that would address intrinsic scientific questions related to this technology. Instead, there is much effort simply to “test” materials to assess their performance. Additionally, much more effort needs to be directed toward understanding durability on the cathode side rather than initial activity of the catalyst.
- The delay in stack testing is concerning. There have been years of fundamental development and studies of NSTF substrates and Pt-Ni dealloying. Stack testing should be predominant in all projects going forward. This approach should be either validated at the stack level or dropped from future DOE funding.

Question 3: Collaboration and coordination with other institutions

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

- 3M has effectively coordinated with other organizations to further develop catalyst activity, evaluate the operational robustness of 3M versus conventional electrodes, and evaluate the durability of all aspects of operation. One hopes that the planned stack testing, preferably with best-of-class MEAs with the addition of Type B interlayers, will give NSTF a full chance to demonstrate whether it, in its ultimate modification, can satisfy automotive requirements.
- The broad collaboration looks carefully managed, and collaborators were selected according to the need for their capabilities.
- This is a very good team of people who are trustworthy in the field, and obviously they collaborate very well.
- There is excellent collaboration with activities originating from all involved institutions.
- The project features good collaborations with appropriate partners.
- The effort between 3M, LBNL, and universities is very well coordinated.
- There are excellent collaborations with some groups that utilize the groups’ areas of expertise, such as modeling and materials characterization. However, the team still does not have a fundamental understanding of what limits NSTF performance. The unanswered questions include, but are not limited to, the following:
    - How protons are actually transported in an NSTF catalyst layer.
    - How the water saturation level in the catalyst layers is changing with changes in the anode GDLs.
    - How the interlayer works and why it improves the transient performance.
- 3M has led collaboration efforts between strong team members. It is noted that there are good collaborations between MTU and LBNL relating to GDL selection and transient response. However, a greater emphasis should be made on the stack testing, which will be beneficial to all team members. It is important to effectively integrate all key components and have a reliable system integrator, such as General Motors (GM), test at a system level.

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

This project was rated **3.1** for its relevance/potential impact.

- The project is fully in line with DOE research, development, and demonstration objectives for a durable, performant, and cost-efficient polymer electrolyte membrane fuel cell for transport applications. Specifically, the project addresses the following 2020 DOE targets:
    - Performance: 1 W/cm^2.
    - PGM content: 0.125 g/kW.
    - Durability: 5,000 hours with voltage loss <10% V.

- The unique capabilities that have been developed for synthesizing materials, building full cells, and testing their performance are an asset to DOE and will be very important in moving the technology forward.
- The project has a potential to be a game changer for the Hydrogen and Fuel Cell Program (the Program).
- If considerably simplified, this could be an important catalyst technology.
- This project has the potential to have outstanding relevance to the Program since NSTF is a promising catalyst architecture with inherently excellent performance and durability. However, the inherent benefits of NSTF have not been fully realized, and after more than a decade of development, it has not displaced the status quo catalyst of Pt on C (with the possible of exception of use in electrolyzers). What is required is the development of advanced catalyst layers that can realize the true potential of NSTF. Instead, the principal investigator has chosen to use "Band-Aids" to partially mitigate the key issues, and these fixes do not address the fundamental issues or promote the fundamental understanding that is required to successfully convert new catalyst architectures into high-performance and robust MEAs. It is possible that this project has uncovered a new decay mechanism, which is claimed to result from the deposition of ionomer degradation products. However, there is as of yet no convincing evidence that this mechanism is correct.
- NSTF, with its intrinsic durability against voltage cycling, could have a significant impact on the development of widely commercializable fuel cells and electrolyzers. However, a number of shortcomings as compared to conventional MEAs, properly addressed in this project, need to be overcome if NSTF is to become usable in any but a few highly specialized applications. 3M management's blanket policy of not discussing manufacturing costs for any of its products or potential products significantly degrades this project's utility to the advancement of the fuel cell field, as costs cannot be adequately estimated. It would be quite possible that a significant amount of society's resources could be spent pursuing developments with 3M that ultimately would prove too costly for practical application.
- The project is aligned well with DOE goals and objectives. However, operational robustness (under load transients, low-temperature operation, etc.) should be addressed. Furthermore, the use of an interlayer to meet DOE's target may be reconsidered.
- The project addresses a critical challenge facing DOE. However, go/no-go decisions regarding the future of NSTF need to be made so that either (1) the technology can be advanced or (2) resources can be diverted to other efforts (such as alkaline membrane approaches).

Question 5: Proposed future work

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

- The project has identified the remaining barriers (robustness and durability) and has devised plans to overcome them. At some point, component improvement has to cease and a decision on the project's performance has to be made so that testing at the stack level can finally be executed.
- Despite its weaknesses, the proposed work may still resolve many key issues with NSTF catalysts in fuel cells. That said, it appears this project is ending in August 2015, so it is difficult to judge the relevance of the proposed future work without further DOE support.
- It is to be hoped that the planned stack testing, which (one hopes) will incorporate best-of-class MEAs with the addition of the more durable Type B interlayer, will provide a conclusive test of whether NSTF can prove acceptable in automotive applications without very costly, and technically questionable, modifications to balance of plant. If the planned stack testing does not give acceptable activity, durability, high-current performance in air, and operational robustness, difficult modifications of the basic NSTF structure to give a thicker catalyzed layer with adequate porosity may be needed for further progress to be made.
- During its remaining time, the project team should focus on elucidating the mechanism responsible for the decay observed, which may be relevant to the entire fuel cell community. This effort should focus on the degradation of NSTF without the interlayer because the mechanism for interlayer degradation is obvious (the same as other Pt/C electrodes) and will mask the decay of the NSTF layer, which appears to be unique.
- The proposed future work is focused on overcoming barriers related to catalyst and membrane durability.
- The proposed key future work is focused on overcoming the remaining barriers using the NSTF cathodes (with higher mass activity and improved durability) developed outside this project. Considering the short time left for this project, this approach might be the best choice, but the benefit for DOE is not clear. The short stack testing would be most critical.

- The interlayer and Ni leaching problems remain. No definitive resolution is proposed.

Project strengths:

- There are many strengths to this project, which stem from clearly recognizing the importance of connecting fundamental science to real systems. The capabilities developed by 3M to synthesize all parts (e.g., the cathode, anode, and MEA) of the fuel cell are indispensable to making this connection. Finally, the willingness to admit that, even with these great capabilities, there are still many issues (e.g., water management and the durability of the cathode) that must be solved to make this a viable technology demonstrates a clear understanding of what must be done to move the technology forward.
- The project has continued development to take advantage of the durability advantages of the NSTF catalyst layer structure. The project is starting to properly consider the special problems that occur in air at high current density for electrodes with relatively low Pt surface areas (i.e., problems that behave as if a local oxygen transport resistance occurs very close to the active Pt surface). This is one of the most important problems now facing development of fully satisfactory automotive cathode catalysts.
- This new catalyst has resulted in raising interesting questions for the fuel cell technical community, such as how protons transport in NSTF layers with no ionomer. Understanding this may result in the design of new types of catalyst layers with less ionomer than is used in conventional catalyst layers. The ultra-thin catalyst layers, with very low total surface areas, have also been a model system for the impact of contaminants, which may help to reveal new decay mechanisms. However, neither of these key potential benefits has been fully realized to date. This project has also clearly demonstrated that radically new catalyst architectures can also require very different catalyst layer designs (and the development of these new catalyst layers can be challenging but must be included for any novel catalyst architecture).
- Strong team members are making collaborative efforts to meet DOE’s targets. It is noted that the efforts to combine modeling and experimental works would be beneficial to better understand the current problems and find better solutions.
- The project has a strong research team, strong resources, and good funding.
- The effort is technically strong and well coordinated.
- The project uses a combination of real-life tests with modeling and advanced diagnostics.
- The PGM content is higher than DOE 2020 targets.

Project weaknesses:

- The NSTF catalyst layer structure itself has insufficient void volume to properly handle liquid water under start-up and load-transient conditions. While the project has made progress in addressing these issues, the overall operational robustness of the MEAs produced to date still appears to be inadequate for automotive utilization without substantial and costly modifications to the balance of plant (e.g., subatmospheric anode pressures). The interlayers that attempt to patch up the cold start and transient issues comprise conventional dispersed catalyst layers, leaving the modified NSTF system susceptible to the same voltage-cycling degradation that plagues dispersed catalyst systems and to which the original NSTF was remarkably resistant. However, it is possible that more corrosion-resistant supports that do not work very well in conventional electrodes could still be effective when used in interlayers. If Type B interlayers prove to be both effective and durable in stacks, this project “weakness” could become a “strength.”
- One key weakness is the lack of systematic work. Testing itself is not enough to understand the key limitations and how to overcome them to improve fuel cell performance. It is obvious that there is still a large gap between the catalytic activity observed with classical rotating disk electrode measurements and MEA performance, and 3M may be in a unique position to bridge some of these differences. The team is encouraged to make use of 3M’s unique capabilities to really focus on addressing this difference in performance.
- After more than a decade of NSTF MEA development, the key issues have still not been mitigated sufficiently to enable this new catalyst to replace more conventional MEAs, primarily because 3M has not been willing to make any significant changes to the original NSTF catalyst layer structure. The reluctance to make major changes to the catalyst layers is understandable, but it is a major weakness not to include changes to the layer that is limiting these MEAs.

- While 3M's expertise in NSTF catalysts and General Motors' support are the key assets of this project, researchers have relied heavily on the use of interlayers and an anode GDL to overcome fundamental challenges faced by NSTF catalysts. This solution brings with it many other critical issues.
- The project uses an incremental, rather than a transformational, approach, and the modeling does not have predictive capability.
- Weaknesses include the high PGM contents in catalysts and the complex technology.
- The performances and durability are weaknesses.
- Overall, further progress should have been made at this point, given the significant previous investment in this approach.

Recommendations for additions/deletions to project scope:

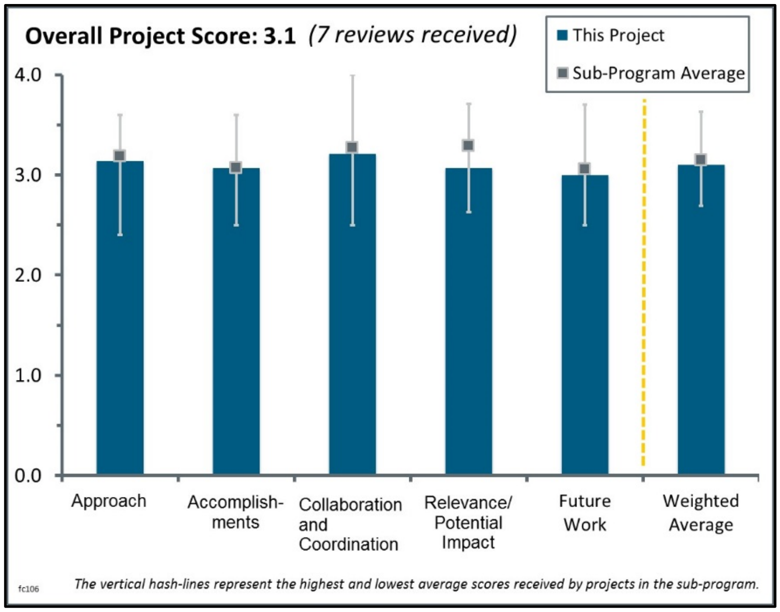
- One hopes that the MEAs to be tested in stacks will incorporate the Type B interlayer in hopes of achieving some level of durability of transient response. Otherwise, the MEAs will have little chance of proving adequate for integration into automotive fuel cell systems. NSTF stacks should be tested with practical anode feedstreams and conditions, (i.e., those representative of anode recirculation or related strategies).
- The project should define a go/no-go threshold for future component improvements so that the project is steered in its overall course.
- With the short time left on this project, a greater emphasis should be placed on the short stack testing of best-of-class MEAs.
- The Ni leakage after dealloying should be addressed.
- It is recommended that DOE hold a review to assess the potential for NSTF/Pt-Ni dealloying to determine whether this continued support is the best investment of federal funding.
- DOE should not fund future NSTF projects unless they include the development of substantially new catalyst layer architectures. DOE needs to recognize that the development of new catalyst layers must be part of any novel catalyst structure.

Project # FC-106: Rationally Designed Catalyst Layers for Polymer Electrolyte Membrane Fuel Cell Performance Optimization

Deborah Myers; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to realize the oxygen reduction reaction (ORR) mass activity benefits of advanced Pt-based cathode electrocatalysts in membrane electrode assemblies (MEAs) and stacks operating at high current densities and on air and at low platinum group metal (PGM) loading. Specific goals are to (1) determine the properties of electrode/catalyst layers that limit the high current density/air performance of electrodes based on advanced Pt-based cathode catalyst; (2) use information from characterization efforts to determine the performance-limiting property of the current d-PtNi electrode; and (3) design the catalyst layer composition and structure and support functionality to mitigate the performance limitations, guided by computational modeling.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The proposed approach is to determine the properties of electrode/catalyst layers that limit the high current density/air performance of electrodes based on advanced Pt-based cathode catalyst and, in particular, PtNi (d-PtNi) developed by Johnson-Matthey Fuel Cells Inc. (JMFC) (within the General Motors-led FC-087 catalyst project). This effort is completed by characterization and by designing catalyst layer composition and structure and support functionality to mitigate the performance limitations. Regarding the metrics obtained for this dealloyed PtNi, this approach makes sense.
- The approach is well designed and focused on identification of performance-limiting property of catalyst layers employing dealloyed PtNi catalyst with low loading.
- The overall approach looks good, especially because this is an electrode project and not a catalyst project. Use of the JMFC catalyst is fine. The approach of understanding performance and inks is good, but there needs to be more understanding gained (aggregation from the diagnostics). There should be more transport-related diagnostics and in-cell characterization for an electrode optimization project.
- This is important work to understand better the role of ionomer in low-Pt-loaded catalyst. There is a lot of speculation regarding the oxygen diffusion rates through ionomer used in low-Pt-loaded catalyst. Some comment on this mechanism and how the work in this project is affected by the oxygen limitations (or not) would be helpful.
- This project is focused on the development of MEAs with advanced Pt-based catalysts for high current densities on air at low PGM loading. The Pt catalysts used in this project are d-PtNi catalysts developed by JMFC during a previous U.S. Department of Energy (DOE) project (FC-087). ANL’s efforts include (1) determining the limiting factors of d-PtNi at the high current density on air and (2) developing better catalyst layer composition and structure and support functionality to address the critical issues.
- The approach is fairly general, but it is based on the relevance of the project. Simply put, the project team will use all characterization methods at its disposal to figure out why performance is low at high current density for electrodes made from dealloyed PtNi. Then, the project team will attempt to improve the

electrode. The collaboration slides point to JMFC as a supplier of inks and catalyst coated membranes (CCMs), but the approach slides would be improved if they clarified which organization is making the inks and CCMs. Perhaps a flow chart of tasks would be useful. It may be useful to understand more about the cell fixtures used. The operating conditions are different (which takes a "snapshot" of the inlet of a full-scale cell), so perhaps whether the flow field is serpentine or straight is not as crucial, but it may matter. The ionomer-to-carbon (I/C) ratio experiments might benefit from looking at low O_2 concentration, similar to the organic versus aqueous comparison.

- The project features a well-designed approach of taking a high-performing but commercially viable catalyst and developing an understanding around the electrode design requirements. A significant concern is the continued leaching of the Ni and the impact this has on the ionomer and associated performance parameters. This raises the question of whether a self-contaminating system is ultimately a viable approach for very low catalyst loadings. On the other hand, if Pt-metal alloys continue to provide the best path forward in terms of scalable catalysts, then the work is of utmost importance. The extensive use of characterization and linkages to models is a solid approach. However, most of the results on I/C ratio effects are based on only two levels of I/C. More are required to understand trends and to quantify effects. The project is focused only on beginning-of-life or early life effects (up to two weeks of testing). This is appropriate because there is still much to understand and optimize for the initial performance effects. However, additional, previously unidentified effects may be uncovered with durability testing, and it is unlikely that durability will be effectively addressed in this project.

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

This project was rated **3.1** for its accomplishments and progress.

- Significant progress has been made toward DOE targets on MEA performance at 800 mV and 675 mV. Careful analysis of the effect of Nafion® ionomer content and ink composition on the performance of low-loaded catalyst layers is of great significance. Performance-limiting properties have not been identified yet.
- There has been good improvement in performance since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review, but because the project is two-thirds done, there needs to be almost the same level of improvement again by next year to achieve the project targets. Also, the results achieved are under high-stoichiometry, one-dimensional conditions. Actual MEA results will likely be lower. The identification of the effect of Ni^{2+} on the ionomer in terms of O_2 permeability and electrode resistance is an important finding, as well as the fact the Ni oxidation is influenced by the ionomer.
- This project has exceeded go/no-go decision criteria and met several key milestones. In particular, the principal investigators (PIs) have taken good approaches and obtained meaningful data on the effects of ionomer content and the type of organic solvent in ink, as well as successfully demonstrated the effectiveness of the acid-washing process of MEAs. However, the development of the catalyst support surface functionality to improve low relative humidity (RH) performance does not look promising and may need to be reconsidered for the future work.
- This project seems on track to meet the stated DOE goals.
- The team has accomplished a significant amount of work, but the presentation is quite difficult to follow. It should be better structured to emphasis the main highlights. All the go/no-go points and milestones have almost been achieved. Regarding the results, some questions remain, such as what the impact of the treatment (thermal treatment and acid leaching) is on the carbon support, and whether the effect of the catalyst (Pt particles) activity or the effect of the carbon wettability change is observed. The carbon support could be graphitized during thermal treatment and oxidized during acid leaching. Indeed, on slide 8, it is written, "Decreased the performance of the d-PtNi/C cathode in the mass transport region on air at 100% RH (relative humidity)," which is typically observed for hydrophilic support. It is unclear whether the stability of the catalyst has been studied in a single-cell test. Not much progress has been made with respect to the durability of the dealloyed catalyst.
- There are many questions that could be asked about the organic solvent versus aqueous solvent polarization comparison. Some of the results are subtle enough that the subtle increase in loading with an organic solvent could be responsible. It is difficult to make a generic statement that organic solvents are superior without an experimental design that adjusts mixing times, temperatures, levels of agitation, and other

parameters for the particular solvent used. The organic solvent was shown to enhance particle breakup while also increasing gas permeability of the resulting layer, given the same solvent mix and I/C ratio. However, if the two solvent types require different recipes and mixing to achieve particle breakup and high layer permeability, then perhaps a wider parameter range needs to be investigated. Ni loss data need to be reported in association with the methods used for hot pressing and CCM fabrication. The limiting current trends reported for Pt/C, annealed Pt/C, and dealloyed PtNi/C could all be related to parameters other than the particle sizes of Pt and PtNi. Despite similar Pt weight percentages, perhaps there were variations in catalyst layer thickness. It may be helpful to break down pressure-dependent mass transport losses from non-pressure-dependent losses, or to even go further and use methods similar to Nonoyama et al. (2011) to distinguish Knudsen diffusion from resistances related to ionomer film thickness. For what the project is attempting to accomplish, the throughput of data is high, and the data are of high enough quality that conclusions can be drawn based on the processing context in which the project lives.
- The work on inks was interesting, but it needs some further clarification; modeling would help. In addition, it is unclear whether there is any beam damage that may be altering the profiles with drying. The use of RDE studies for determining permeability of the ionomer is questionable because the environment is different. The use of equivalent circuit models, especially with the catalyst layer, is questionable, particularly because the electrochemical impedance spectroscopy can also incorporate Ni movement into the conductivity. It is unclear whether the low surface enhancement factors correspond to what was seen in particle sizes in the inks. The improvement and metrics are noteworthy, although some more guidance to developers on the key issues would be better. More cell diagnostics are needed to provide understanding as well as visualization of the catalyst layer, where the only presented work came from outside of this project. The free ionomer may be providing the conductivity in the layer, so it should not just be disregarded.

Question 3: Collaboration and coordination with other institutions

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

- The project features very close collaboration and well-coordinated effort between Argonne National Laboratory (ANL), JMFC, United Technologies Research Center (UTRC), and universities.
- While it is clear that collaboration is occurring, the presentation needs to more clearly explain the roles of the collaborators. If JMFC is preparing an ink, a catalyst layer, or a CCM, this should be spelled out. It appears UTRC is performing tests, but this also needs to be clarified. For purposes of reviewing, it is important to know whether a catalyst layer is prepared by a commercial supplier or by a national laboratory. The Indiana University – Purdue University Indianapolis (IUPUI) collaboration provides interesting results. It would be interesting to see confirmation of the functionalization of the carbon, as well as whether directly functionalizing the carbon yields similar results to those parameter spaces in the rest of the project where I/C contact is enhanced. Collaboration with the University of Texas (UT) was used to show that ionomer tends to associate itself with Pt or PtNi in preference to carbon. It may be interesting to see whether this same trend remains for the IUPUI materials.
- The teaming arrangement is good with national laboratory facilities, a group with stack experience, and a material supplier. Interactions with automotive original equipment manufacturers would be good. It is not clear why the work detailed on slide 13 is done outside of this project, why it is presented as part of the project, and why UT did not contribute, as it seems to be its role. The role of the academic partners seems much more limited in the presentation than as stated in the text.
- The collaborations among several industry, academic, and national laboratory partners are very impressive. It is unclear whether the catalyst dealloying was done at ANL or at JMFC.
- While good collaboration efforts have been made to meet DOE’s technical targets, it was disappointing to learn that it took such a long time for the team to adjust UTRC’s fuel cell testing fixture for the MEA developed in this project. It appears that more cell testing works under the right conditions (e.g., cell pressure) should be done in the coming year(s).
- The coordination appears to be correct, but it may be improved by using all the characterization techniques and resources offered in FC-020 (K. More).

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

This project was rated **3.1** for its relevance/potential impact.

- The project is relevant to the objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. Achieving high mass activity of advanced Pt electrocatalysts at high current density is of great importance to the commercialization of these materials if they are also durable.
- PtNi catalysts are an important new development. Finding optimized electrode constructions is very relevant for these systems.
- This project is highly relevant and has good potential to meet DOE’s targets and goals. A greater emphasis should be placed on cell testing and durability studies for this project to be successfully implemented with high impacts in the end.
- The performance of a catalyst layer or entire MEA begins with processing. The processing affects the structure (or the fluidity thereof during operation), which then affects properties (e.g., pore size distribution, gas diffusivity, and electrical or thermal resistances), which in turn affect performance. Because of this, there are two possible risks to the relevance of a DOE-funded project that attempts to integrate a highly active catalyst into an MEA: (1) higher-volume ink processing will differ substantially from the lower-volume ink processing demonstrated in the project, and (2) there are engineering changes that could be made to enhance processing for a given parameter, despite a poor result within the time frame of the project. In other words, the project could make an attempt to state as scientific fact a result that could be addressed with engineering variables (e.g., solvent, mixing times, and temperatures at different steps). The team does attempt to address a very relevant concern, which is the facilitation of high power density using an alloy catalyst that demonstrates high activity for oxygen reduction.
- The work is very relevant, but the targets are not sufficient for longer-term automotive performance. The increased understanding around the Ni dissolution effects as a function of MEA conditions and the resulting impacts on ionomer are an important step toward achieving better results. There is a concern that even if the Ni is acid washed, the Ni will continue to leach out, and the integrated catalyst system may in the end not be durable enough to maintain performance at the high current density conditions. Because much of the work involves the effect of the Ni interactions with the ionomer, this may reduce the relevance of the work.
- The work in the project, especially the inks, is good, although there needs to be more focus on how this impacts overall cell performance. The project addresses the need to understand how catalyst layers form, but not necessarily the functionality and key structures of the catalyst layer. The functionalization is quite interesting and should be continued with more focus on what is occurring. Perhaps there is a way to do the functionalization before making the catalyst.
- Although the project aligns very well with the Hydrogen and Fuel Cells Program, its potential impact is diminished because it employs the leaching PtNi catalyst.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- A few things could be added to the next steps: detection of Ni in the membrane (perhaps even in the anode layer) and data interpretation for performance curves from 40° to 95°C. Many of the items mentioned in the next steps are worthwhile, including nanoscale computed tomography and the use of results to assist with modeling. Proton conductivity measurements for the catalyst layer are also worthwhile. Given the troubles with Ni, it may be wise for the project to consider the dealloyed PtCo that also was investigated in the General Motors (GM)/JMFC project. This project may be in a good position to clarify the leaching tendencies of Co versus Ni from a dealloyed catalyst. The team should include some metrics that correspond to CCM quality, such as the uniformity of Pt loading and the uniformity of catalyst layer thickness. Experimental bandwidth could be expanded to include the effect of more graphitized carbons than Ketjen black, as well as the effects of engineering parameters involved in ink processing and application.

- The future work described is aligned with the proposed work of the project. The evaluation of the carbon support impact on the treatment (e.g., temperature and acid leaching) should be done, and durability evaluations should be started.
- Focusing on the drop in performance at high current for the d-PtNi/C system makes sense. If significant amounts of Ni dissolve in the membrane, then one would expect reduced high current performance. No durability studies were proposed. If Ni leaching is significant, one would expect the voltage decay to be significant over time.
- The proposed future work is focused on identifying other reasons for mass-transport limitations at high current densities. Porosimetry analysis needs to be complemented by analysis of hydrophobic and hydrophilic pores in the catalyst layer.
- The proposed future work is adequate, although ambitious, for the remaining time period. The focus should be on understanding and the remaining questions instead of just more diagnostics—there is not enough time to bring together the findings. More structural data and long-term stability would be good.
- The surface functionalization of carbon supports should be reconsidered. The gain (i.e., proton conductivity) is significantly less than the loss (i.e., decreased ORR mass activity by 55%) observed thus far.

Project strengths:

- ANL is capable of collecting an extraordinary amount of data. It has maintained a systematic approach to the study, maintaining certain control factors to be constant to focus on particular trends (e.g., particle breakup with more ionomer or with different solvents). ANL has collaborated with an MEA supplier (JMFC) and a stack developer (UTRC). It has used characterization techniques that are particularly for the study of inks (e.g., light scattering). ANL has access to numerous collaborators within the national laboratory system. The project began by using a catalyst that has already been shown to be stable in another publicly funded project.
- The project team is a strength, with ANL and JMFC heavily engaged in catalyst preparation, ink preparation, and post-mortem characterization; UTRC in cell testing; and UT and IUPUI in characterization. The project covers catalyst materials and fabrication, catalyst layer characterization, and modeling and diagnostics.
- Significant characterization is conducted to understand the effect of various variables on the electrode structure. This characterization will be linked to performance using models to arrive at an improved understanding. The assembled team is very strong.
- Overall, the good approaches taken and the strong team members are the strengths of this project. It seems the team activities have been well managed by the PI.
- This project addresses critical needs in terms of catalyst layer fabrication. The overall progress has been good, and the project features a relatively strong team.
- The project features very thorough characterization of ink properties and the impact on fuel cell performance. The modeling supports the experimental work very well.
- A strength of the project is how it combines advanced diagnostic and characterization tools with MEA testing capabilities.

Project weaknesses:

- The project is operating in an area that is essentially an engineering area; a vast number of parameters are available to make something work. This is different from many other DOE projects, where conclusions can be drawn from fundamental science and, therefore, more of a “pass” or “fail” rating can be achieved. From this project, a conclusion may be that the dealloyed PtNi catalyst simply cannot be processed in a certain way into a CCM. An unfortunate conclusion would be if the results generated a false negative to say that dealloyed PtNi cannot be incorporated at all. More attention should be focused on processing parameters that may enable success of dealloyed PtNi at high current densities. There may also be other ink constituents (beside solvent, ionomer, and catalyst powder) that would help with particle breakup and the resulting catalyst layer porosity. The project could use more focus on manufacturing and quality metrics.

Some questions may be asked regarding the production scale being represented in this project and the possible effects of non-uniformities and defects on the results.

- It is not clear whether the modeling is just describing data or providing guidance for fabrication and inks. The project contains a lot of data and diagnostics, but there needs to be further analysis of all of the data.
- It is unclear whether Ni-based catalysts are stable enough for long-term durability in fuel cells. The future work listed a variety of characterization techniques but did not relate those clearly to the remaining gaps in meeting performance targets.
- Employing the leaching catalyst adds complexity to the project. The additional acid-pretreatment step will add cost to the system.
- The focus is on the d-PtNi/C catalyst. Although it seems to be a good choice because of the commercial relevance (coming from a GM project, synthesized by JMFC), the findings around the Ni dissolution may dominate other effects.
- The MEAs containing d-PtNi catalysts have been so sensitive to humidity, and surface functionalization of carbon supports would not be the right solution.
- The lack of durability evaluation of the d-PtNi is a weakness to be overcome.

Recommendations for additions/deletions to project scope:

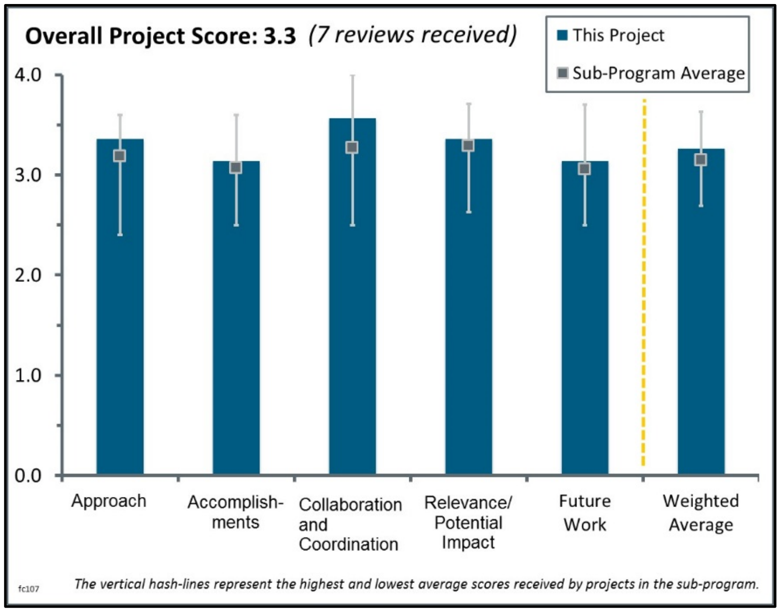
- At this time, there are no recommended deletions. Recommended additions include the following:
    - Greater emphasis on the effect of carbon supports, and on the effect of processing parameters in making inks and catalyst layers.
    - Characterization of ionomer location with carbon functionalization.
    - More attention to catalyst layer, catalyst ink, and CCM quality.
    - Comparison with JMFC dealloyed PtCo.
    - Differentiation of mass transport resistances (e.g., Knudsen, ionomer film).
    - Greater interpretation of results collected from low to high temperatures. Analysis of Ni content in membranes should be reported.
- The project team should provide more visualization of the catalyst layer and also cell-level studies. ANL needs to bring together all of the improvements and understanding for best-of-class MEAs. There are a lot of variations shown, but it is not clear whether they are additive.
- The researchers should increase their focus on the Ni stability in the final fuel cell under normal or accelerated operating conditions. To evaluate the effect of dissolved Ni on performance, it might be useful to study the degree of dealloying versus performance at high current.
- The team should perform experiments to evaluate the carbon support impact on the treatment (e.g., temperature and acid leaching). ANL should start durability evaluations.
- The MEAs containing d-PtNi catalysts have shown poor performance at low RH, and more efforts should be made to improve mass transport at low RH by improving the cathode catalyst layer structure.

Project # FC-107: Non-Precious-Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design

Piotr Zelenay; Los Alamos National Laboratory

Brief Summary of Project:

The overall objective of this project is to advance non-platinum-group-metal (PGM) cathode technology through the development of new materials and implementation of novel electrode concepts, together resulting in (1) high oxygen reduction reaction (ORR) activity, viable for practical automotive systems; (2) improved catalyst durability; (3) high ionic/electronic conductivity within the catalyst layer; and (4) adequate oxygen mass transport and effective removal of the product water.



Question 1: Approach to performing the work

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

- A very comprehensive approach was outlined.
- The project team understands the key issues in developing a non-PGM catalyst: increasing the site density, understanding which sites are responsible for oxygen reduction, using a carbon species that is resistant to corrosion, and developing the tools (e.g., models and fabrication techniques) to minimize the catalyst layer thickness and the associated mass transport resistances. The project scope is compact and avoids activities that add less value, such as building a stack. Ultimately, the catalyst must not include Fe to be compatible with membranes and the ionomer. The approach allows for Fe-free catalysts to be made and tested. However, an enhanced approach would include either greater emphasis on this or greater emphasis on using Fe to understand the mechanism of reaction better. The approach will identify reactive sites, but it leaves out mechanistic studies.
- The project team is incorporating a multi-pronged approach to achieve real progress in the use of non-precious metal (NPM) catalyst. Activity is addressed through modeling and other studies to understand active sites. Durability is measured and characterized, and change in active sites is explored. However, durability cycling in N_2 has low relevance to actual systems. The performance in the membrane electrode assembly (MEA) is addressed through electrode studies and modeling. The use of the Nafion® mapping is interesting, and the linkage to the models is a good approach.
- The project utilizes an effective combination of synthesis, characterization, and modeling. This has led to significant improvements in performance. However, it is unclear whether the modeling implicitly suggests that CM-PANI-Fe-C-based catalysts are limited.
- The project has established defined approaches to increase the activity and number of active sites, and to understand better the nature of active sites in the non-PGM catalyst based on CM-PANI-Co-C and CM-PANI-Fe-C systems. It is not clear how many heat treatment and leaching steps are involved for the catalyst synthesis.
- Given the complexity of understanding performance for non-PGM fuel cell materials, the principal investigators (PIs) have made impressive efforts to utilize all available modern tools to better understand these systems. One important component of this work is to combine experimental results with computational modeling; however, the power of any calculations to model not only the activity of the active centers, but also their stability, is doubtful.

- The focus on non-Fe-based catalyst is a solid approach. The team needs to quantify the amount of metal leached from the catalyst layer to the membrane.

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

This project was rated **3.1** for its accomplishments and progress.

- The project team has made significant progress since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review in terms of physical characterization and modeling work to identify the catalytic active sites for ORR and electrochemical characterization to study the catalyst performance.
- The project team has made steady, incremental progress in improving the catalyst and identifying catalytic sites.
- There is good progress against the targets, and all project performance measures and milestones are either met (some exceeded) or remain on schedule to be met.
    - The project has adopted the updated CWG targets, which are more challenging than the original project targets. The June 2015 durability and selectivity targets were achieved and exceeded, and no Fe was detected in the membrane, which is important for membrane durability. However, the durability target is on N_2, and there was a ~200 mV loss due to cycling in air. There needs to be further work to understand and address this issue. There is good progress on understanding active sites, using a combination of measurements, modeling, and experimental approaches.
    - There is good progress to date on the catalyst layer (CL) activities. There is much more to be done, but the project is heading in the right direction. The Nafion® mapping is interesting, and the approach to use the morphological property distribution inputs from nano-X-ray tomography (nano-XRT) imaging and transport property simulations should provide good insight. The model is validated for the shape of the curves and trends for Nafion® content and water content, but absolute performance values are not predicted. Model prediction for no liquid water indicates a path forward for improvements.
    - The Microstructured Electrode Scaffold (MES) also provides valuable information to probe the ORR and conductivity within the CL as a function of relative humidity (RH). The thinner CL and resulting significantly improved performance data shown is on oxygen. If there are O_2 mass transport limitations, then they are very severe. This result should be further explored with the model. The polarization curves on air should be shown as well.
    - There is quite a mix of conditions shown, such as data on both O_2 and air, but not consistently, and a variety of membrane thicknesses. The team should provide increased clarity to enable comparison of data.
- The team has made good progress, but it needs to focus more on high current density performance improvement under H_2/air testing.
- Progress toward DOE goals is good; however, reference was made to previous goals as well as new goals outlined by the Catalyst Working Group (CWG). It was not always clear to what extent these goals were being reached. This should be more clearly articulated in future presentations, via tables.
- Modest progress has been made so far, especially toward improving the stability of materials. The nature of the active sites, however, is nothing new. These types of active centers have been proposed many times. To make non-PGM materials attractive relative to standard materials, the PIs should consider pursuing more challenging directions. The key criticism is the manner in which PIs are addressing the nature of the active sites. As they are very well aware, determining the nature of the active sites is very difficult now using available techniques. As a result, attempting to develop a reaction mechanism based on the nature of the active sites is very dangerous with the current information presented. In situ spectroscopic techniques are required to even begin to make any such claims.
- Co-based, Fe-free catalysts showed low performance, beginning with low open circuit potential (<0.9 V). Peroxide generation was 10%.
- X-ray absorption spectroscopy (XAS) was performed with Fe-only (no Co) catalysts. Results appear to confirm that the Fe-N_x sites are those that are active for oxygen reduction. Although performance improvements appeared to come from the addition of Co, there was no XAS shown to indicate why that would happen.

- Peroxide generation between 1% and 2% is still too high.
- It would be good for the catalyst layer thickness to be reported on some of the polarization curves.
- The team appears to have validated the model predictions versus the experimental results; it is unclear whether the model was used to improve the performance of CM-PANI-Fe-C. LANL appeared to have investigated numerous catalyst layer thicknesses using the same catalyst loading. However, it is unclear which thicknesses were associated with the performance improvement shown, and whether the model would have predicted the improvement.
- It was unclear what the cycles were for the XAS durability study. The cycling may be 0.3–0.7 V according to one slide, but it is hard to say.

Question 3: Collaboration and coordination with other institutions

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

- The project has excellent collaboration among national laboratories, academic institutions, and industries. So far, each collaborator has performed its specified tasks in support of the project objectives.
- The project lead has put together an outstanding team of PIs who are providing a wealth of valuable information required to move the field forward.
- The collaborators appear to be well coordinated, and the presenter made clear their respective roles.
- This is a large project team, with what appears to be good coordination between groups.
- Collaboration is needed with the University of Waterloo on Fe-free catalysts. Hopefully, collaboration can be used to develop better Fe-free catalysts. The nitrogen oxide dissociation observed by the University of Rochester helped to confirm what was also seen by XAS: that the active site is Fe-N_x. The nanoscale computer tomography performed by Carnegie Mellon appears to have greatly assisted the effort to produce a catalyst layer model, so as to predict proton conduction and oxygen diffusion. Oak Ridge National Laboratory showed that there are still disconnects in the catalyst layer between ionomer and the active sites. The project team has done well to add both a supplier and a developer—IRD Fuel Cells and General Motors (GM), respectively. IRD appears to have added to the project by enabling better fuel cell performance, although some of the background on this is not in the presentation. The collaboration with GM does not appear to be represented in the presentation.

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

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

- Because the project follows the adjusted targets for non-PGM catalysts, it maintains relevance. These targets are based on the premise that stack size should not be increased to accommodate the removal of Pt. An increase of stack size drives issues with cost, packaging, and robustness at low ambient temperature operation. The removal of Pt would be extremely helpful in allowing commercial fuel cell vehicles to achieve cost targets.
- The project aims at the development of non-PGM cathode catalysts, which are important for the development of PEM fuel cells (PEMFCs) for automotive applications.
- The potential impact of this work is immense; however, the challenges are equally large. If the PIs would be able to develop active and stable non-PGM material, this would be outstanding. Many past effortsts have failed to introduce materials that do not have Pt as the active site. DOE should definitely support more research in this field; however, the progress should be much faster to be able to determine whether working with non-PGM materials is the right direction.
- It is still difficult to determine whether NPM catalysts will have a prolonged role in automotive fuel cells. The work is relevant because the goal to minimize Pt from the PEMFC is worthwhile. However, a more relevant goal would be to target a maximum total PGM per vehicle and stack cost, rather than just the elimination of PGM. The relevance of durability target V cycling in N_2 is low. The cycling in air resulted in much higher degradation and is of much higher relevance.

- The cost analysis shows this catalyst is economically viable, but the results do not definitively suggest the performance will ever be high enough.

Question 5: Proposed future work

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

- A strength of this proposal is its careful and systematic approach. It seems clear this clear approach will be applied to the next steps of scale-up and MEA integration.
- The team has proposed reasonable future work for the remaining project period. It would be good if the team performs durability studies of the most promising non-PGM catalyst developed in this project.
- The team has laid out the important future work to be addressed. However, the durability issue on air requires further attention.
- It would be useful to see more information on how the project team plans to improve Fe-free catalyst activity, improve open circuit voltage, and decrease peroxide generation. It would be useful to see more reporting on the model validation. The model was generated to fit data, but this likely involved some parameter adjustments. The question then remains whether the model can accept a nanoscale computed tomography image of a GM or IRD catalyst layer, and then still predict the resulting performance. Active site determination is mentioned in the future work. However, there should also be emphasis on determining the oxygen reduction mechanism. A number of the future work items are reasonable: improvement of Fe-free catalyst activity, determination of active sites, nanoscale computed tomography on new catalyst layers, and further work to study degradation.
- The research team needs to understand the impact of catalyst layer ionomer content and membrane thickness or the use of state-of-the-art membrane on the H_2/air performance.
- There was not a great deal of details provided, so this is more difficult to assess. The team should provide fewer proposed work items and describe them in greater detail.
- There was not a clear path in the proposed work toward developing non-PGM materials for real-world applications.

Project strengths:

- The lead PI is a world-leading expert in this field, and there is a real opportunity to make a contribution. The unique synthesis capabilities of Los Alamos National Laboratory (LANL) and the ability of the other partners to characterize materials under realistic conditions are impressive. In particular, the use of spectroscopy and transmission electron microscopy (TEM) imaging is incredibly important because the combination of these techniques is really the only way to define the materials' properties and limitations, and ultimately to determine what contribution non-PGM materials will make to the fuel cells community.
- Led by LANL, the project has access to considerable collaboration and analytical capability. The project is led by investigators with extensive history in non-PGM oxygen reduction catalysis. The project has tasks that address most of the barriers to non-PGM catalysis, including mass transport and proton conduction resistances, lack of active sites or active site density, and the need for developing Fe-free catalysts. The project has incorporated collaborators that include a supplier, a developer, and a university with a unique ability to image catalyst layers.
- The project features a large, multi-talented team that is addressing the work from various angles—density functional theory (DFT) and electrode modeling, novel characterization methods, detailed analyses, understanding of active sites, and industrial partners.
- The PI has very good collaboration with national laboratories, universities, and industrial partners. The team has a thorough understanding of the problems associated with the non-PGM catalyst development.
- This project integrates efforts from several different partners effectively. There appears to be close, open collaboration between the partners.
- The creative and capable team is a strength of this project.

Project weaknesses:

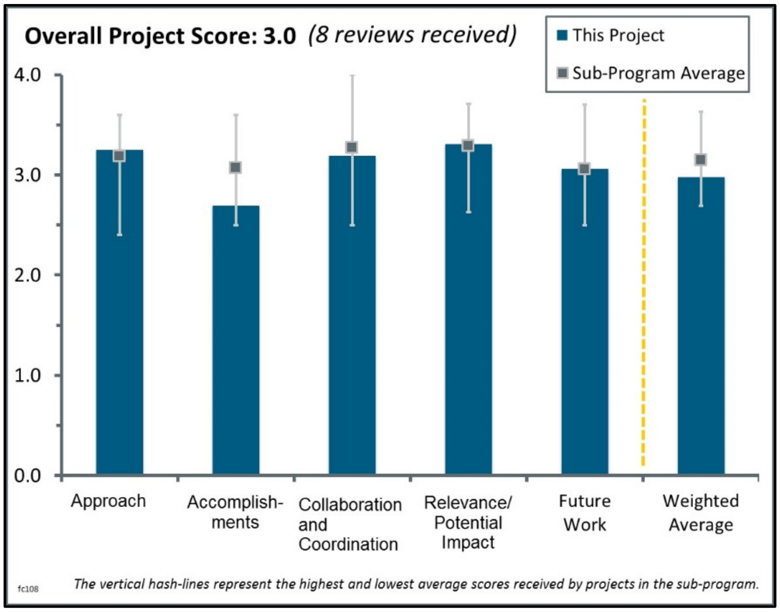
- LANL needs to identify a strategy to understand the oxygen reduction mechanism for all catalysts involved: Fe-based, FeCo-based, and Co-based. The generation of hydrogen peroxide is still too high for most catalysts. High current density is still an issue, and it may be difficult to address even with improvements in the catalyst layer. Power density is still only near 0.5 W/cm^2, at best. There appears to be an acknowledgement that durability of the $Fe\text{-}N_x$ site is a problem, but it is difficult to see whether there is a strategy to address this issue.
- LANL should more clearly articulate progress toward DOE targets. There was reference to the original DOE targets as well as to updated targets based on the CWG. It was not always clear in the presentation which targets were being used as a reference point. A summary table of these targets versus progress/ milestones would be useful in the future.
- As is, there is no true relation between the number of active sites, the nature of these sites, and the stability and reactivity of these sites. Furthermore, there is no clear direction toward other classes of materials if the materials currently being studied do not work.
- It would have been better if the team had presented some durability results for the CM-PANI-Co-C and CM-PANI-Fe-C catalysts.
- The inconsistency in the data and conditions was an area of weakness. The scope may be too broad for the team to effectively accomplish everything.
- The path to scale up these catalysts to 100 g batch sizes is unclear.

Recommendations for additions/deletions to project scope:

- The project should place greater emphasis on the mechanism for both oxygen reduction and the degradation of the $Fe\text{-}N_x$ active site. It would be a problem if the project overachieved in developing the very best catalyst layer for a catalyst that was not active, that was not durable, and that contained a membrane-degradation catalyst (Fe). LANL should add a plan to improve Fe-free catalyst activity.
- The team could use the models to run a scenario analysis and determine what an ideal CL would look like, and what optimum performance could be achieved with current catalyst parameters. Further, it is unclear how this would vary with catalyst activity and active site concentration, within expected achievable parameters. This would provide an assessment of possible maximum performance achievable.
- Future work should include a discussion about the future of these materials. The science itself is absolutely fascinating, and the cost is so low that it is difficult to resist going in this direction, but the question is how fast one can get there.
- It would be interesting to see the correlation between the amount of nitrogen in the catalyst and the catalyst activity/durability.

Project # FC-108: Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells

Bryan Pivovar; National Renewable Energy Laboratory



Brief Summary of Project:

The goals of this project are to synthesize novel perfluoro (PF) anion exchange membranes (AEMs) with high temperature stability and high water permeability and to employ those high-performance PF AEM materials in electrodes and as membranes in alkaline membrane fuel cells (AMFCs).

Question 1: Approach to performing the work

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

- The approach of pursuing PF AEMs is also a good choice to maximize the possibility of developing AEMs that ultimately have the desired properties. The emphasis on fundamental understanding of the chemistry and the composition and properties of the resulting membranes is also excellent.
- The approach for this project is well founded and seems to be leading to excellent results.
- The approach is interesting and worth exploring. The reasoning—that the morphology generated through the acidity of perfluorosulfonic acid (PFSA), which has been found beneficial, should also prove beneficial in AEMs—is solid. The synthetic pathways chosen by the researchers were straightforward and reasonable.
- The approach to utilize PF polymer electrolytes has merit because the PF electrolytes are chemically robust, and from polymer electrolyte membrane (PEM) ionomer experience, the PF polymer backbone appears to aid in obtaining phase segregation and an appropriate microstructure for ion conduction. Plans to attach the cation through an electron-rich segment such as an aryl group or aryl amide group should reduce the electron withdrawing effect of the PF polymer. The cation groups being employed have decent stability, but they are not the most stable.
- The great majority of AEMs are based on hydrocarbon polymers. The approach of this project consists of developing AEMs with a PF backbone. The PF backbone, while electron withdrawing, should provide higher stability to the final AEM. The challenge here is to synthesize membranes with chemically stable cations and—at the same time—reasonable OH- conductivity.
- The overall approach to this project is good; it is based on the principle of functionalizing a perfluorinated polymer backbone with quaternary ammonium group and a non-alkyl spacer to prevent the Hoffman degradation reaction. While the chemistry is sound for making materials, the project is struggling with making membranes with practical hydroxide ion conductivity. The conductivities are currently more than an order of magnitude too low for practical use, and there is no clear path forward for improving these conductivities. The perfluorinated polymer backbone approach has proven to improve the water transport properties of the membrane, which was one of the stated goals of this project.
- The presentation clearly highlighted the status of the work and the challenges involved. This is indeed a challenging effort, and the scope of the work may have been too ambitious from the start. Future efforts should separate the synthetic chemistry work from the fuel cell stack testing work (which is where the delay is occurring). There were three distinct areas of work mentioned, and all three could readily constitute stand-alone tasks, given the complex nature of the problems: (1) synthesis of polymers/ionomers for alkaline membrane electrode assemblies (MEAs), (2) stack-level testing, and (3) modeling of carbonate formation. This task should really only be focused on item 1, and it is recommended the U.S. Department

of Energy (DOE) Fuel Cell Technologies Office (FCTO) solicit separate proposals to cover areas 2 and 3 in the future. With regard to item 1, the project is taking the correct approach.
- A coherent, focused approach in this project is hard to discern given the several different synthesis approaches which have shown mixed success.

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

This project was rated **2.7** for its accomplishments and progress.

- The accomplishments and progress appear to be impressive and seemed well received with the audience.
- Progress for the amide linkage chemistry has been slowed by the choice to initially characterize the chloride form, which did not allow the researchers to see the formation of the much less conducting zwitterion in base. Adding an additional reaction step may allow the researchers to bypass this by methylating the sulfonamide link under basic conditions. Work with small molecules suggests this should fully methylate the sulfonamide position; however, reactions with the polymer suggest incomplete reaction. The alternate synthetic strategy to utilize Grignard reagents to attach the cationic moeity has not been any more productive. Researchers have encountered difficulties finding a suitable solvent that will dissolve, or at a minimum swell, the polymer enough and also be compatible with the Grignard reagent. Semi-fluorinated hydrofluoro ether (HFE) fluids appear to have some promise, and small molecule Grignard reactions work in these solvents. The researchers do not yet have results with the polymer and molecules of interest. The synthetic approaches have been unsuccessful, so MEA preparation, testing, and characterization have not been occurring. The project is behind schedule and will likely need to extend beyond the scheduled end date to prepare and test the AEM in MEAs.
- Significant progress has been made in all fields of work. While the progress toward the development of a PF AEM polymer seems to be satisfactory, bringing these polymers into a membrane, and consequently into a non-platinum-group metal (PGM) MEA that shows high fuel cell performance (>350 mW/cm^2), remains a huge challenge. The reported fuel cell performances for the synthesized MEAs, compared to the CellEra baseline, are still too far from the proposed objectives.
- Much work has been done, and several approaches have been tried, with less-than-complete success. No chemistry to date seems to make the grade, although slide 4 claims victory through 12/31/14. Future milestones are TBD. The team is learning a lot, although the results are disappointing. It would be helpful for the team to provide a summary list of accomplishments.
- The group has unfortunately suffered a lot of setbacks at the synthesis step; this is not terribly surprising because these perfluorinated polymers are very difficult to work with in terms of reactivity and solvent compatibility. The lead's strength, just by resume and reputation, is really in MEA development and characterization, and not as much in polymer synthesis; however, the researchers do have collaborations with very strong synthetic polymer chemists. Their determination to keep finding new pathways is to their credit. In the final analysis, however, there is very little here that can be used either in terms of actually leading to a commercially viable product or deeper insight into AEMs.
- The team has completed 60% of the project work, with 85% of the scheduled project duration complete. This is due to the team setting overly ambitious project goals initially. If the project were to receive a no-cost extension, it may be able to fulfill the stack test work.
- There was very little progress toward reaching the project goals this year. While the fiscal year 2015 milestones have apparently been met, the milestones should have included a hydroxide ion conductivity target rather than, or in addition to, the water permeability target. The project is still struggling with making membranes, and the demonstrated conductivities are too low for these membranes to be practical. In addition, the fuel cell performance, only shown in the backup slides, is very poor compared to the commercial hydrocarbon membranes.
- It is somewhat disappointing that the project is not further along than it is at this point (e.g., cell testing), but it is clear some critical things are being learned that should enable faster progress in the future. The addition of cell modeling work is greatly appreciated, especially in the current absence of cell data. The use of some literature data on carbonate equilibrium to validate the model is also good. However, cell data will be required to validate the complete cell model.

Question 3: Collaboration and coordination with other institutions

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

- The principal investigator (PI) obviously has an excellent working relationship with his collaborators, and 3M's contributions to the project are particularly worthwhile because it appears these contributions have enabled the team to make significantly larger and more uniform membranes. The addition of the modeling work is also valuable.
- A fantastic team has been assembled here. 3M and the Colorado School of Mines (CSM) have the best synthesis experts in this area, and CellEra will likely be first to market with these materials.
- The collaboration on this project is excellent and includes a very good mix of academia, national laboratories, and industry.
- The project seems to have excellent collaboration between the different institutions and is well coordinated.
- The team is well rounded and competent, and there are established working relationships.
- The collaboration between 3M, CSM, and the National Renewable Energy Laboratory (NREL) appears to be working OK. The inclusion of CellEra is a positive.
- While NREL has assembled an outstanding, highly qualified team for this project, it is unclear what all the project partners have contributed to the project. While the PI did call this comment out in his "response to reviewers' comments" and said it was addressed through a more detailed description of the team members' roles, the detailed description still showed overlap between the organizations' roles and no clear indication of what project progress is attributable to what organization. This could have been resolved by identifying the source of the data and materials on each accomplishment slide.
- The project received good support from 3M, which is positive. Strong vendor interactions will be required for project success. CellEra could not yet be engaged in a meaningful way because of the synthetic challenges. In the future, the project team should engage additional partners that have strong synthetic organic backgrounds to assist with the CSM effort.

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

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

- The development of AEMs has a large potential impact because they would be an enabling technology for alkaline fuel cells that could effectively utilize inexpensive non-PGM cathode catalysts. These fuel cells could have large cost savings compared to current PEM technology. The proposed work attempts to address performance issues with current AEMs.
- This is a good example of the type of high-risk, but potentially high-reward, research that should be included in DOE's portfolio. It is unlikely that AEMs will receive much industry interest/investment unless some of the major risks have been reduced. Yet, if successful, AEM fuel cells could be game-changing, primarily because they offer the potential for lower catalyst costs.
- The project is targeting the main challenges in the development of fuel cells—elimination of the expensive PGM catalysts currently needed in PEM fuel cells..
- AMFCs continue to be an important technical challenge DOE should be tackling as a parallel path to reduce fuel cell operating costs.
- Development of AMFCs aligns with the FCTO's mission.
- AEMs still have a number of challenges, but this project is addressing the biggest issues.
- The consensus seems to be that a new AEM is important, but it is too early to determine whether this is the right approach.
- With only a few months left in the project, there is quite a bit to do. The project needs to overcome many hurdles to demonstrate the polymer materials developed in this project will have any impact on the performance or durability of AEM fuel cells.

Question 5: Proposed future work

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

- The proposed future work seems in line with the objectives and has the potential for great impact.
- The proposed plan appears to be appropriate, considering the current status of the project.
- The proposed future work is logical and appropriate to pursue, although it is not certain this work will solve the problems encountered with the polymer chemistry, especially for the Grignard approach. It may be necessary to start with lower equivalent weight (EW) material and then do crosslinking, or to try other synthetic strategies. Membrane characterization should be performed in the hydroxide form before MEA fabrication and testing are performed.
- According to slide 22, the project has to be focused on improved polymer synthesis as the critical enabling element toward AEMs in energy applications. It is, however, important to identify, specify, and justify the different directions to avoid possible trial/error approaches. At this stage, it looks like that by avoiding one problem (i.e., zwitterionic amide linked polymers), other problems will appear (e.g.., piperazine being a potential crosslinking agent and hygroscopic).
- The future work is perfectly appropriate; it would just be better if the researchers were further along in the project. The use of new functionalities and the chemistries to achieve those functionalities are exactly what the researchers should be investigating.
- The planned future work is rational. Completion in the remaining time seems unlikely.
- The prospects for success of the future work have been dimmed somewhat by the synthetic challenges—MEA preparation and testing may not be possible. The team should drop the CO_2 modeling effort because it is a distraction. CO_2 modeling should be funded as a separate effort next year.
- The proposed future work is a good portion of the entire project's scope, and there are only a few months left in the project.

Project strengths:

- Strengths include the following: (1) the project team's expertise in different polymer synthesis, (2) the project team's expertise in membrane fabrication, (3) the project team's ability to identify the problems associated with the loss in performance (fuel cells), (4) that partners are full participants and well coordinated, and (5) that partners are aware of the high-risk/high-return spectrum when working with AEMs.
- The approaches toward functionalization of a perfluorinated polymer backbone are strong. The project features a potentially strong team, although it is not apparent in what way the team members are contributing to this project.
- The project features a very strong team with good collaborations. There is a sound rationale to the approach, and the project is on a path that should be explored.
- The team's focus on trying to fully understand the synthesis and the resulting membranes is an area of strength.
- The partnership with 3M brings particular strength to this project.
- The team and its creativity are an area of strength.
- The diverse project team seems very strong.

Project weaknesses:

- There is a lack of progress and lack of foresight on how membranes would be fabricated from these materials. There is too much ground to cover in the remaining few months of this project.
- The project has been hampered by the researchers' inability to get the desired reactions to go to completion with the polymer systems chosen.
- The project has experienced difficulties with regard to identifying the problems before assembling the polymers into an MEA configuration.
- The project is too ambitious and should be focused solely on the synthetic challenges.
- Progress on the synthesis is very slow.
- To date, there has been a lack of relevant cell data.

Recommendations for additions/deletions to project scope:

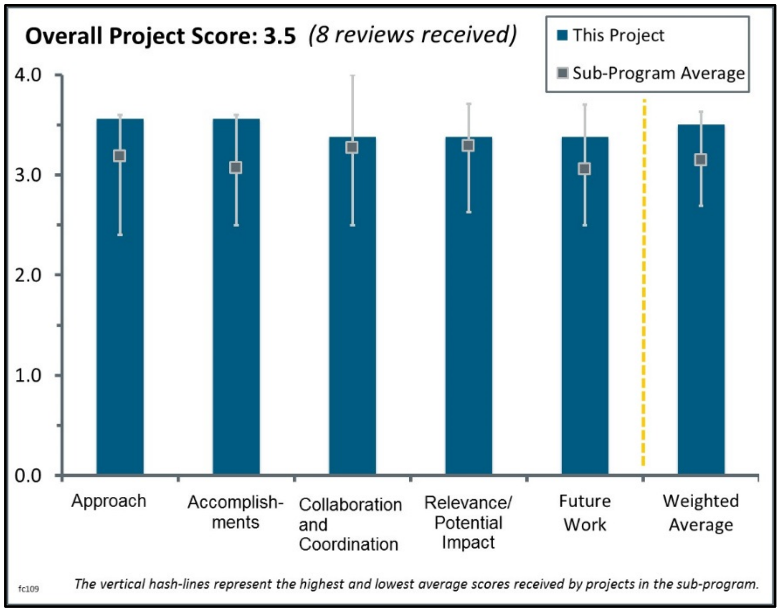
- The cell model should include the impact on ionic conductivity due to the equilibrated concentration of carbonate species (e.g., as shown on slide 17) in both the membrane and the ionomer in the electrodes. In addition, the cell model should include the possibility of free ions in the liquid phases of the cell that are therefore subject to migration and diffusion during cell operation. The presence of concentration gradients of carbonate species may be an issue and may result in localized precipitation of carbonates under certain conditions. If the researchers think the presence of free ions is unlikely, they should demonstrate (in beaker tests, at a minimum) that water in equilibrium with these membranes remains neutral.
- Currently, 3M is providing starting material, but the project may want to find someone who can conduct the synthesis from the start or provide a polymer that is easier to modify. This is likely out of 3M's scope or interest, however, and it is almost impossible to find someone to do tetrafluoroethylene (TFE)-related synthesis.
- The challenges associated with the fabrication of stable ionomers to be used in the catalyst layers have to be considered. Membrane characterizations have to be more focused to its hydroxyl form.
- The carbonate modeling and MEA preparation/testing should be moved to separate tasks.

Project # FC-109: New Fuel Cell Membranes with Improved Durability and Performance

Michael Yandrasits; 3M

Brief Summary of Project:

The overall objective of this project is to meet all of the U.S. Department of Energy (DOE) Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan membrane targets for performance, durability, and cost simultaneously with a single membrane. Tasks include ionomer development, nanofiber development, ionomer and membrane testing, membrane electrode assembly (MEA) fabrication and fuel cell testing, and stack testing.



Question 1: Approach to performing the work

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

- The work is aligned with DOE goals and addresses the barriers of cost and durability. This project addresses DOE membrane targets and is designed to meet all DOE membrane targets simultaneously with a single membrane. The project combines and attempts to improve upon previously effective approaches to reduce swelling and improve performance. The project takes a very systematic approach to developing membranes by looking at how variables such as the number of acid groups per side chain and fiber fraction affect conductivity and swelling.
- 3M is pursuing perfluorinated polyimide acids (PFIAs) as membrane electrolyte ionomers to improve the performance and durability of polymer electrolyte fuel cells. This approach is promising and has the potential to overcome performance and durability issues faced by conventional perfluorsulfonic acid (PFSA) ionomers. The issues with swelling of these low equivalent weight (EW) materials are being addressed by fiber reinforcement, either through traditional incorporation of a weave of an inert support or by electrospinning fibers of the PFIA and support polymers.
- This project is following a well-thought-out plan of synthesis, membrane preparation, membrane testing, MEA preparation, and MEA testing that thoroughly tests out a promising direction of membrane chemistry. The project investigates both new base ionomers for the membrane and new forms of membrane reinforcement in a drive to satisfy all DOE goals simultaneously.
- Up to this point, the approach to achieving the milestones appears solid. The efforts of the different institutions appear well integrated.
- The use of fibers to improve membrane properties is excellent, and results show partial success at this time. The ionomer should really be studied in parallel because it is the key component of the catalyst layer. There are questions about whether a soluble ionomer is available and how it performs compared to Nafion. This should be an essential part of the study, but it appears the principal investigator wants to obtain separate funding to address this issue in the future.
- This project seeks to develop new PEMs perfluoro ionene chain extended (PFICE) with improved conductivity and mechanical properties. Mixed fiber mats are a novel approach—they significantly reduce membrane in-plane swelling while retaining good conductivity (at 80 vol% PFSA). The membranes have been tested for a series of properties, including ion conductivity, swell and water solubility, and mechanical properties. It would be great if some membrane transport properties (e.g., water uptake, diffusivity, and gas permeability) were shown.

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

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

- The 3M-led team has shown excellent progress this year in increasing membrane conductivity at low relative humidity (RH) (i.e., a fivefold increase in conductivity achieved versus state-of-the-art PFSA at 50% RH). The 3M PFIA membranes now have conductivity exceeding 0.1 Siemens (S)/cm at 50% RH, which is a key achievement toward improving fuel cell performance at low RH. 3M has demonstrated that the PFIA membranes have very low solubility in water—an important consideration when reducing membrane EW. The PFIA membranes do show considerable swelling, which needs to be addressed. 3M is planning on addressing this issue by utilizing nanofibers of PFIA interwoven/fused with inert or PFSA polymers.
- The project has achieved significant accomplishments. Two major breakthroughs were made. For the PFICE-4 membrane, a conductivity of 0.1 S/cm was achieved at 80°C and 40% RH, which is a fivefold improvement. For the dual-fiber PFSA/polyamide-imide (PAI) membrane, membrane lateral swelling was reduced to 5% as ionomer content dropped to 80 vol%, while decent conductivity of 0.08 S/cm (at 100% RH) was maintained. Good correlations—membrane water solubility versus EW and membrane linear swell versus EW—have been generated. The swell predication model allows for evaluating nanofiber materials easily and effectively. Pressure ramping to burst mode is well applied to evaluate membrane failure.
- 3M has made a PFIA membrane that showed performance in a single cell better than its supported 750 EW 3M membrane at 95°C and 26% RH (inlet) and could achieve greater than 0.5 V at 1.5 A/cm^2 at 95°C and 50% RH. This same membrane met the open circuit voltage (OCV) hold target and mechanical stability (RH cycling) target. 3M improved conductivity by approximately a factor of five compared to NR112. This effectively moves the RH at which one gets a conductivity of 0.1 S/cm from 80% RH to 40% RH at 80°C. In the past year, development of PFICE-4 membranes has progressed, and the researchers have achieved a conductivity of >0.1 S/cm at 80°C and 40% RH. The researchers have developed a model that can predict membrane swelling based on the fiber modulus and fiber fraction. They have identified two paths to a membrane that should meet the targets. Data and testing at high temperatures (120°–95°C) are lacking. The DOE target table targets a maximum operating temperature of 120°C. It is not clear how the dual-fiber electrospun membranes compare to other nanofiber-supported membranes, and whether there is an advantage to the dual-fiber electrospinning approach.
- This project has made good progress on synthesizing advanced ionomers, forming them into membranes, and testing the chemical and physical properties of the membranes. Fabrication of 50 cm^2 MEAs and testing of performance and durability are about to start. The project has achieved ionomers of low EW that are also insoluble in water—an improvement over PFSA. It is not clear that currently available (2015) membranes are unable to meet fuel cell requirements, so this area of research need not have the same priority as other, more pressing issues in fuel cell development. It is good to still have two paths available toward meeting Milestone 8.
- Good progress has been achieved over the past year, and development appears to be on track.
- The progress to date appears to be excellent. Ionomer development has progressed, with a number of samples showing promising performance. Data on the OCV hold test indicates that the PFIA membrane passed the test; however, this conclusion is questionable. The OCV for the PFIA material decreased by ~100 mV within <100 hours, and is then compared against other material where the OCV is stable at ~0.93 V. Comparing durability at OCV of 0.82 versus OCV of 0.93 is not a fair comparison. The researchers failed to show crossover data, and the OCV is only a portion of the story. This evaluation needs to be more fairly presented and made; it is possible that the PFIA membrane really failed this test within 50 hours, because the OCV decreases by >100 mV.
- Milestones have been met, albeit with different materials used to meet different milestones.
- Success has been shown in obtaining a membrane that performs better than Nafion at low RH. It is not clear why conductivity measurements have not been shown for 100% RH and liquid water.

Question 3: Collaboration and coordination with other institutions

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

- The project has a great team working on membrane synthesis and characterization. 3M has been well recognized for developing fuel cell membranes. General Motors (GM) is very good at membrane characterizations and tests. Vanderbilt has great expertise on electron-spun nanofiber fabrication.
- The collaborations with GM and Vanderbilt appear to be going well. The electrospinning work is progressing, and testing at GM has been progressing and is valuable to the project.
- The collaborations appear well utilized. The expertise of the different institutions is leveraged well, with no apparent hindrance to synergistic goals.
- The project features effective collaboration between the partners, although the true test of the strength of the interactions will be shown by the level of thoroughness of the upcoming testing in stacks. Project leaders have been helpful with advice and materials to help keep other DOE-funded membrane projects moving forward.
- The interactions with both GM and Vanderbilt seem productive.
- The project features strong contributions from collaborators.
- 3M has assembled a highly qualified team to address the issues. While Vanderbilt's role is clearly defined and necessary as an alternative approach to forming supported membranes to reduce issues with swelling, GM's unique role is a bit less clear—it seems 3M can and does perform many, if not all, of the measurements that GM is performing. GM's role, beyond testing, appears to be in additive development, but this was not covered this fiscal year.

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

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

- The project is very relevant because it is aligned with DOE goals and would have a large impact on system cost. A membrane that can meet DOE targets and operate at low RH and higher temperatures would be extremely beneficial for the FCTO because it would allow one to eliminate the membrane humidifier and reduce the size of the coolant system, leading to substantial cost reductions in the balance of plant.
- This approach is promising and has the potential to overcome performance and durability issues faced by conventional PFSA polymers, especially the sensitivity of the conductivity of conventional PFSA to low RH.
- The ability to operate at higher temperatures and lower RHs is a substantial benefit to fuel cell system developers because it increases the operating envelope, facilitates heat removal, simplifies control, and decreases the size of the humidifiers. This project can positively impact the viability of commercial fuel cells.
- Higher-conductivity, more stable membranes are useful. A benefit analysis of these materials versus the current state of the art would be useful; the project appears to address the membrane conductivity, but it is hard to know whether there is a cost-benefit.
- Although current membranes are satisfactory, having a membrane that works at low RH is a good idea. Operating a PEM fuel cell at higher temperatures is not a good idea because the catalyst layer will fall apart and degrade at higher temperatures, even if the membrane survives.
- The potential impact is high, given that the project is on track to develop membranes that meet the 2020 DOE milestones. However, the use of different materials to satisfy the stability versus performance metrics is a potential shortcoming. The true validation of the potential impact will not be clear until Milestones 10–12, when the membrane will be evaluated in an operating fuel cell.
- Membranes with improved conductivity and acceptable mechanical properties could improve fuel cell performance. This project helps keep one of the few laboratories that can synthesize perfluoro ionomers active in the development of advanced membranes at a time when other formerly active enterprises are either inactive or getting out of the business. Membranes have improved so much in the past decade that it

is not clear that further membrane development is essential. This project seems unlikely to significantly reduce membrane costs.
- The improved conductivity at low RH (40%) and improved mechanical property are significant accomplishments. The objective of this project is to meet membrane performance, durability, and cost targets simultaneously in a single membrane. The cost of nanofibers is a concern. In addition, the research is focused on 95°C and 50% RH. It should be stated why this condition is highlighted; for standard conditions (80°C and 100% RH), there are many good existing membrane candidates.

Question 5: Proposed future work

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

- The planned future work addresses the appropriate barriers and is focused on meeting DOE performance and durability targets.
- The future plans seem well thought-out and likely to yield positive results, assuming all partners remain willing to carry out their planned roles.
- Efforts to refine membrane design and conduct stack testing are on track and logical progressions for the project.
- The 3M-led team has an excellent grasp of the remaining issues and how to address them. The development of stabilizing additives and how this is incorporated in the future of the project is not clear.
- The future work plan is detailed and reasonable. However, it should include membrane chemical stability testing and membrane transport properties (e.g., water uptake, diffusivity, and gas permeability); the latter would impact MEA performance at high current density.
- It would be good to see more MEA test data by the next DOE Hydrogen and Fuel Cells Program Annual Merit Review (although data may be limited during the second quarter in 2016). MEA testing should not be limited to stack testing but occur on single cells, and thus not be limited to material scale-up. It is unclear whether the nanofiber development is going to be used or not. If it will not be used in the membrane materials, it is unclear why it should continue.
- The future work should include characterization of the ionomer and its use in the cathode catalyst layer. The impact of the permeability of oxygen and hydrogen on the performance can be clearly understood by using these materials in the catalyst layer.
- It is unclear how it will be determined whether the PFIA- or PFICE-based membrane will be selected for pursuing Milestones 9 and 10. The former exhibits desirable mechanical properties, but the latter exhibits the greatest potential for high conductivity. There is not a clear path forward for how to obtain both of these salient metrics in a single membrane. It is also unclear what the path forward is for improving the mechanical properties of the nanofibers while retaining high conductivity.

Project strengths:

- The project has a high-quality team with the capability to do manufacturing and good knowledge of the current membrane state of the art and requirements in real-world applications. The concepts for improving membrane conductivity and limiting swelling have been proven. The plan to make and test a commercially relevant membrane, which includes the improved ionomer, an improved support, and a chemical stabilization package, is a strength.
- This project provides a highly reasoned development pathway to improve membrane performance while maintaining or improving mechanical properties. This project keeps one of the few laboratories that can still handle the synthesis of perfluoropolymers active in the development of improved membranes, while most of the rest of this industry is moribund.
- For the PFICE-4 membrane, a conductivity of 0.1 S/cm was achieved at 80°C and 40% RH, which was a fivefold improvement. For the dual-fiber PFSA/PAI membrane, membrane lateral swelling was reduced to 5% as ionomer content dropped to 80 vol%, while decent conductivity of 0.08 S/cm (at 100 % RH) was maintained. Comprehensive mechanical tests of the membrane have been performed. Having a great team with complementary experience will ensure the project makes good progress. The combination of experimental data with modeling is a plus.

- The project technology appears to have a clear, tangible benefit for fuel cells that is a distinct improvement over current technologies and can readily be incorporated into existing platforms.
- Material synthesis and testing efforts are progressing well.
- The project features an excellent approach and execution.

Project weaknesses:

- The difference between the mechanical properties in the machine and transverse directions has not yet been overcome, and no clear ideas on how to deal with this appear to have been given in the presentation. 3M management's blanket policy of not discussing the manufacturing costs of present or potential products decreases the value of this project in guiding DOE's development efforts and could lead to inefficient use of society's resources if technically promising developments were to turn out to have costs that are too high.
- Transport properties such as water uptake, diffusivity, and gas permeability are desirable.
- There are questions about the OCV stability of the membrane or the MEA, and why the OCV decay was relatively rapid down to ~0.82 V.
- A weakness is the lack of study of the ionomer by itself and in the catalyst layer.

Recommendations for additions/deletions to project scope:

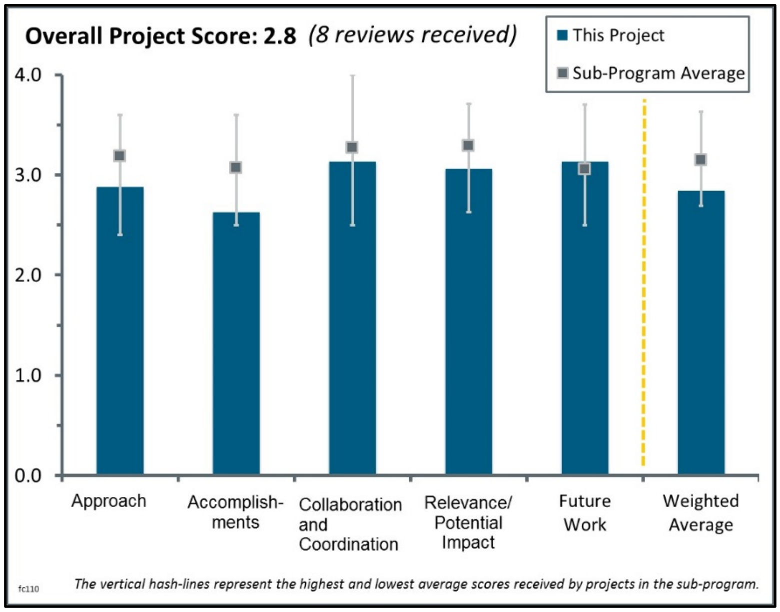
- There are no recommendations for additions/deletions to the project scope—the current scope is very appropriate.
- It would be good to see more single-cell MEA testing. The chemical stability needs to be reevaluated and compared more directly against other current membranes. While it is recognized the researchers used the standard OCV test, comparing one membrane's durability against another with OCVs that differ by ~100 mV is not a fair comparison. The researchers need to present gas crossover data, not just OCV data. Efforts to understand why the OCV decayed so rapidly (within 50 hours) should be added to the project scope if the cause is not just gas crossover. If the rapid decay is just due to increased gas crossover, then this membrane really failed Milestone 4, and the chemical stability needs improvement.
- Although MEA development and testing are tasks within the project, it is not clear whether the catalyst layers are conventional or 3M. If possible, the effort should be extended to ascertain the effect of using imide ionomers in conventional catalyst layers because there could be potential performance benefits, especially at low RH.
- The team should study the ionomer's properties independently and the ionomer's application in the catalyst layer.

Project # FC-110: Advanced Hybrid Membranes for Next-Generation Polymer Electrolyte Membrane Fuel Cell Automotive Applications

Andrew Herring; Colorado School of Mines

Brief Summary of Project:

The overall objective of this project is to demonstrate a low-cost hybrid inorganic/polymer from super-acidic inorganic functionalized monomers with (1) area specific resistance (ASR) <0.02 Ω cm^2 at operating temperature of an automotive fuel cell stack (95–120°C) at low inlet relative humidity (RH) <50%, and (2) a 50 cm^2 membrane electrode assembly (MEA) with desired mechanical properties and durability. The current-year objective is to optimize the two best candidate systems for low ASR, mechanical properties, oxidative stability/durability, and incorporation of electrodes, ultimately eliminating the lowest-performing system.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- This project follows one of the few really novel approaches to improved membranes and has finally generated a material that should be testable in fuel cells (heteropoly acid [HPA]-FC-2178).
- The multi-directional approaches taken by the team for the completion of all tasks are adequate. All the analytical techniques had been thought through appropriately. The study on materials synthesis based on functionalized super-acidic inorganic moieties is the reasonable approach. However, stabilization of HPA in a polymer matrix seems to be a great challenge.
- The membrane looks promising, and much progress has been made in incorporating a film into a fuel cell. As with many new membranes, materials durability in an operating fuel cell has been a big challenge in the past. Thus it is recommended that an approach be developed and demonstrated that gives the U.S. Department of Energy some indication of membrane material lifetime—in particular, the chemical stability in an operating fuel cell, even if fuel cell performance is low.
- Using HPA functionalized membrane materials is an approach that is not being utilized with other developers, and it could potentially provide lower-cost, performing high-temperature membranes. Regarding the limited samples made to date that are free-standing—primarily thin films on other substrates such as Kapton—it appears that these materials are going to require reinforcement for mechanical strength. There appear to be some fabrication issues that have not been addressed to date and that do not appear in project plans. Regarding the MEA, catalyst layer integration is going to be required, and there are limited plans.
- A well-integrated approach was proposed for this difficult problem that balances risk of failure and beneficial outcomes with three different membrane chemistries. Water transport properties (water diffusion coefficient, electroosmotic drag) will not be measured, but these are likely important to understand membrane conductivity in a low-RH environment.
- The approach taken by the principal investigator (PI) this year is described as the plan would indicate, and it seems that System II with the use of Dyneon has shown itself to be interesting. However, characterization data of the membranes were insufficient to judge whether other barriers such as permeation and durability can also be achieved by the same ionomer.

- The project is addressing performance first, which is a reasonable approach as long as sufficient work has been done to confirm a potential path to meeting durability and cost, but it is not completely clear whether this has been done. Specific details of risks and mitigations are not all clearly addressed, and the approach should be more systematic. There is not enough analysis of relating properties of currently achieved systems with targets, nor is there enough subsequent development of correlations to allow tuning of properties to simultaneously achieve multiple targets. The oxygen and hydrogen permeability data relevance for the low-HPA membrane is not clearly explained. How this will relate to the increased HPA system was not clear, and therefore the permeability data were either irrelevant, or worse, misleading, if these low permeabilities cannot be maintained.
- Professor Herring has shown in his past projects that incorporation of HPAs into polymer electrolyte membranes (PEMs) is a promising approach to meeting fuel cell performance requirements in dry conditions. Unfortunately, nearly two years into the project, there is no conductivity of fuel cell performance data at conditions drier than 95% RH. Professor Herring says that he is at the stage of the project at which he can “tune” the membrane to meet performance and mechanical properties, but no detailed approach was provided for how the mechanical durability requirements will be met.

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

This project was rated **2.6** for its accomplishments and progress.

- The project is on track. The membrane picture (slide 12) is, unfortunately, misleading and does not reflect the team capabilities. Clear films without black areas were produced with good thickness control over the film area (doctor blade). Circular features reflect the Teflon frame used to handle the film. A patent was filed for the third-generation FC-2178 chemistry.
- This group’s persistence and synthetic skill finally seem to be paying off in a novel material ready to be tested in fuel cells. The new process for functionalizing FC-2178 seems now to provide a pathway for testing the HPA-derivatized membrane concept in fuel cells. Progress in the calculational-chemistry-inspired shift to a low-viscosity but high-temperature solvent for the trifluoroethyl vinyl ether (TFVE) reaction mechanism is encouraging. It is highly disappointing that even with the improved preparation method, the HPA/TFVE is still too brittle to be formed into films to be tested.
- It is good that the team has settled on a system, hybrid HPA-3M FC-2178, to move forward to try to meet the targets. It is a bit disconcerting that after nearly two years, the project is still struggling to make films that are good enough to collect fuel cell data. Last year, the team was asked to collect conductivity data at lower RH, but that has still not been done. Also, no mechanical or swelling data were shown. Professor Herring did say that swelling was not a concern, but it would be nice to see the data. Durability has not been explicitly addressed. It would also be good to see some sort of cost assessment now that the project has narrowed the research down to one approach.
- There is insufficient detail to estimate the probability of meeting all project targets. The membrane systems have improved significantly and are meeting or exceeding some of the targets at some conditions. However, the conductivity at lower temperature and for drier conditions has not been established. There is also insufficient information on swelling, mechanical properties, cost, and durability. It was claimed that significant progress was made in process development: higher yields, good control, much-improved materials, overcoming solvent isolation after every step, and solutions to other criticisms of the old method of manufacturing. Films of sufficient surface area and uniformity are available for partner testing. However, no details were provided, as this is considered proprietary information, and team members are applying for patents.
- Good progress has been made, but some key points still preclude a complete solution to the problem. It is not clear how DOE is to know that this membrane approach has the potential to bring membrane costs down to $20/m^2. It is also unclear how this membrane is better than other membranes in terms of conductivity; the chart on slide 11 shows 0.2 Siemens/cm at 60°C, which is similar to Nafion. Simply making the membrane thinner to meet the ASR target is not suggestive of an improved material.

- On the positive (pros) side, the casted films on Kapton based on the FC-2178 material seem to show promise in attaining the DOE goal of ASR <0.02 Ω cm^2. Here are the cons:
  - Permeation data were not normalized to thickness; therefore, one cannot tell whether this was achieved by the same membrane that achieved the low ASR. When asked about the thickness of the membrane for which the crossover data were measured, the PI could not answer.
  - The PI claims that the "thin films with target ASRs at low RH [are] now system ready" (slide 19, even though this is under the Remaining Challenges and Barriers sections). However, it is not clear whether the films were tested at low RH (the presentation includes no data at low RH). Therefore, it cannot be concluded that the films will have a low ASR at low RH.
  - The PI did not make clear how durability (both chemical and mechanical) is being addressed.
- Progress to date seems slower than anticipated or desired; despite being approximately 60% through the project, the team is still trying to make films that allow testing. Few free-standing films appear to have been produced to date, and those that have been produced are clearly extremely brittle. The project needs to make significant progress in developing usable films. The team will probably need to incorporate mechanical reinforcements and methods to allow incorporation of electrode layers.
- The improvement of the "System II Membrane," the hybrid HPA-3M FC-2178, does not seem to be a feasible path. The dehydrofluorinated membrane shown in slide 12 does not look to be very uniform, and the ion-conductive domain seems to be non-uniformly distributed. The team should determine whether HPA is precipitating out in the polymer matrix. Also, the presence of -CH_2- groups in the proximity of -CF_2- and -CF_3 groups may be labile, and the team should conduct Fenton's test to establish the stability of the -CH_2-.

Question 3: Collaboration and coordination with other institutions

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

- The team consists of a good mix of national laboratory and industrial partners. Collaboration with 3M, Nissan, and the National Renewable Energy Laboratory (NREL) is very advantageous to the team.
- Materials are just now becoming ready for outside partners to start testing. This project has taken good advantage of 3M's willingness to provide starting materials and advice about how to handle them.
- The partner team is sufficient. Collaborations with Nissan on testing of the materials and with 3M on process/cost input are important.
- There seems to be a solid partnership with 3M. The project is at the stage in which Nissan should start to contribute with MEA preparation and fuel cell testing. NREL's contributions to date are unclear.
- The project has good collaborators with a materials supplier (3M) and an automotive original equipment manufacturer (Nissan), among others for MEA testing. However, very few data were shown from the MEA testing from the collaborators.
- The PI did show slides about Nissan and its participation for the measurement of gas crossover. It is not clear what NREL's role has been until this point. The future work indicates that NREL will become involved for the remainder of the year. It is clear that 3M supplied products for the synthesis, but it is not clear what 3M has done in addition to that. However, the future work indicates that 3M will do characterization and testing and help in the scale-up of System II.
- Some of the work is seemingly duplicated at NREL and Nissan (MEA evaluation). From that standpoint, Nissan is likely the most competent organization to complete these tests. As a result, NREL workload and tasks should be reevaluated.
- It is unclear what, if anything, NREL and Nissan have done in the project to date. Future work is listed, but there does not seem to be any evidence of actual work done to date by the partners. The project is supposed to have third-party testing and have MEAs made, but there seems to have been no interaction to date. The interactions with 3M seem to have been primarily phone discussions.

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

This project was rated **3.1** for its relevance/potential impact.

- The project is relevant to the objectives of the Multi-Year Research, Development, and Demonstration Plan. The activities are aligned to DOE's goal to address the commercial barriers such as performance, cost, and durability. The focus of the project is to demonstrate a low-cost hybrid inorganic/polymer from super-acidic inorganic functionalized monomers.
- Durable, low-cost membranes with low ASR and low gas crossover are essential to automotive fuel cell commercialization.
- A low-cost, durable, conductive membrane is essential to the development of commercially relevant fuel cell systems.
- This project has an innovative path compared to many other projects, with a potentially high payback in terms of higher conductivity at high temperatures and low RH operation.
- A membrane able to meet targets will be highly relevant. However, the membrane's ability to work in the fuel cell may require the appropriate matching ionomer in the catalyst layer. The project team recognizes this and has some activities to address this, but it is not clear whether this can be accomplished within the scope of the project.
- Improved membranes could improve the performance of fuel cells and widen the range of acceptable operating conditions. This project is still a long way from MEA tests demonstrating a real cumulative advantage for their materials. It is not clear that presently available commercial membranes (significantly improved over the past decade) are not adequate for major fuel cell applications, so this area does not require as much research attention as some others.
- The project tries to address the key issues, but so far, after 18 months, the results are not so encouraging. The ASR at high RHs was proven, but permeation and chemical/durability tests were not performed.
- No data or potential was seen for a game-changing reduction in membrane cost or game-changing improvement in membrane performance. The only data that showed significant improvement over Nafion were the gas transport data shown on slides 14 and 15. However, the PI did not know the important factor of sample thickness, so it is not possible to see whether the membrane's material properties are actually improved.

Question 5: Proposed future work

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

- The PI lists all the work that is key to the success of this project as future work.
- Most of the future work path looks appropriate. The project team should consider other design considerations, including mechanical reinforcement, which is lacking from the plans.
- In general, the future work plan looks good. The U.S. DRIVE Partnership's Fuel Cell Technical Team recommended durability testing, such as open circuit voltage (OCV) and RH cycling. ASR measurements should be done if not already planned. The project should include a more thorough cost assessment.
- Along with all the work that the team has proposed in the presentation (slide 23), the team should also work toward getting a uniform membrane and make sure that the HPA is coordinated to the polymer backbone and has not precipitated out into the polymer matrix.
- The proposed future work is logical. However, it does not appear that risks have been adequately assessed and mitigation pathways established. The ability of the membrane to work in an MEA is being assessed but is a very large question at the moment.
- The proposed work is reasonable.
- This project really needs to move forward into testing in MEAs. It is not clear how much faith the project still has in the TFVE/HPA system; it is not clear whether lower molecular weight and/or blending with other polymers can make this system tractable. Given the progress with HPA-FC-2178, it seems uncertain that the group will still put into effort into this. It would be good to get two materials out of this project.

MEA work may require increased commitment from partners in the development of electrodes that can work with the new membranes.
- There should be more focus on demonstrating chemical stability in operating fuel cells or some other ex situ accelerated test.

Project strengths:

- The membrane system front runner is showing very good conductivity and appears to have suitable properties to meet targets. The team has the appropriate partners to accomplish the project.
- The project has demonstrated significant synthetic skill and wisdom in backing away from dead-end approaches. The team is finally back to moving forward with the improved method for functionalization of FC-2178.
- The team is composed of respectable research organizations with adequate expertise. Overall, the team is equipped with the necessary knowledge base, resources, and industry/academia/national laboratory mix that is required for the success of this project.
- Exploring new materials has the potential for game-changing results. The project has a good source (3M) for a large quantity of materials for development work.
- This is really the only DOE project focusing on potentially game-changing PEM concepts. It is certainly high-risk, but there is also a possible high reward.
- The project takes an innovative path not being explored by other developers in the Fuel Cells sub-program.
- The development of three different membrane chemistries reduces the risk of failure.

Project weaknesses:

- Progress appears slower than desired. The number of free-standing films produced to date seems low. The materials produced appear extremely brittle, and the project has not addressed how to make the membranes mechanically viable longer-term, e.g., incorporating reinforcing materials. There was a gap between this project and the prior project, and thus it has taken some time to get back up to speed; nonetheless, this project is far enough through the project path that the gap no longer seems a viable reason for the low number of samples produced. Also, the project seems to have a low integration of project partners to date.
- The following are project weaknesses:
    - Progress is slow. Although the project is at 50% completion, it is not able to prove the ASR.
    - Permeation data are not clearly shown (measurements were taken with different thicknesses). In this case, the data should have been normalized to account for thickness.
    - ASR measurements have been taken only at high RHs.
    - No chemical durability tests, such as OCV hold/cycling, have been performed.
    - No mechanical durability tests have been performed to date, and the project is already at 50% completion.
- The inability to make reproducibly good quality films is a weakness. There are no data for dry conditions, which is where the biggest potential benefit of this concept truly lies.
- The project is thus far unable to convert the promising membrane material into an operating fuel cell. In-fuel cell membrane resistance was 200 times higher than the ex situ membrane resistance tests indicated.
- Membrane water transport properties are not considered but are deemed important for operation in a low-RH environment. MEA evaluations will be carried out at both NREL and Nissan, seemingly duplicating work.
- More focus is needed to prepare polymer HPA composite in which the HPA is bound to the polymer groups.
- Project accomplishments are slow, and the approach as presented lacks rigor on establishing understanding and relationships between material composition and membrane properties.
- This project has shown very slow progress prior to this year but decent progress this year. It is not clear that the motivation to move forward into MEA testing has been sufficiently strong.

Recommendations for additions/deletions to project scope:

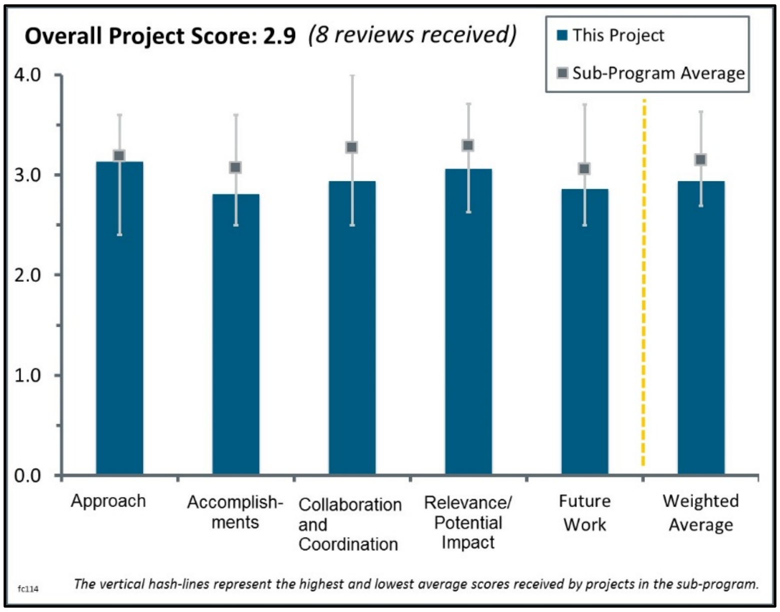
- The team should show some cost indications and compare them to perfluorosulfonic acid (PFSA), even if the team cannot supply actual cost estimates. There is also insufficient information on swelling, mechanical properties, low-RH performance, and durability. It is recommended that the project provide more calculations and predictions on properties. All critical properties should be assessed for risk, with mitigating factors and plans clearly laid out.
- If new ionomers for the electrodes are needed to make the project membranes work, the project should vigorously address electrode development (perhaps through increased commitment of partner resources) rather than declaring electrode development to be the subject of another project.
- More work should be done on making a larger quantity of membranes that can be shared with the MEA manufacturing/testing collaborators. More work on fuel cell tests would serve this project well.
- The project should start doing low-RH ASR and mechanical testing (tensile, swelling, etc.) as soon as possible.
- The project should take measurements of ASR at lower RHs, for example, 50% and 30%.
- Membrane water transport properties should be measured for the down-selected chemistry (2016). MEA evaluation tests at NREL should be eliminated.
- The project should consider adding a reinforcement material so the free-standing films can be better used and evaluated.

Project # FC-114: High-Throughput Synthesis, Oxygen Reduction Reaction Activity Modeling, and Testing of Non-Platinum-Group-Metal Polymer Electrolyte Membrane Fuel Cell Cathode Catalysts

Deborah Myers; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop tools for the rapid synthesis, fabrication, characterization, activity and durability screening, and performance optimization and testing of fuel cell cathode catalysts and catalyst layers in membrane electrode assemblies (MEAs). The low platinum objective is to realize the oxygen reduction reaction (ORR) activity benefits of the Argonne National Laboratory (ANL) nanosegregated platinum cathode electrocatalysts, demonstrated in aqueous tests, in MEAs at high current densities, and in air.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The concept and intention of combinatorial testing and high-throughput fabrication is reasonable, but it would be interesting to see whether this project will result in new catalyst formulation or optimum MEAs. The methods are currently being developed and validated.
- The high-throughput/combinatorial approach may assist in catalyst development because the catalyst particles are sized nanoscale to approximately submicronscale, but this approach has challenges in its ability to optimize the MEA and its related fuel cell performance because the small-spot MEA may lead to an inaccurate performance measurement because of edge effect and inappropriate processing during MEA fabrication and fuel cell fabrication. The team should calibrate their measurements by comparing them with regular fuel cell results to validate their method and show that the trend is consistent with the regular method.
- The approach is to optimize the fuel cell performance of a particular cathode catalyst by making many variations to the catalyst and testing the fuel cell performance of the catalyst in a rapid screening tool intended to simulate actual fuel cell conditions. The underlying approach is to use the same MEA manufacturing and processing procedure for making many catalyst layers with variations to the catalyst material, including the comparison to the Tanaka Pt/C control. The performance shown, even for the control catalyst, is quite low because rapid testing conditions do not exactly mimic an operating fuel cell. Therefore, the formulation that works well in the rapid screening may not work well in an actual operating fuel cell. Furthermore, there is no reason to believe that an MEA manufacturing and processing procedure that is good for the Tanaka Pt/C control is equally good for a novel catalyst material. It would have been better to see an approach that uses a single large batch of promising catalyst material to make real single-cell fuel cells using different manufacturing processing conditions, ingredients, and methods to hone in on the best processing method for a novel catalyst.
- When trying to screen multiple MEAs, the performance, including that of baseline materials, is miserable. It is unclear why. It is also unclear why the researchers would test 25 samples before actually trying to use one of them. If they did try a single sample and performance was terrible, then it is unclear why they moved forward. It is unclear whether they tested blanks (i.e., just carbon fiber paper) to determine resistance, and whether they used pressure paper to ensure even distributions. It is very difficult to understand what problem this project is trying to answer. Perhaps the researchers have far too many

catalysts to screen; if this is the case, it is unclear how many they have to screen. There are also questions about how many man-hours it takes to process each sample. The input, the backlog, and the needed throughput need to be identified. Those questions need to be asked before the project is started to give it direction and measure its success. The same criticism is applicable to measurement, as well as to generation of catalysts; there seems to be little thought about what throughput is needed. Only then can one determine whether this project is needed and has real metrics to measure its success.

- This project aims to use a high-throughput/combinatorial approach to optimize a low-Pt polymer electrolyte membrane fuel cell (PEMFC) cathode and a non-platinum-group-metal (PGM) PEMFC cathode. The low-Pt cathode is based on ANL's segregated Pt alloy catalyst, and the non-PGM cathode is based on Los Alamos National Laboratory's (LANL's) polyaniline (PANI)-Fe_xCo_y catalyst. The high-throughput approaches the project has developed may help to down-select recipes for catalyst and electrode compositions in an effective way. However, because the low-Pt catalyst and non-PGM catalyst belong to two distinctive systems, it does not sound reasonable to combine these two systems into a project. In fact, each catalyst system should take substantial amounts of effort to make optimized electrodes. The focus of the project is thereby distracted.
- The objectives of the project include development of tools for rapid catalyst synthesis, characterization, activity and durability screening, and performance optimization in MEAs. However, the results presented during the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review (AMR) meeting do not represent the major barriers—namely, electrode performance, cost, and durability.
- The segmented gas diffusion electrode deposition method does not seem to work in this method; it is unclear whether a spray/catalyst coated membrane (CCM) approach with masking has been considered. The goals of this work are quite unclear; it is unclear whether the goals are to develop high-throughput methods or MEA/materials. Clarification of the goals would really be helpful for reviewers.
- The objectives are very ambitious for a one-year project, and the approach is similarly broad and complex.

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

This project was rated **2.8** for its accomplishments and progress.

- Considering the number of tasks, two types of catalysts, and different methodologies (e.g., synthesis, fabrication, characterization, testing, and modeling), the accomplishments are impressive. Important achievements include the use of a high-throughput method for synthesis and characterization of non-PGM catalysts, and the use of powder-ionomer inks and fabrication of combinatorial MEAs.
- The accomplishments of this project are reasonably good. The developed robotic platform and four channel flow double electrodes (CFDEs) appear to be very powerful tools and enable one to screen multiple catalysts simultaneously in a very effective way. A high-throughput method has also been developed for synthesis and deposition of powder-ionomer solvent inks and fabrication of combinatorial MEAs. A density functional theory (DFT) model has been developed to screen non-PGM ORR activity and stability, which is a complementary approach to experiments.
- The team has done a good deal of work—especially on catalyst development—that is conclusive.
- The project is relatively new, and much has been accomplished within a short period of time in both the low-Pt and non-PGM projects. On slide 7, it was not clear what the different pol curves were, because the pol curves labeled as nanoframe-1 (NF-1) to NF-4 all have the same ionomer/carbon (I/C) ratio. It is unclear how one determines that there is a trend in performance and what kind of trend, as indicated in the second point on the slide. It is unclear whether the researchers carried out a test with standard electrodes on all 25 segments to ensure that all electrodes show the same performance. It is important to do this in order to ensure that the trend seen with different nanoframe electrocatalysts is related to the different catalysts, rather than the trend coming from the different segments. On slide 8, scanning transmission electron microscopy–energy-dispersive x-ray spectroscopy (STEM-EDS) was used to characterize catalyst inks with different I/C ratios. The highlights on this plot show that Pt and Ni composition is maintained. However, one would expect that the purpose was to show different I/C ratios using STEM-EDS. On slide 9, it is good to see that a model is being developed to analyze alternating current impedance data. H_2/N_2 impedance is a powerful technique to determine the catalyst layer effect, and it will be good to see more details on this approach and the results. The team demonstrated that a robotic system can be used to prepare different salt

precursors and can produce same-phase composition as a large single batch synthesized at LANL. It is unclear whether there are any issues with contaminants in the process of preparing LANL catalysts. For the CFDE setup, it is unclear how many working electrodes (WEs) and counter electrodes (CEs) there are for the 4 channel 4 WEs, how large the CE area was, and what type of RE was used. On slide 17, it is not clear how one ensures that the catalyst loadings for all electrodes are the same. When comparing the ORR activity using CFDEs and with large-batch rotating disk electrode (RDE) data, the current does not match. It is not clear whether surface area, catalyst loading, etc. were all kept the same. It is not clear how one compares the trend if the current is not normalized the same way.

- As of April 30, 2015, the team claimed it has met two of the three milestones. However, the fuel cell performance in combinatorial fuel cells for the Pt_3Ni nanoframe catalyst (slide 7) and the CFDE results of high-temperature PANI-Fe, Co-C catalyst (slides 16 and 17) are not comparable to the ones generally obtained in a single fuel cell and rotating ring disk electrode experiments. Considering the fact the project is ending in September 2015 and that only 64% of the proposed work has been completed, the team may not have sufficient time to get any meaningful results to substantiate the objectives and approaches of this project.
- The milestones were very low-risk, and they were not well accomplished. The “stretch” goal, which was the one project element with risk, was not well addressed. The researchers did generate a number of samples and a number of catalysts. However, if the goal of this project is to increase throughput, then metrics for comparison are needed. It is unclear how many catalysts can currently be generated and characterized per month per person, and by how much this process improves that figure. The mere fact that the new operation works does not say very much.
- Even if the rapid screening method selects a catalyst that is better than the control, then that manufacturing method needs to be scaled up to a process that could be used to make actual fuel cell MEAs.
- Statistical correlation of the large dataset is a major aspect of understanding screening work; however, it has not been done.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- There is good coordination and collaboration between ANL and LANL, as well as among experimentalists, characterization efforts, and modeling efforts. It was also nice that the project got the combinatorial fuel cell test fixture and Arraystat from Nuvant Systems for free. The project features good collaboration and leveraging of the available and DOE-funded capability.
- The principal investigator (PI) has good collaboration with Oak Ridge National Laboratory (ORNL), LANL, and an electrochemical systems manufacturer to meet the project objectives.
- The project features excellent collaboration with experts in particular areas.
- There is extensive collaboration between national laboratories.
- The collaboration with LANL is good. The participation of a major fuel cell company (e.g., Ford, General Motors, or Ballard Power) would be very meaningful.
- This is an ANL/LANL/ORNL collaboration, but it seems to be missing the obvious inclusion of industry experts in ultra-low-loading CCM construction and high-throughput methods.
- Collaboration with an MEA manufacturing partner would benefit this project.
- There is not much input from other national laboratories. There is no industrial collaboration, either from those that might use these techniques or those that might market them.

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

This project was rated **3.1** for its relevance/potential impact.

- The project is very relevant to DOE fuel cell catalyst objectives and targets. In particular, ANL’s segregated Pt alloy catalyst and LANL’s PANI-Fe_xCo_y catalyst represent the two most promising catalysts, PGM and non-PGM, respectively. However, previous efforts were mostly on RDE and small-range MEA fabrication. The proposed high-throughput approaches may help to down-select catalyst compositions and electrode conditions so as to further promote the application of these advanced catalysts at more practical levels.

- The project's efforts are directly related to DOE research, development, and demonstration objectives.
- High throughput is a good approach to screen catalysts and catalyst layers in MEAs. However, the approach should be guided by theory and/or modeling because there can be many different combinations one can try. Otherwise, it will be a trial-and-error exercise.
- The results will affect future efforts in this area.
- The results presented during the 2015 AMR meeting are not promising in terms of meeting the project goals of developing tools for the rapid synthesis, fabrication, characterization, activity and durability screening, and performance optimization and testing of fuel cell cathode catalysts. From the presentation, it is not clear how the durability of the low-PGM and non-PGM catalysts can be evaluated by the end of September 2015.
- Both electrode construction of these highly active PtNi catalysts and optimization of the non-PGMs are aligned with DOE goals. It is not clear, however, that the high throughput has significant value to either goal, nor is it clear that the methods have demonstrated potential to do so. In a very complex experimental variable space, such simple and not fully defined efforts do not seem to have a high value/effort proposition.
- The project seems like it has a long way to go to provide any useful feedback to the manufacture of fuel cells with new catalysts that operate well.
- It is very doubtful anyone outside of this group will use the techniques developed here.

Question 5: Proposed future work

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

- Considering the timeline of the project, the future plan is reasonable.
- The list of future work seems reasonable.
- This project's significance is in its ability to increase/improve the throughput of catalyst generation and characterization. This has to be kept in the context of what is currently being done. To justify the project's cost, $1 million, one needs to know, if a laboratory had been given $1 million to hire new scientists, how many catalysts could have been generated and characterized without this project. In other words, if this task is 100% successful, one needs to know when it will pay off. If it currently takes $10,000 to generate and characterize a catalyst, and with these tools it will only take $1,000, then it will pay for itself after only 110 catalysts. It is unclear whether the change is that dramatic and whether there will be that many new catalysts. These are the questions this project has to answer.
- The team has proposed performing a number of studies, including CFDE studies, electrode fabrication methodology, fuel cell testing, and physical characterization studies. The proposed studies need at least a year to get any promising results.
- The proposed future plan is very comprehensive. However, the project will be ending in September 2015. It is not very clear whether most of these proposed work plans can be implemented.
- The proposed future work is quite substantial, considering the limited time (three months) left in this project.
- The future work involves finishing incomplete tasks.

Project strengths:

- The project features collaboration with an electrochemical system manufacturer and with two national laboratories that have expertise in developing low-PGM and non-PGM catalysts. The project team takes a very good theoretical approach to understanding the ORR active sites of a non-PGM catalyst.
- High-throughput approaches are very powerful and effective for catalyst composition down-select and electrode optimization. In addition, a DFT model has been developed to screen non-PGM ORR activity and stability, which is a complementary approach to the experiment-based approaches.
- The project features a very strong team with a long history of doing this work. If this work needs to be done, this is undoubtedly the right team.

- Project strengths include the technical strength of the groups and the PI, as well as the communications.
- The project has a strong team and resources related to catalyst research.
- This project features a very strong team and excellent collaboration.

Project weaknesses:

- One weakness is the utility and proof of high-throughput methods. Another is the selection of M-OH bond strength as a criterion for optimization. This criterion has led to an active site structure that is inconsistent with experimental evidence for the active site, hence bringing into question the criterion. Comparison to ex-silico information is needed. A third weakness is that statistical correlation of the large dataset is not addressed.
- The combination of two totally different systems into one project has diminished the project focus. In addition, the entire work structure appears to be disorganized, likely owing to the combination of two different catalyst systems.
- The project has very limited time to fulfill the proposed objectives. A two-year project, rather than a one-year project, would have been beneficial.
- The project features too many tasks and diverse methods to accomplish them.
- A relationship between the rapid scanning screening method used in this project and actual operating fuel cells would benefit this project.
- There is a complete lack of proper metrics.
- The MEA fabrication is the weakness.

Recommendations for additions/deletions to project scope:

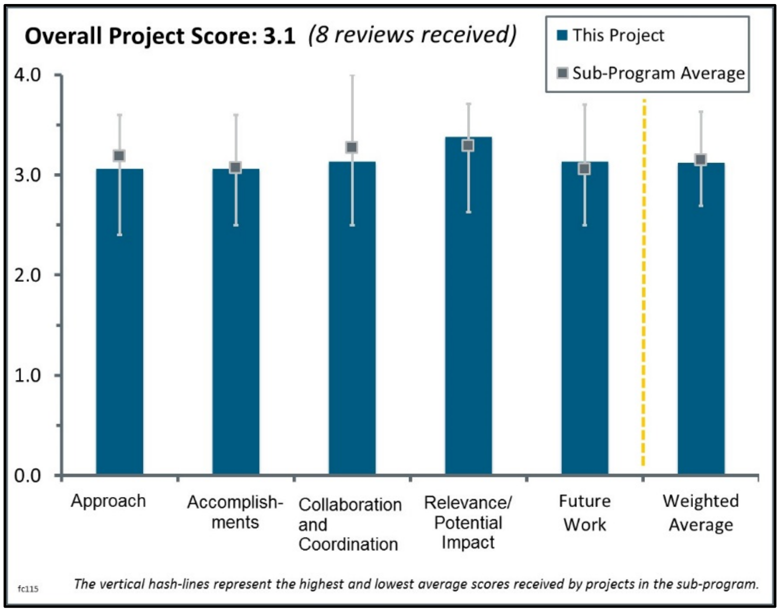
- No specific additions/deletions are needed.
- The team should include industry experts in ultra-low-loading CCM construction, catalyst synthesis, and high-throughput methods.
- If possible, the project should be focused on either low-Pt cathode or non-PGM cathode because there are only a few months left.
- Focusing on a fewer number of tasks would be beneficial for the outcome of the project.
- Adding an MEA manufacturing team member would help this project.

Project # FC-115: Affordable, High-Performance, Intermediate-Temperature Solid Oxide Fuel Cells

Bryan Blackburn; Redox Fuel Cells, Inc.

Brief Summary of Project:

The overall objective of this project is to improve the performance of intermediate-temperature (≤600°C) solid oxide fuel cell (SOFC) technology operating on reformed natural gas through the (1) development of an optimized bilayer electrolyte with increased open circuit potential and thus greater fuel efficiency, (2) optimization of compositions and microstructure for the electrodes to improve performance and impurity tolerance, (3) use of a custom multiphysics model and advanced materials to optimize the performance of bilayer stack designs, and (4) demonstration of a ~1 kW stack for intermediate-temperature operation under combined heat and power (CHP) conditions.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The team's approach toward developing intermediate-temperature fuel cells relies on the successful development of Bi_2O_3 (bismuth oxide)/CeO_2 (cerium oxide) ceramic membranes. The materials compatibility will be challenging (i.e., matching thermal expansion, chemical reactivity, and low-cost manufacturing). The approach is one of few potentially viable methods to develop intermediate-temperature solid oxide fuel cells (SOFCs) with good performance.
- The approach includes modeling and experimentation for SOFC bilayer structures. The bilayer approach is intended to provide stability and low electronic conductivity. The team needs to discuss and analyze the interface.
- The approach logically uses scale-up in a stepwise manner to achieve progress.
- The project is currently designed to meet the barriers identified and is structured appropriately.
- The approach seems reasonable, but the absence of planned durability testing leaves a fairly big hole.
- The project needs to speak to total life of cells at high power density and low temperature. Anything can work at high power for a short time—life is a critical factor and should be evaluated as soon as possible. The team should evaluate co-diffusion of gadolinium-doped ceria (GDC) and Bi_2O_3 as a potential issue (or benefit). The effect would be a broadening of the GDC/Bi_2O_3 interface that could affect overall performance and life. A broadened interface may make the bilayer more robust to system upsets that could result in a lower oxygen partial pressure. It could also be detrimental—it is not clear whether co-diffusion will occur or what the impact may be. The researchers should see Oak Ridge National Laboratory's microscopy project (FC-020) as possible support for assessing the interface performance.
- Approaches to performing the work and results obtained to date were not given in the slides or discussed in detail in the presentation. For example, the statement "Leverage 25 years of SOFC [research and development]...." (slide 16) does not convey any information on the approaches proposed in this project to address the critical barriers of the technology.

- In addition to electrolyte resistance and electrode activity, other challenges should be addressed for intermediate-temperature SOFCs. The mechanical strength of the ceria-based cells and long-term operation stability are among those challenges that need to be addressed.

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

This project was rated **3.1** for its accomplishments and progress.

- The team has made good progress for GDC/erbium stabilized Bi_2O_3 (ESB) bilayer electrolyte thickness optimization:
    - Achieved Milestone 1.1: ESB/GDC Bilayer Button Cell open circuit potential of ≥0.9 V at ≤600°C.
    - Is close to meeting Milestone 2.1: area-specific resistance ≤0.2 Ω-cm^2 and ~1 W/cm^2 at ≤600°C.
- Single-cell testing has commenced. Preliminary results look promising. It will be good to see the durability data.
- The project has demonstrated the high power density of the cell at 600°C, which is a promising achievement.
- The results to date indicate that the team has made progress toward meeting DOE goals. Presenting anticipated results does not add value to the accomplishments. It will be interesting to see the sulfur stability results. Capturing any performance decrease and the ability to recover is important.
- The project is nine months old. Reasonable progress has been made in terms of performance and modeling. Durability (especially of the interface) does not seem to have been addressed. The open circuit voltage seems low. Cost is not addressed.
- It is early in the project, so judging accomplishments is difficult, but the progress to date seems good.
- Transitioning to a larger format is good; however, there is much that still needs to be learned at the button cell level. Claims of operation on conventional fuels are not currently supported by data. Direct use of gasoline and/or diesel is unlikely because of cracking/carbon deposition at the target temperatures (e.g., ~600°C). Sulfur content of those fuels is also going to be a problem. The presentation should not be a sales document, and unsupported claims are not appropriate in this context.
- Well-defined metrics are needed for this project. For example, the success criteria for the 1 kW stack demonstration should be defined. Numerous statements in the slides (e.g., on slides 8–11 and 13–14) are so general that it is difficult to comment on accomplishments and progress.

Question 3: Collaboration and coordination with other institutions

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

- All aspects of the project are covered by knowledgeable organizations.
- The project includes the following collaborations: University of Maryland, cell research and development; Trans-Tech Inc., cell manufacturing; MTech, commercialization; and Redox Power Systems, cell/stack development and testing.
- The team works closely with the University of Maryland.
- Collaboration exists; however, it is difficult to evaluate the collaboration based off of the presentation.
- The mix of collaborators seems appropriate, but it is difficult to tell where responsibilities lie.
- The actual contributions of the collaborators were not clearly explained or defined. Perhaps it is too early in the project for much in the way of contribution from the collaborators. If so, the team should explain this and provide a schedule of when collaborator contributions are expected.
- In addition to collaboration on multiphysics stack modeling, close collaboration with organizations with expertise in multicell stack design and stack operation/testing may be needed for this project.

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

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

- Many DOE Hydrogen and Fuel Cells Program fuel cell barriers have been addressed:
  - Durability:
    - Lower operating temperatures for Redox SOFCs than for competing SOFCs
    - Internal reforming with catalysts for enhanced sulfur and coking tolerance
  - Cost reduction:
    - Using no PGM materials
    - Lowering the operating temperature to allow the use of simple stainless steel commercial off-the-shelf compressive gaskets
    - Using fewer cells because of higher power density per cell
    - Lowering the system cost
  - Performance:
    - 10x10 cm anode supported cell demonstrating >1 W/cm^2 at 650°C (using natural gas)
    - Performing laboratory-scale demonstrations with peak power density of 2 W/cm^2 at 650°C
    - Maintaining performance at ~600°C through various cell enhancements, and improving stability
    - Demonstrating the availability of high-quality heat for CHP (2020 Fuel Cell Technologies Office target for 90% CHP)
- The project clearly identifies the DOE goals it is targeting and the progress it has made to date. It has already met or exceeded some of the identified goals.
- The potential impact is very high. Intermediate-temperature fuel cells offer excellent characteristics for stationary CHP.
- This project seems very relevant. If successful, it could have a great impact on SOFC system costs.
- Low-temperature SOFCs are attractive and in line with DOE goals.
- The success of the project will accelerate the deployment of fuel cells for stationary applications.
- The bilayer approach with these materials is very interesting and potentially a good approach to high power density. Caution is necessary on predicting fuel cell lifetimes with this approach. The claims of internal reforming of commodity fuels are questionable until demonstrated for hundreds of hours.

Question 5: Proposed future work

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

- The plans could lead to achieving goals:
  - Use the upgraded model to optimize stack design for a bilayer cell.
  - Consider different operating conditions that might improve durability and reduce degradation (e.g., reduced thermal gradients).
  - Use the cell portion of the model in conjunction with ongoing button cell and 10x10 bilayer thickness optimization.
  - Translate the already achieved performance at the button cell level (i.e., ≥0.9 V and ~1 W/cm^2 at ≤600°C) to the 10x10 cm cells.
  - Finish mapping the stack performance up to the full 1 kWe size and use residential CHP conditions with natural gas to obtain similar performance for the 10x10 cm single-cell and short-stack levels in the ~1 kWe stack size under CHP conditions.
- The project has a clearly identified path forward for future work and go/no-go decision points. The path forward will achieve the DOE goals identified and overcome current barriers.
- Scale-up from single-cell testing at the laboratory scale to short stacks at 1 kW at CHP conditions is planned.
- The future work plan is acceptable.

- The proposed future work seems appropriate and in line with the objectives; however, the addition of durability testing would seem appropriate.
- The researchers should address the bilayer and overall stack degradation rate before investing excessively in system or full-scale stack development. Systems, particularly CHP systems, are expensive to build and test. This is only appropriate after the stack has been shown to be robust and long-lived—or at least shown to be acceptable for at least a couple of hundred hours.
- The proposed future work does not include sufficient details, especially on the planned approach and risk mitigation.
- The team needs to demonstrate the long-term operation stability and mechanical strength of the cells.

Project strengths:

- The project features a novel approach to achieving high-efficiency SOFCs that operate well below 700°C. The team is highly knowledgeable, with many years of experience in SOFC development.
- Strengths include the clear project goals and identified barriers. The go/no-go decision point will help in evaluating the project at the 12-month mark.
- The team is developing an intermediate-temperature electrolyte and electrodes to reduce the operation temperature of SOFCs.
- The ESB/GDC bilayer is very interesting and potentially a breakthrough technology. It is definitely worth additional investigation.
- The project's strength is its potential impact.
- The project focuses on cell scale-up and stack demonstration.

Project weaknesses:

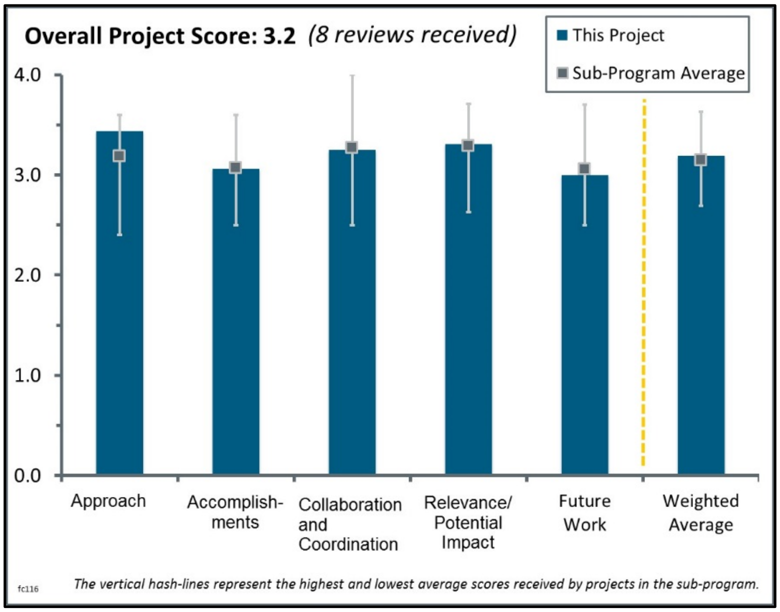
- There is no emphasis on expected lifetime or degradation rates. This is a major concern that seems not to have received any attention. If the cell lifetime is short, it may take a significant investment to find the root cause and advance the technology to increase cell life. Investments in system or full-scale stack development are not appropriate until the lifetime question has been answered.
- The project is focused only on the electrolyte and electrode development, which is not enough for the stack fabrication and demonstration.
- The presentation did not clearly identify which partners contributed to which portions of the accomplishments.
- The project may be too ambitious for the funding levels. A larger project may be required to determine the feasibility of the approach.
- The project lacks well-defined metrics, risk mitigation, and detailed work plans.
- The recognition of (long-term) issues at the bilayer interface is insufficient.
- One weakness is the lack of planned durability testing.

Recommendations for additions/deletions to project scope:

- The researchers should refocus significant effort to demonstrate lifetime under realistic conditions. Domestic natural gas is a good starting point—if that does not work (because of sulfur content or carbon deposition), then none of the other proposed fuels is likely to work. If natural gas exhibits good lifetime, then building a full-scale stack and supporting balance of plant may be justified. Gasoline and diesel are much more difficult—those should be saved for another project.
- The project team should investigate the long-term stability of the bilayer electrolyte and infiltrated electrode catalyst. The team does not need to do direct hydrocarbon oxidization in anode at this stage of technology development.
- Assuming stable performance is achieved with sulfur, the team should analyze the performance loss and the ability to recapture that performance once sulfur is removed. It is unclear whether the system can operate for thousands of hours with sulfur.
- The team should pursue durability testing and study the stability of the approach.
- The researchers should start single-cell durability testing early in the project.

Project # FC-116: Smart Matrix Development for Direct Carbonate Fuel Cells

Chao-yi Yuh; FuelCell Energy, Inc.



Brief Summary of Project:

The overall objective of this project is to develop an innovative, durable, direct fuel cell electrolyte matrix ("Smart" Matrix) to enable >420 kW rated stack power and 10-year (80,000-hour) stack service life. The objectives for the current project year are to (1) develop plans to achieve "Smart" Matrix goals and to enhance degradation mechanistic understanding; (2) develop a high porous matrix structure with controlled pore size; and (3) initiate cell testing of the "Smart" Matrix.

Question 1: Approach to performing the work

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

- The project has clearly defined barriers and effectively conveys how it is going to overcome those barriers. The project is set up well, logical, and feasible.
- The project addresses the critical issue of matrix microstructure degradation for molten carbonate fuel cells (MCFCs) and focuses on evaluation of a new matrix with commercial-sized cells.
- The discussion of the $LiAlO_2$ issues is broad. The work should provide a sound mechanistic understanding.
- There are many thought-out approaches to achieving the objectives.
- The project represents an evolutionary approach toward improvements in a mature technology. The approach seems to be continuing to study the $LiAlO_2$ electrolyte support. The pore size stability tests seemed to be a bit haphazard; however, the project is in its early stages. Very little information was presented about what the "Smart" Matrix technology actually entails. It is not clear that the pore size control is the lifetime limiting factor for MCFCs.
- The project approach is reasonable, except for the goal of achieving 80,000 hours of life in three years. FuelCell Energy (FCE) would need to demonstrate that its accelerated testing is valid out to 80,000 hours, and because it has not achieved this with its current designs, FCE must provide details on accelerated tests. Outstanding questions include how many FCE systems have achieved >43,000 hours and how many have not, and whether FCE did anything special to achieve >43,000 hours, such as derate the power plant.
- The issue with current matrix material is the coarsening at the anode side of the cell, which is more related to the material ($LiAlO_2$) properties in reducing atmosphere, instead of microstructure. Reducing the initial pore size is not likely to achieve a twofold lifetime improvement, as targeted in the project.

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

This project was rated **3.1** for its accomplishments and progress.

- The results achieved to date are contributing to overcoming the defined barriers. The project has tightened the control of the pore size diameter in the "Smart" Matrix, which is an important step. Process consistency was demonstrated on the porosity for good reproducibility.
- The team has successfully manufactured a laboratory-scale, high-porosity "Smart" Matrix.
- The progress to date is encouraging and impressive, considering that the project is nine months old.

- Significant progress has been made in the first six months of the project.
- The improved pore structure shows progress. It is not clear whether FCE will be modifying the basicity. More information is needed. The project team did a good job identifying challenges. It is unclear whether all other components are capable of reaching 80,000 hours—that was not identified in the presentation.
- The accomplishments are satisfactory; however, they are not integrated with lifetime improvement models that show that matrix improvements will greatly extend the system life. The MCFC technology is relatively mature, and it will have difficulty competing with polymer electrolyte membrane (PEM) and solid oxide fuel cell (SOFC) improvements.
- Matrix durability is not the bottleneck of current stack life. Reducing the cost in the current stack could have more of an impact in terms of meeting DOE goals.

Question 3: Collaboration and coordination with other institutions

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

- The partners are recognized experts in MCFC technology. The team has a long history of collaboration on MCFC issues.
- FCE has established strong collaborations with the University of Connecticut (UConn) and Illinois Institute of Technology (IIT).
- UConn/IIT has significant prior experience and analytical capability; the project has solid, experienced partners.
- The UConn collaboration is well established.
- The project is leveraging expertise in multiple universities to gain full understanding of the “smart” matrices from multiple different angles. Coordination is required to develop the matrix, as well as to ensure it supports the performance required for the project to be successful.
- Collaboration with an $LiAlO_2$ producer may be needed.
- The presentation did not discuss the partner’s progress.

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

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

- The project is highly relevant. The project aims to develop an innovative, durable direct fuel cell electrolyte matrix (i.e., “Smart” Matrix) to enable >420 kW rated stack power and 10-year (80,000 hour) stack service life; increase market penetration for stationary fuel cells; enable technology for hydrogen infrastructure and CO_2 capture; and enable domestic clean energy job growth.
- The project has DOE goals in mind and is progressing toward those goals. The project aims to reduce cost and improve efficiencies and operating life. This will contribute to increasing the return on investment on stationary power and combined heat and power systems and help grow the market.
- The project aligns with DOE Hydrogen and Fuel Cells Program goals and objectives.
- FCE MCFCs are an established technology with the potential to meet DOE’s technical durability targets.
- This could be a high-impact project if 80,000 hours can be attained.
- The relevance is moderate. The project will result in modest improvements in the established technology.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work is focused on solving the matrix problem and has a good mix of material development and endurance testing.
- FCE is pursuing key activities in the future to achieve the following goals:
    - Optimize matrix formulation and processing conditions.
    - Develop stabilized materials based on mechanistic understanding.

- This project has good go/no-go criteria and set points to keep it focused and successful; however, some accelerated test methodologies should be involved in order to more accurately claim success of operating for the very high 80,000-hour target.
- The project is focused on the beginning of life properties of the matrix. However, the team did not allocate enough resources to $LiAlO_2$ coarsening root cause studies or to reducing the cost of the process.
- It is not clear what mitigation approaches will be applied to the results from $LiAlO_2$ coarsening (slide 9).
- The proposed future work is a bit vague. Not much information was presented on how the matrix material will be optimized.
- More details should be given on the approaches for the future work.

Project strengths:

- The project focuses on commercial-sized cells and operating conditions. The project team has extensive experience in MCFC technology.
- FCE is the leader in MCFCs. The development of the project can be smoothly integrated into final products.
- The project team is making incremental improvements toward a commercially demonstrated technology.
- The project is well formed and on target to overcome the identified barriers.
- FCE brings the greatest expertise in MCFCs.
- The project features the world leader in the technology.

Project weaknesses:

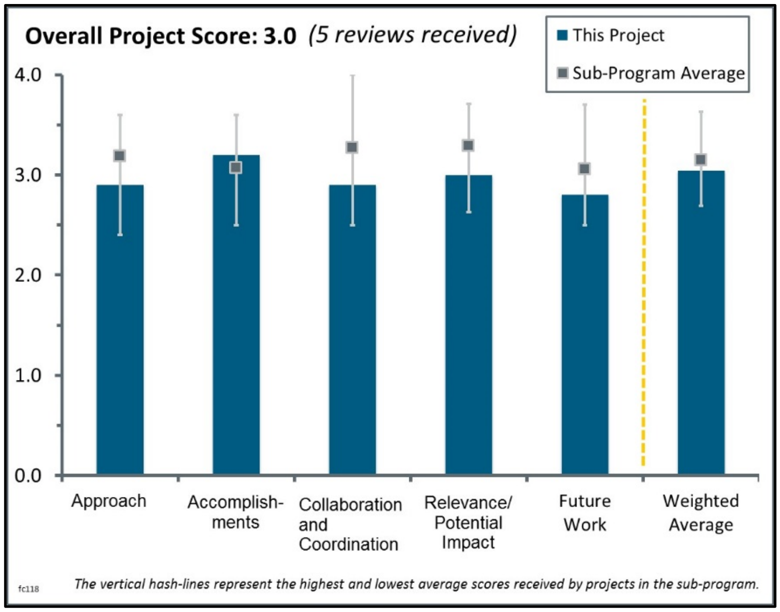
- The project does not focus on the key issues of MCFC stack life. Optimizing the initial pore structure is not likely to achieve the technical goal (10 years of operation life). The work plan does not include the efforts for cost reduction.
- The project has a high target of 80,000 hours of life; it is unclear how a 5,000-hour test provides data to show any improvement over the baseline 43,000 hours.
- MCFCs are having a very difficult time competing with natural gas combined cycle power plants. It is difficult to see how this investment will make them substantially more competitive.
- The team will need to discuss durability testing at the next review. Other components that may reach 80,000 hours need to be identified.

Recommendations for additions/deletions to project scope:

- Perhaps the team should add some validated accelerated test methods or test data from the first 5,000 hours of the baseline system for comparison to the 5,000 hours of the “Smart” Matrix system.
- The project team should include the cost reduction of the fabrication process.

Project # FC-118: Novel Non-Platinum-Group-Metal Catalysts from Rationally Designed Three-Dimensional Precursors

D.J. Liu; Argonne National Laboratory



Brief Summary of Project:

The overall objectives of this project are to (1) design, synthesize, and evaluate highly efficient non-platinum-group-metal (PGM) cathode catalysts using rationally designed three-dimensional (3-D) precursors with significantly improved fuel cell performance; (2) maximize electron, heat, and mass transport by incorporating the catalyst into a porous nano-network structure; and (3) support non-PGM catalyst development through structure-function relationship investigations.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- Argonne National Laboratory's (ANL's) focus on zeolitic imidazolate framework (ZIF) metal-organic framework (MOF) and membrane electrode assembly (MEA) testing has shown to be fruitful. The team demonstrated significant improvement in fuel cell performance under practical conditions and has produced one of the best, if not the best, non-PGM catalysts. Incorporating organic ligands into the MOF is also promising.
- Studies on benchmarking and understanding the stability of these catalysts are lacking. The transition away from the Fe-based material is very slow. However, considering the short length of the project, this is understandable.
- Incorporating a non-PGM catalyst into a 3-D, porous nanonetwork structure of high-surface-area MOF materials (ZIF) for catalyzing the oxygen reduction reaction (ORR) is apparently a good approach.
- Synthesis of MOFs provides a route for controlled variation of CNFe catalyst precursors, but most of the nitrogen and most of the initial structure are lost during thermal activation, so the final product is not all that different from more conventional non-Pt catalysts prepared by ammonia etching of carbon blacks.
- This project has quite properly moved to MEA testing at an early stage, and it has included a fair amount of data on air, which is the greatest challenge for non-Pt catalysts.
- The project has so far compared its results only to the areal current density targets promulgated in the catalyst working group. These targets correspond to performance that is far too low for automotive application, and they are too low for cost parity with Pt-based catalysts, even for less-demanding applications.
- ANL has yet to report volumetric current densities (A/cm^3), which are the first numbers that should be checked and reported in non-Pt catalyst work, although the field has advanced beyond the need for that number alone.
- This project is repetitive of previous work; the originality and the value proposition are unclear. This is true of the materials set, characterization, and analysis (Dodelet and Jouen did this work 10 years ago, 10.1126/science.1170051, while several groups have made the precursors using the same approach, http://dx.doi.org/10.1038/nprot.2013.100). The relevance of the principal investigator's (PI's) past experience to this project is unclear. The performance reported is for a very short time frame, and testing conditions seem to deviate from U.S. Department of Energy (DOE) protocols and comparable testing conditions reported elsewhere.

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

This project was rated **3.2** for its accomplishments and progress.

- ANL has generated a considerable amount of results, particularly related to synthesis and MEA testing. Obviously, the team is capable of making an adequate amount of catalyst in an efficient way. The team has achieved one of the best non-PGM MEA performances. The ORR activity was also close to meeting the DOE target.
- Remarkable area activity has been obtained for the 3-D tetrahedral precursor incorporated in ZIF. The high surface area helps the researchers achieve a high geometric current density; therefore, the per-site activity should be determined to clarify real activity. The durability of the catalyst is not addressed, which should be an immediate task.
- The initial MEA data on O_2 are encouraging, but they still need improvement for practical operation.
- Initial MEA data on air are also encouraging, but ANL still needs extensive work on electrode-layer optimization.
- Much more work is needed on durability.
- Volumetric activities were not reported. Assuming the ~3.6 mg/cm^2 loadings of catalyst have densities similar to those of conventional carbon-black layers, these electrodes would be about 100 μ thick. From slide 9, the volumetric activities would be about 25 A/cm^3 from the 0.8 V data or about 60 A/cm^3 if (improperly, but done in the literature) extrapolated back from 0.9 V to 0.8 V. This is about five times below the state-of-the-art kinetic ORR activity for non-Pt catalysts. However, at this stage in the development of non-Pt cathode catalysts, improvements in durability and high-current-density performance in air are more important than improvements in kinetic activity.
- The “record” power densities claimed here are of limited practical value because they were achieved at such low cell voltages (<~0.65 V) that heat rejection would be excessive and efficiency would be way too low.
- The performances and metrics reported and used are neither relevant nor novel. High and transient performances of non-PGMs are not useful in any real sense. It is unclear why researchers chose to repeat short tests instead of carrying one out for hours or days.
- The synthesis approach is more novel, yet a cursory literature search shows seemingly identical efforts done all over the world, including the FC-086 project (which had yielded a well-performing non-PGM with much better stability).
- The use of Co instead of Fe is to be commended.
- It is unclear how this project contributes to DOE goals related to making technologically relevant non-PGM catalysts. The precursors used are much more costly than those in the Los Alamos National Laboratory (LANL) project, without real performance improvement. Further, because LANL has a more significant effort, it is unclear how this project furthers the technology path.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The collaboration is appropriate for the project’s size and goals.
- This project team seems to have done a very good job in coordinating the efforts at a diverse group of laboratories, taking advantage of both advanced synthesis and competent MEA preparation and testing, although it is not clear that the calculational work has provided any new information. It would be good to identify where the MEAs were prepared and tested (in the absence of specific information to the contrary, one assumes this was done at the lead laboratory, ANL).
- The industrial partner for the PEMFC MEA work should be named.
- The project’s collaborations involve academia, some industrial laboratories with theoretical studies and structural studies.
- While collaborations are listed, they are not clear.

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

This project was rated **3.0** for its relevance/potential impact.

- The non-PGM catalysts provide hope of removing the PGM risk from the technology, although significant challenges still remain, including serious stability and performance issues. ANL's MOF approach is one rational approach to meet the targets.
- This project has been making progress toward the "holy grail" of cathode catalyst work—a non-Pt catalyst with adequate performance over a practical range of current densities and potentials. The results remain far from what would be needed for practical application in fuel cells.
- Proof of durability of both kinetic activity and high-current-density performance in air would be needed before very large resources could productively be expended on this pathway.
- The project seems to be addressing some of the issues needed to get adequate performance at high current density in air out of the thick electrode layers needed for non-Pt catalysts. This problem and durability are the major issues the non-Pt field must address.
- If the catalyst's durability and easy synthesis and scale-up can be verified, this work could have a notable impact.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The issues of stability and one-pot synthesis are the focus in the proposed future work.
- The project team plans to focus on improving activity and durability by using high-throughput screenings of MOF design and organic additives, although the plans were not described in detail.
- New materials development should be focused on a non-Fe system.
- ANL should focus on improving performance at high current density in air; stability in MEAs; and the reproducibility of synthesized catalysts.
- The work with non-Pt catalysts (particularly in making good MEAs for testing of high-current-density performance in air) is sufficiently difficult that it is probably unrealistic to expect that high-throughput pathways will be productive.
- Much greater emphasis must be placed on durability.
- Measurement and demonstration of the stability and durability of these materials is critical.
- The materials set in the proposed work has been extensively studied by Lefre, Dodelet, and Jouen, with poor stability in all cases. It is unclear how this work is different or will lead to stable catalyst performance.

Project strengths:

- Project strengths include the capable team, practicality, and product-oriented culture. The project's organization and management are also strengths.
- The focus on non-Fe catalysts is commendable and should be enhanced.
- The project team has good synthetic skills.
- The project has properly emphasized testing in MEAs, including data on high-current-density performance in air. The poster should have clarified where this MEA testing has been carried out.
- The team achieved facile synthesis of complex precursor materials that allow for a wide range of subtle variations in precursors.

Project weaknesses:

- The goals are nebulously defined, and metrics really need to be more explicit.
- This project is repetitive of previous work; the originality and the value proposition are unclear. This is true of the materials set, characterization, and analysis (Dodelet and Jouen did this work 10 years ago, 10.1126/science.1170051, while several groups have made the precursors using the same approach,

http://dx.doi.org/10.1038/nprot.2013.100). The relevance of the principal investigator's (PI's) past experience to this project is unclear. The performance reported is for a very short time frame, and testing conditions seem to deviate from U.S. Department of Energy (DOE) protocols and comparable testing conditions reported elsewhere.
- The relevance of the "Molecular" design approach to materials pyrolized at high temperatures is not proven.
- Very little, if any, durability data have been reported to date.
- Starting precursors may be needlessly complex for a material whose structure will be extensively altered by activation through pyrolysis.
- Weaknesses include the continuity of funding and the use of Fe in the catalysts.
- Project weaknesses include the small team and a lack of durability studies.

Recommendations for additions/deletions to project scope:

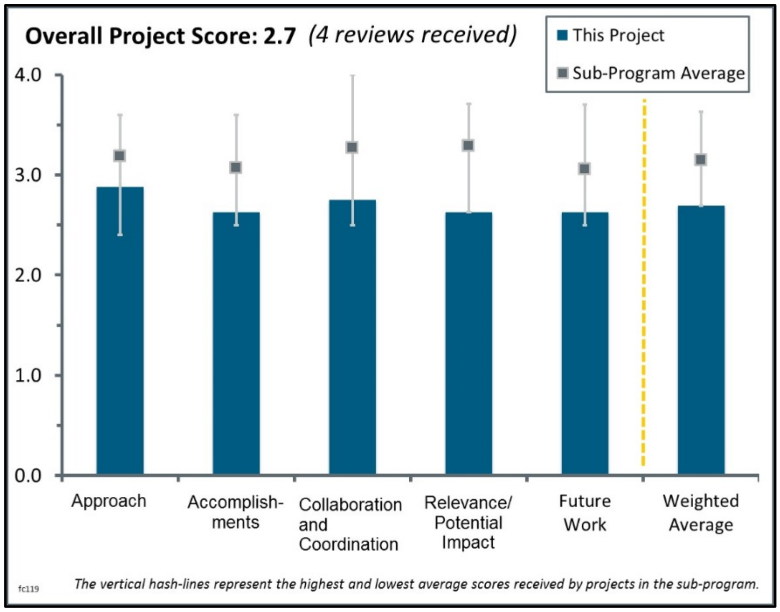
- In MEAs, cathode catalyst layer densities (i.e., thicknesses), porosities, and pore-size distributions should be measured and reported. Durability data should be taken for potential ranges that will give practical efficiencies (i.e., not at 0.4 V RHE, as was done in one oft-quoted paper). It might be good to try to mix project catalysts with conventional carbon-black supports (which give good pore structure) in an attempt to improve mass transport and high-current-density performance in air.
- Reported performance should be of some stability metric.
- The focus on non-Fe catalysts is commendable and should be enhanced.
- The project team should study leaching of Fe and Co, and the effect on the membrane's conductivity.
- The team should pursue a better understating of catalyst poor stability and develop a catalyst without Fe.

Project # FC-119: Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells

Hector Colon-Mercado; Savannah River National Laboratory

Brief Summary of Project:

The overall objective of this project is to co-synthesize highly active, low-cost non-precious-metal catalysts for the oxygen reduction reaction (ORR) by doping nitrogen-activated metal complexes into a novel nanocarbon support in a single-step process that is easily scalable and market relevant. A target of the project is to demonstrate performance of non-platinum-group-metal (PGM) catalyst prepared using a chemical vapor deposition (CVD) system to meet 6 A/cm^3 in rotating ring-disk electrode at 0.8 V in acid solutions.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- Non-PGM catalysts (such as co-pyrolized Fe and/or Co complexes [simple and macrocyclic] with polyacrylonitrile) were developed by Ernest Yeager under Ken Kinoshita of Lawrence Berkeley National Laboratory more than 30 years ago. This paper is similar and advances earlier work by inserting metals in carbon nanotubes and graphenes for better dispersion of metal as well as better conductivity and mass transport. This is a very good approach for advancing the prior state of the art. The team uses a good synthetic approach: CVD and multi-walled carbon nanotubes (CNTs) with NH_3 and Fe, which is better than high-surface-area (HSA) graphite with NH_3 and Fe; it also compared using Fe versus no Fe and found using Fe to be better, but more activity is still needed compared to Pt.
- Fabricating non-PGM using the CVD process has been suggested and deserves investigation. However, its benefit on the performance and stability is not clear. The main benefit is claimed to be its potential lower processing cost. However, non-PGM cost is quite low compared to PGM catalyst; therefore, cost should not be an important motivation. In addition, the high cost of metallic precursors used in the CVD process can cause higher cost than traditional synthesis methods. Evaluation of catalyst relies on rotating disk electrode (RDE) measurement.
- The budget for this work is very modest, so it is difficult to believe that the principal investigators (PIs) will be able to embrace all of the available techniques necessary to make the approach compelling. The CVD approach to synthesizing materials leads to materials that are very ill-defined. Transmission electron microscopy (TEM) images of these materials do not provide a complete picture of the materials' structure, much less the nature of their activity. If the PIs truly wish to use RDE measurements, they should become much more familiar with the technique before proceeding.
- A single-step, scalable process was the goal, yet the poster and slides speak a lot about as-made and surface modification. It is unclear whether this means that the process is no longer single-step. The use of Fe remains undesirable in light of the current membrane durability issues.

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

This project was rated **2.6** for its accomplishments and progress.

- The processing of new materials is well controlled, scalable, and done at a low cost. The resulting catalyst materials are well characterized. The performance of these catalysts is consistent with state-of-the-art non-PGM fuel cell cathode catalysts, but still far lower in activity than supported HSA Pt.
- The accomplishments are reasonably good. It is obvious that with the CVD method, the PIs can make a "new" class of materials. The biggest issue is the method they have developed to assess the activity of these materials. With rotating ring-disk experiments (RRDE), one can do many things (e.g., loading, number of cycles, and potential window) to achieve any activity one desires. The issue of the durability of these materials is not addressed at all.
- The RRDE activity targets in activity per volume (A/cm^3) were already revised for the bigger projects of Mukerjee and Zelenay; it is unclear why they were not in this project. Allegedly higher active surface area is obtained with heat treatment, but the cyclic voltammograms (CVs) really only show an increase in carbon area, coupled with an increase in ORR activity that is not quite of the same magnitude. No explanation is given of how the area increased (only "unzipping"), or why the activity is not proportional to this increase. Furthermore, the selectivity toward water is smaller with the higher area, which is contrary to the durability target. The mechanism of ORR activity increase in the N-doped CNTs, going from 800°C to 850°C, is unclear. The Fe content does not seem to increase, and neither does the area (in this case, the activity increase is proportionally larger than the area increase).
- The progress of the project appears to be very slow. Some results (which were quite low) using the traditional synthesis method were shown. Only a small amount of results using the proposed method were shown.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- It is positive that the PIs have included a variety of partners (e.g., big companies and start-ups). Combining the various expertise possessed by the partners may enable the PIs to do something truly new.
- Most work is being done at Savannah River National Laboratory (SRNL), but with good input from end users such as Ballard and carbon nanomaterials and fuel cell catalyst development companies such as NanoTech Labs and Greenway Energy, respectively.
- The collaboration is appropriate for the project's size and goals.
- This seems to be mainly a single-institution project, with slight guidance and materials supplied by the industry partners. It is not obvious whether there is actual cooperation in development and planning.

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

This project was rated **2.6** for its relevance/potential impact.

- Three things are impeding the deployment of fuel cells: cost, cost, and cost. Most of the real cost is in the fuel cell catalysts. Success in this kind of work is vital for making low-cost, effective fuel cells, and this type of work is to be strongly encouraged.
- Non-PGM catalysts provide hope of removing PGM risk from the technology, although significant challenges remain, including serious stability and performance issues. The project goals appear to focus on potential cost reduction, which should be a lower priority for this type of catalyst.
- Non-PGM catalysts are viable but still too far from applications for the DOE Hydrogen and Fuel Cells Program (the Program) to commit funding for them. This is especially true in this project, where most of the research should be considered "academic." This would be better if it were funded by the DOE Basic Energy Sciences (BES) program.

- At this stage, the relevance of the project is very modest. The PIs should be much more creative in order to make this project more relevant to DOE objectives and directions.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The materials development part is about as good as it gets. With the understanding that most catalysts work is trial and error, one suggestion is for the researchers to team with a theorist to assess working catalysts and give a less empirical and more fundamentally rational plan for future syntheses.
- Most of the future work proposed is in basic research. This is good, because non-PGM materials are in this state at the moment. However, it should not be DOE that funds this work. It would be a lot more useful to generate encompassing research toward active sites versus total area versus water-transport properties. There must be more benefits than merely cost for non-PGM catalysts to make the leap toward application.
- Unfortunately, the future work is based primarily on trying to improve the morphology of these materials, rather than focusing on a specific problem—the activity of the active centers. It is very difficult to synthesize promising materials without understanding the role of components in the material that may contribute to activity and stability.
- The progress has been very slow. The project still remains in an infant stage of development. The PIs should reevaluate what they want to accomplish in the remainder of this project.

Project strengths:

- The project features a good team, with SRNL serving as the lead and conducting catalyst characterization. Most work is being done at SRNL, but with good input from end users such as Ballard, nanocarbon provider Nanotech Labs, and catalyst synthesizer Greenway Energy. Perhaps a theorist could be added.
- Evaluation of cheaper non-PGM catalysts is valuable in assessing the feasibility of application in the future. Basic research in defining core properties and determining essential components is important.
- The biggest strength of this project is the use of CVD to try to develop a new class of non-PGM materials.
- The industrial partners are a strength of the project.

Project weaknesses:

- Similar to all non-PGM catalyst development, the work seems empirical but focuses on the catalyst support rather than the catalyst itself. More fundamental inputs or rational explanations of success might accelerate progress.
- There is a lack of a clear-cut approach to how to characterize these materials and evaluate a true activity-stability relationship.
- Weaknesses include the project goals, approaches, and planning.
- This is too fundamental for the Program to fund; at the moment, this research belongs in BES.

Recommendations for additions/deletions to project scope:

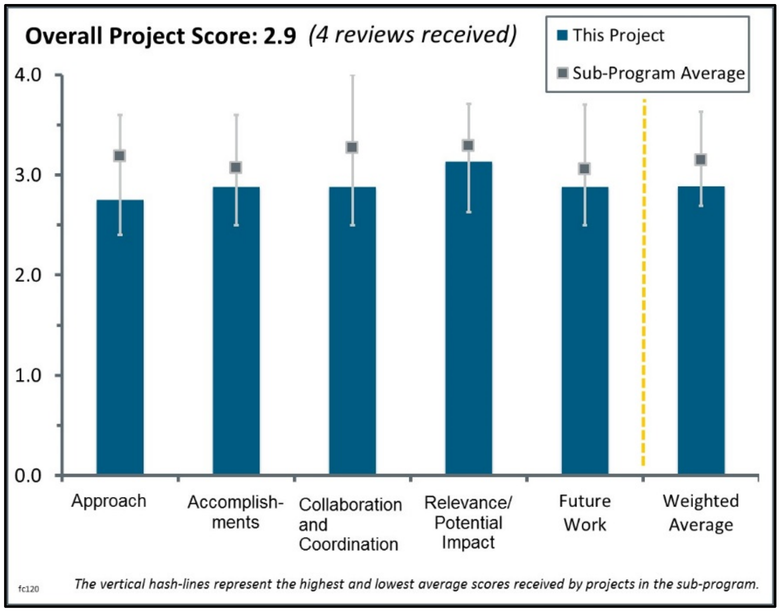
- With the project ending in three months, there is little to change in the scope. The team should scrap most of the proposed future work to really double down on the most essential aspects of the catalysts in order to improve those aspects. It may be useful to make sufficient catalyst for at least a few membrane electrode assemblies (MEAs) to check for basic properties in the MEA environment. This would assess possible trouble in integration in fuel cells (e.g., water transport, gas diffusion, and efficiency). This project should not be extended.
- The PIs should try to establish collaboration with a group(s) that has experience with much more comprehensive characterization of catalyst materials, as well as with how to evaluate the true activity of these catalysts.
- The team should think about getting input from a theorist for non-PGM oxygen reduction catalysts and expanding to non-PGM anode catalysts for hydrogen oxidation and oxygen reduction.

Project # FC-120: High-Performance and Durable Low-Platinum-Group-Metal Cathode Catalysts

Yong Wang; Pacific Northwest National Laboratory

Brief Summary of Project:

The overall objective of this project is to improve the stability of catalysts by enhancing metal/support interactions through engineered graphene for enhanced diffusion properties and by improving carbon support durability with an indium tin oxide (ITO) coating. Electrochemical evaluation using a rotating disk electrode (RDE) test station will demonstrate both the oxygen reduction reaction activity and stability, while membrane electrode assembly (MEA) testing will demonstrate the durability of the graphene catalyst.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- Moving from two-dimensional (2-D) to three-dimensional (3-D) engineering of graphene to use as a support for catalysts seems like a good idea. ITO is very stable in a polymer electrolyte membrane fuel cell acid environment, but ITO has very low conductivity. It is harder to deposit Pt selectively on a graphene support than on one where the graphene is coated with ITO.
- The approach seems excellent.
- The overall approach is reasonable, but in total, it is much too broad and ambitious for a single-year project. Little background is provided as to why ITO would promote durability improvements. It is unclear whether the 3-D graphene would result in improved transport.
- This relatively small project deposits ITO nanoparticles on graphene and uses the ITO to anchor Pt nanoparticles in order to improve the corrosion resistance of the support. ITO has been shown by several groups not to be stable in MEA operation. It is unclear why the team anticipates a different outcome from this project.

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

This project was rated **2.9** for its accomplishments and progress.

- The team engineered a successful 3-D graphene and dispersed ITO well on this 3-D graphene. The researchers showed improvement in durability for the ITO-added support, but tests were done using an RDE. MEA tests are very necessary to verify these results. Other groups have shown that ITO forms hydroxylate species in MEA, so performance and durability may not be the same as seen in an RDE. Also, the presentation did not show clearly what weight percentage Pt was deposited on the support.
- The progress has been good, considering the project’s size and duration. The team needs to include comparisons with commercial Pt (similar Pt particle size) on graphitized carbon to provide a reference against the state of the art.
- The results, to date, are good. However, it is disappointing that no MEA testing results are included by this time.

- Some initial results were shown using RDE. The team has not presented any MEA results or conducted any stability tests yet.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- There is very good collaboration between two laboratories. Pacific Northwest National Laboratory is taking a solution/wet chemistry approach to synthesize the catalyst, and Los Alamos National Laboratory is taking a vapor deposition approach. It will be nice to see the comparison between the two methods.
- The collaboration is appropriate for the project's size and goals.
- The collaboration is appropriate, considering the project's size.
- The two national laboratory partners seem to be collaborating well, but it is disappointing there are no other partners. For example, a non-cost industry partner would be an excellent addition to weigh in on the viability of this approach. Ideally, partners would include an MEA supplier and/or an automotive original equipment manufacturer that could advise on the viability and costs of the manufacturing process.

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

This project was rated **3.1** for its relevance/potential impact.

- The project is very relevant to the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. With some thorough investigation, this study could be very useful.
- Corrosion-resistant support can reduce the cost of a fuel cell system by about a few hundred dollars per system. This approach could be useful if it meets DOE targets at a modest increase in catalyst cost.
- The project is directly relevant to DOE goals.
- This project is certainly focused on addressing a key target—catalyst cost and durability; however, at this point, it is very difficult to judge the impact this project may have because no MEA testing or durability data is reported.

Question 5: Proposed future work

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

- The proposed future work is appropriate.
- The plan is appropriate; hopefully it can all be completed in the time remaining.
- Demonstrating the same improvement in MEA that is observed in RDE is a very important task. However, the presentation did not mention any efforts to understand why ITO is enhancing the stability. It is not clear if Pt that is deposited on ITO is useful, considering that ITO has very low conductivity.
- The team should evaluate the Pt-support interaction in more depth to understand the role of ITO.

Project strengths:

- Project strengths include the expertise and capabilities of both the national laboratories to carry out this research, that the team successfully engineering 3-D graphene and ITO integration, and that the project is taking two different approaches to deposit Pt.

Project weaknesses:

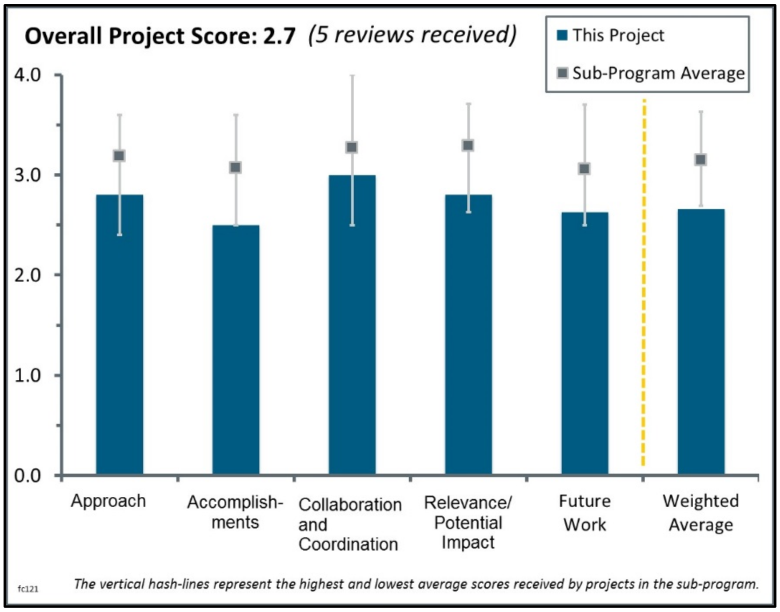
- Project weaknesses include that there has not been a thorough investigation in MEA yet, and the lack of understanding about whether Pt deposited on ITO is useful.

Recommendations for additions/deletions to project scope:

- As proposed in the future work, the team should carry out MEA testing; it should deposit low Pt weight percentage on support, then study whether similar results can be obtained.
- The team should conduct MEA testing and benchmarking against Pt/graphitized carbon.

Project # FC-121: Magnetic Annealing of Pt-Alloy Nanostructured Thin-Film Catalysts for Enhanced Activity

David Cullen; Oak Ridge National Laboratory



Brief Summary of Project:

The overall objective of this project is to explore the potential of high magnetic field annealing to produce highly active surface structures in platinum-alloy oxygen reduction reaction (ORR) catalysts. The impact of magnetic annealing on Pt_3Ni_7 nanostructured thin-film (NSTF) model structures will be characterized by rotating disk electrode (RDE), x-ray photoelectron spectroscopy (XPS), x-ray diffraction (XRD), and scanning transmission electron microscopy (STEM) testing.

Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- This is a very preliminary project; the viability and the relevance of the approach are unclear, but the execution of the stated work is excellent. At the same time, some of the most logical preliminary control and characterization work is lacking. Simple, well-proven, and inexpensive techniques should be pursued before more costly ones. Also, RDE tests are really not sufficient; at least membrane electrode assembly (MEA) tests are needed.
- The approach is generally effective; it uses a limited scope of parameters that are varied in a logical progression to assess the effects of these parameters on catalyst morphology and activity. It appears that the only barrier explicitly addressed to this point is activity, while durability and cost have not yet been addressed. However, the desired performance metrics or goals are not clearly indicated. While the project was unsuccessful in reproducing the morphology evolution and activity gain seen by van der Vliet (Nature Materials 2012), the researchers were limited to low-temperature annealing because maintaining the structural integrity of the support Kapton film and perylene red whiskers was a prerequisite. This was not required in the previous work of van der Vliet.
- The project was predicated on attempting to realize the benefits of annealing NSTF catalysts (reported in the literature) with an alternative method (i.e., magnetic annealing). The potential benefit is to avoid the negative impacts of high-temperature (HT) exposure to the perylene-red support. However, the project team has not been successful in achieving this—the mass activity is reduced, and what is believed to be contamination is observed. The project team needs to isolate what positive (and detrimental) results are due to HT versus magnetic interactions versus normal process development/debug, but it has not done this to date.
- The approach might sound unique, but this reviewer does not believe in the ability of magnetism to make a meaningful difference in the activity of Pt-3d transition metal alloy catalysts. Magnetism is usually considered a secondary effect when designing active catalyst materials. A much more powerful effect is the well-established temperature-induced segregation of 3d transition metals in Pt-based alloys.

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

This project was rated **2.5** for its accomplishments and progress.

- To this point, the only barrier addressed is performance—ORR activity to be specific—and every attempt to modify the morphology and grain structure through high magnetic field annealing resulted in a decrease in activity (both in terms of mass and specific activity), as compared to the as-grown NSTF catalysts. In addition, comparing the samples annealed in the same gas but with and without a magnetic field shows negligible differences in the activity. Annealing in hydrogen in a 9T magnetic field shows a marked increase in the grain size; however, this also likely occurred during annealing in hydrogen at 0T. Because of the limited annealing temperatures, the ideal (111)-like, smooth Pt-segregated surfaces shown by van der Vliet et al. (2012) were not obtained. To be fair, the NSTF alloy composition used here is much richer in Ni than that used by van der Vliet et al., which likely has some impact on the annealing process.
- The observed ECA, specific activity, and mass activity are lower than the catalyst as received. XPS suggests that carbon contamination is a contributor. STEM may show some interesting results, but the project team needs to isolate what is due to the magnetic interaction and what is due to temperature annealing. However, more importantly, the project has not demonstrated the benefit of this approach.
- The systems studied are not close to being characterized well enough for the principal investigators (PIs) to be able to provide any true insight into the role of magnetism in enhancing activity.
- There seems to be a lot of characterization, but not much analysis of the results.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The partners worked well together.
- The project team is coordinating with the right parties, including both 3M (developer of NSTF) and the original investigator who reported the annealing benefits. In addition, the PI and the National Renewable Energy Laboratory have the expertise to address the characterization. Perhaps more assistance is required in determining the root cause(s) of the contamination. However, it appears the team has the expertise to do so.
- This is a simple project, but apparently it features good division of labor.
- The group of collaborators listed is very good, but the lack of a critical approach toward evaluating the role of magnetism is surprising.

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

This project was rated **2.8** for its relevance/potential impact.

- The concept, if proved out, could contribute positively to the programmatic goals, if the following conditions are met: (a) it results in improved catalyst performance, (b) it can avoid negative effects such as support contamination, (c) the process is amenable to scale-up and cost-effective manufacture (the presentation did indicate the concept can be used with rolled goods, which is positive), and (d) it can be shown to be cost effective (the economics of high magnetic field annealing are unclear). However, the researchers have not gotten past (a) or (b) at this time.
- Creating a dominant surface orientation tailored toward the low energy (111) structure of Pt alloys is known to greatly enhance the activity of nanoscale catalytic ORR materials. If this ideal orientation can be translated to the NSTF catalyst architecture, it could greatly enhance the ORR activity of these catalysts, which already exhibit high specific activities for nanoscale catalysts. The use of high-transition-metal-content NSTF is somewhat defeating the purpose because even if grain size is increased and surface structure is smoothed to a relatively low index vicinal (111) surface, post-annealing de-alloying will quickly roughen the structure, nullifying any improvements associated with this annealing procedure. As it turns out, the nanoporous geometry is highly desirable because it greatly improves the electrochemical

surface area of NSTF, limiting the amount of buried precious metal and consequently improving the mass activity. For this approach, however, the homogeneity of the initial alloy, rather than the surface morphology or compositional profile, is the most important aspect of the initial alloy. In addition to surface structure, improving the alloy homogeneity should be a goal of this project because the as-grown alloys are very inhomogeneous, even when using co-sputtering or sputtering from an alloy target.

- While the execution and relevance are unclear, the concept of annealing catalyst has been proven before, demonstrating there is at least potential.
- This magnetic annealing approach is not the best direction to pursue. At the moment, it is very difficult to recommend this approach as the future for making a new generation of catalysts.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The project focuses on RDE evaluation. The approach to incorporate in full-size MEAs would be added value.
- The future efforts are focused on adjusting the annealing conditions and alloy composition, conducting durability tests, and performing more modeling efforts. It is somewhat useless to continue with durability and post-mortem characterization efforts if no activity improvements can be obtained beyond that of the as-grown material. The future efforts should be focused on improving structural ordering and the effect of the magnetic field by using alloys with higher magnetic moments, improving homogenization of alloys at limited annealing temperatures, and limiting catalyst deactivation due to support evaporation and re-deposition on the catalyst surface.
- The proposed future work is very broad and clearly would not all be addressed during the project's remaining time. During this remaining time, the project team should focus on the following:
    - Better process control (i.e., identifying and correcting the cause of contamination).
    - Identifying/isolating the impact of magnetic annealing versus the temperature-annealing effect. The researchers should try magnetic annealing at lower temperatures and with a greater range of magnetic fields (including higher Tesla, if feasible). It would be good to know the actual effects of magnetic annealing without the (believed to be) detrimental temperature effects.
- The relevance of RDE on this effort is unclear, and the future work plan seems to be too general; it mirrors the work to date and does not seem to reflect any conclusions from the work done so far.
- The authors propose to use Pt-Co, which is known to have paramagnetic properties and might seem like a good direction to pursue. However, how successful this direction will be is questionable.

Project strengths:

- This project addresses the need to optimize the surface structure of the NSTF catalyst architecture because it is inherently rough because of the deposition process. This structural reorientation as a consequence of annealing is limited to relatively low temperatures because of the presence of a polymer and molecular solid support. The use of magnetic field-induced annealing could have a significant effect on the reorientation because of the magnetic-field-induced changes of structural ordering in these magnetic thin-film materials. The integration of high-throughput materials synthesis, annealing, catalytic testing, and extremely high-quality microscopy analysis is very efficient in identifying improvements and quickly informing/guiding the project progression.
- The project's strengths include its strong technical skills and its promising preliminary results that show magnetic annealing effects.
- The biggest strength of this proposal is the group of collaborators that has been assembled.
- The diagnostics and characterization capability of the PIs are strengths of this project.

Project weaknesses:

- The modeling efforts are useless because significant computational results in combination with well-defined experimental results have clearly identified the active sites for ORR. The magnetic moment of Pt_3Ni_7 appears to be too small for magnetic field annealing to have any significant impact. Perhaps the usefulness of this approach is limited to a delicate balance between the temperature required to induce surface diffusion to drive preferential orientation and the curie temperature of the alloys (i.e., demagnetization).

- The amount of work seems very limited, and conclusions are therefore difficult to draw. There seems to be a lot of characterization, but not much analysis of the results. The economics of magnet operations are unclear.
- Weaknesses include the control of the process (i.e., contamination) and the experimental approach (the team should take a more systematic approach to identifying magnetic field effects).
- Unfortunately, the magnetic annealing approach is not the right direction to pursue.

Recommendations for additions/deletions to project scope:

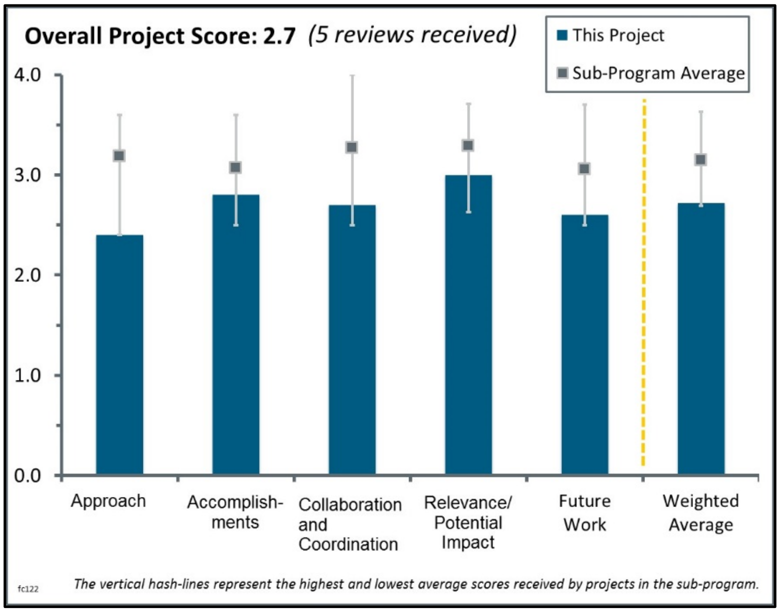
- The researchers should use alloys that are not as rich in the less noble component because they are very susceptible to de-alloying and porosity evolution, which would be counterproductive to the goals of this project. They should try using some alloys with larger magnetic moments, such as Pt_3Fe. These may be more greatly affected by the magnetic field. If they are continuing with high-transition-metal-content alloys, they should also focus on alloy homogenization. The researchers should limit modeling efforts because the ideal ORR active site has already been thoroughly studied in previous computation studies. They should also identify strategies of mitigating carbon layer formation on the precious metal catalyst surface due to support decomposition during the annealing process. Alternatively, they should develop techniques for facile removal and “activation” of the catalyst post annealing.
- The team should focus on good preliminary work instead of sophisticated analysis—for example, XRD refinement to augment aberration-corrected transmission electron microscopy (ACTEM) and thermogravimetric analysis (TGA) instead of a superconducting quantum interference device (SQUID).
- The team should focus on addressing the problems. It should deemphasize modeling until benefits are shown. In addition, durability should be contingent on successful mass activity results.

Project # FC-122: High-Conductivity, Durable, Anion-Conducting Membranes

Tom Zawodzinski; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objective of this project is the development of highly conducting, durable anion exchange membranes (AEMs) and their demonstration in fuel cells. To address this goal, Oak Ridge National Laboratory will leverage its experience in preparing AEMs for zinc-air batteries with high conductivity; new findings regarding the durability of these membranes and how degradation pathways can be controlled; and its capabilities for developing and coating electrodes.



Question 1: Approach to performing the work

This project was rated **2.4** for its approach.

- The high-throughput approach may be beneficial for membrane synthesis, but details regarding what systems are being investigated are not provided. The principles or theory guiding the high-throughput effort have only been vaguely described, and not with enough detail. Without some description of the guiding principles or hypotheses about what will improve the properties of interest, there are simply too many possible combinations to investigate, and high throughput becomes searching for a needle in a haystack. It is not possible to determine whether the approach is applicable to alkaline exchange membranes if the basic chemistry of the polymer systems being investigated is not disclosed. The stability of the polymer backbones, the stability of the cationic functional group, the potential for high conductivity from the functional group, the likely mechanical properties, or even whether these systems have already been investigated or developed cannot be judged with the information provided. The project takes a two-pronged approach to help reduce risk: traditional AEMs and KOH-soaked cross-linked loaded membranes (CLAMs). It is not clear what the benefits of the CLAM approach are, and how the approach will improve on current alkaline fuel cells (AFCs). This approach does not appear to provide the same benefits as conventional polymeric AEMs. It is not clear that this approach will address carbonate formation in AFCs; it seems likely KOH/H_2O uptake in a polymer medium will still result in potassium carbonate formation and decreased conductivity with time. It is also not clear how this approach will prevent loss of KOH under some operating conditions.
- The general approach of tailoring a cross-linked AEM with different cross-linkers, cationic groups, and polymer backbones is reasonable, but none of the chemistry has been disclosed, so it is difficult to provide a thorough assessment of the approach. It is a concern that the KOH would not remain in the membrane during extended fuel cell testing, which would be a durability issue.
- The approach of the polymer synthesis is not clearly given, so it was hard to judge the merit of the approach. The approach has been explained in very generic terms, most likely for intellectual property (IP) protection. However, the team has just mentioned the key words, such as “proto”-functionalized backbone, cross-linking agents, additives, and blending polymers, so it is not possible to understand the actual approach taken.
- The approach seems reasonable in concept, but it is difficult to evaluate without discussing the specific materials. The need to protect IP is understandable, but one cannot give a rating higher than “satisfactory” based on what is publicly discussed to date. The U.S. Department of Energy (DOE) should not view this as a “neutral” rating at this time.

- While the conductivity of the AEMs is high, the area-specific resistance is also high due to the thick membranes. The team needs to study the impact of membrane thickness on performance and durability.

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

This project was rated **2.8** for its accomplishments and progress.

- The project has been in place for less than a year and is 50% complete. In this time, the researchers have prepared more than 40 distinct compositions. In this short time, they have achieved some impressive conductivity results for their CLAMs. The reported initial conductivity of 0.8 Siemens (S)/cm is higher than recently reported values for the maximum obtainable with KOH solutions of 0.65 S/cm. It is unclear how much KOH is in these membranes and under what conditions the conductivity was obtained, but one would not expect the conductivity to exceed that of a KOH solution. Mechanical properties were not investigated and stability toward electrolyte loss has not been investigated. If the CLAMs are saturated with KOH, conductivity will be dominated by the KOH, and one would expect the conductivity to be the KOH conductivity X the volume fraction of the KOH phase. The important aspects will then be the stability of the KOH-CLAM system, and whether the CLAM immobilizes the KOH. No results were shown for tests investigating the stability and ability to immobilize the KOH. No results were shown for more traditional AEMs. The poster claims "Over 40 distinct compositions studied." For a high-throughput approach, 40 distinct compositions is not very high throughput.
- The team has met the conductivity and resistivity goals for the membranes. The team has claimed that the CLAMs meet targets for conductivity (>100 mS) at lowered relative humidity (50%), but no data was presented to substantiate the claim. Disclosure of some performance data could have helped reviewers understand the merit of these AEMs.
- Several conductivity values were reported that are very impressive. It will be good to learn more about these materials. The reviewer was concerned that the CLAM approach may not be viable. The permanence of the KOH solution is questionable. The stability of these materials needs more attention.
- Preliminary conductivity and area specific resistance (ASR) targets have been met, although an ASR of 0.1 ohm-cm^2 is not a reasonable goal. For automotive applications, an ASR around 0.02 ohm-cm^2 is needed. Also, it is not clear why "no cathode precious metal" is relevant for an ASR target.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The team consists of a good mix of national laboratory, academic, and industrial partners. The collaboration with Eastman, Los Alamos National Laboratory, and the National Renewable Energy Laboratory is advantageous to the team.
- The principal investigator (PI) mentions working with industry to enable scale-up. There is no apparent coordination with other AEM projects. There is no mention of collaboration or interactions with the major players in the AFC or alkaline electrolyzer areas.
- Even though this is a small project of short duration, it would be nice to see more substantial collaborations. It is good to see technology transfer from related zinc/air research.
- There is no evidence of collaboration, because this is an early stage of the project.

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

This project was rated **3.0** for its relevance/potential impact.

- The project is relevant to the objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The activities are aligned to DOE's goal to address the commercial

barriers such as performance, cost, and durability. The focus of the project is to develop and demonstrate chemically stable hydroxide-conducting AEMs.
- This project is one of several AEM projects that appear to be in the exploratory stage. This is important work in defining viable chemistry for this type of membrane/MEA.
- Polymer alkaline electrolyte membrane work is relevant to both hydrogen production and fuel cells. It is not clear what the expected advantages of the CLAM are, compared to existing alkaline electrolytes, or what targets or shortcomings they address.
- It is unclear how this project addresses high-level DOE Hydrogen and Fuel Cells Program targets. Even if the researchers are successful in meeting their objective of 0.1 ohm-cm^2 ASR, the membrane electrode assemblies (MEAs) will still not meet power density requirements for automotive applications. Also, without any disclosure of the chemistry or synthesis processes, there is no way to assess the potential cost implications.
- The overall performance of an MEA with AEMs is unclear.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The future work is aligned with the project proposal and the remaining time left for the project.
- The details of the durability testing and how the researchers will achieve their deliverable on determining the relationship between AEM fuel cell durability and accelerated protocols is not provided. So far, the focus seems to be on conductivity loss, which is certainly important. Tailoring mechanical properties is also important, but there is no information provided on the status of the mechanical properties or what properties are required for sufficient durability. Although not included in the presentation, the PI did say the researchers would do thermal stability testing, which is crucial for AEMs.
- The future work appears focused on traditional AEM membranes using the high-throughput approach. This is scheduled as a one-year project; the future work appears to be more than can be done in the remaining three months with the budget provided.
- The future work includes a lot of very difficult tasks: catalyst-coated membrane making, degradation mechanisms, catalyst making, modeling, etc. One fears that the size and time frame of this project will not allow completion of these tasks. One wonders what tasks will realistically be completed by the end of the project.
- The future work should consider using membrane reinforcement to reduce the thickness to less than 25 µ, as well as reducing ASR to <20 milliohm-cm^2.

Project strengths:

- The team is composed of respectable research organizations with adequate expertise. Overall, the team is equipped with the knowledge base, resources, and industry/academia/national laboratory mix required for the project to be successful.
- This project is screening a large range of membrane chemistries and designs, even though the details have not been disclosed, pending IP protection. The researchers have achieved reasonable conductivity with thick membranes.
- This project appears to have made several AEMs with excellent conductivity. The presentation described a very broad number of types of synthetic compounds. This may allow evaluation of a wide range of membranes and selection of an optimum option for performance and durability.
- The project features a solid fuel cell/membrane background.

Project weaknesses:

- The lack of disclosure of specific chemistry, while understandable, makes a full evaluation difficult. The number of chemistry options seems very broad and may need to be more focused in future work. The durability of the cationic functional groups is a key concern for all AEMs at this point. Without specific knowledge of this functional group or the additive groups, this question remains.

- The ASR target may be too high. There is no plan laid out for durability testing. The lack of disclosure of chemistries makes a thorough review impossible. It would be nice to gain fundamental learning about which options provide best conductivity, stability, and durability to provide other developers with guidance in their work.
- The project does not disclose enough about the chemistry to be able to determine whether the ideas have merit. The project utilizes a high-throughput synthesis, but it does not have high-throughput analysis or testing in place yet. This will bottleneck the approach at the testing stage.
- The team has spent significant time on membrane development. It could have conducted some AFC tests to demonstrate the merit of some of these membranes.
- The presentation material lacks the necessary details for one to clearly understand the project’s progress. The project also lacks partners to help make good membranes from this polymer.

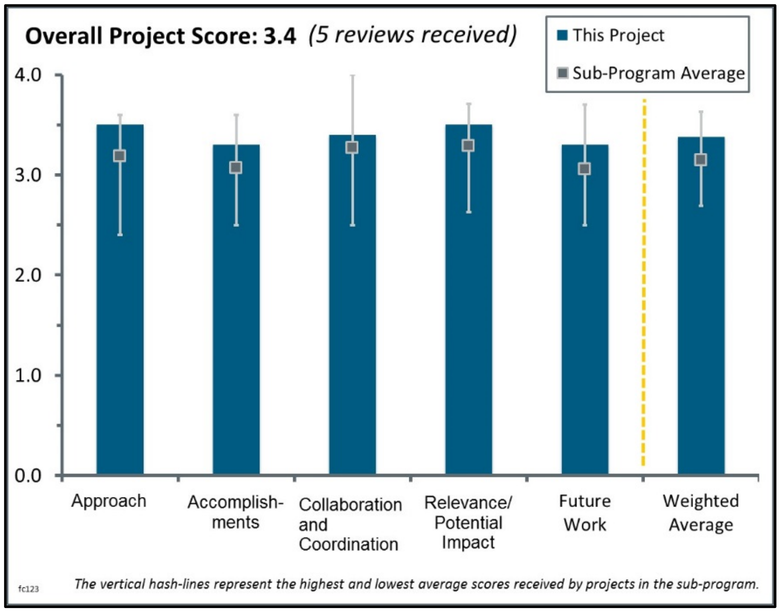
Recommendations for additions/deletions to project scope:

- The team should focus on making thinner membranes (<30 microns) so that the AEMs can hopefully approach automotive ASR targets. It should also start testing for thermal stability. It should test to see whether AEMs lose KOH, and therefore conductivity, during extended fuel cell operation in wet conditions.
- The future work seems much greater than the timing and funding for this project would allow. While all the tasks are relevant, the team should identify a few achievable milestones to be completed by the end of the project.
- The researchers should conduct durability testing to determine whether CLAMs retain the KOH and their high conductivity.
- The project team should add a membrane original equipment manufacturer.

Project # FC-123: Advanced Hydroxide-Conducting Membranes

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:



The objectives of this project are to develop (1) chemically stable hydroxide-conducting anion exchange membranes (AEMs), (2) solvent processable perfluorinated ionomers, and (3) modeling approaches to demonstrate high-performance/durable alkaline membrane fuel cells (AMFCs). In fiscal year 2015, the perfluorinated ionomer with alkyl amide linkage was designed to increase amide stability under basic conditions; fuel cell performance measurement using these ionomers is ongoing.

Question 1: Approach to performing the work

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

- The approach is excellent. This is the best "alkaline fuel cell membrane" this reviewer has seen to date. In fact, it is the best AEM this reviewer has seen to date. It is better than neosepta, etc. The approach to stabilize the decomposition of the ammonium site looks excellent and is the vital step. The team achieved good stability by eliminating the ether linkage. There is no added OH^- and there is still good conductivity. This should lead to an OH^- CO_3^{-2} conducting membrane with sufficient stability and lifetime to test whether it is true that there are better, cheaper, and more durable fuel cell catalysts available for oxygen reduction and hydrogen oxidation using polymer electrolyte membrane (PEM) fuel cells based on hydroxide (and/or carbonate) rather than proton conduction.
- The Los Alamos National Laboratory (LANL) approach targets the performance and durability barriers for AEMs. The approach specifically targets durability by improving the chemical durability of the cationic functional group and of the backbone polymer. The cationic functional groups being investigated are more resistant to degradation by SN_2 (substitution nucleophilic second-order) reactions than benzyl trimethyl ammonium groups. Also, replacing the aryl-ether linkage with ether-free backbones will prevent ether cleavage in alkaline solutions. The approach to look at multiple backbone chemistries provides reduced risks as well as the potential to discern the impact of phase segregation and electronic effects on AEM performance. The inclusion of modeling efforts to understand CO_2 interactions and water distribution in an MEA should prove beneficial in optimizing operating conditions for AEM fuel cells and minimizing problems with water management. While investigating multiple systems reduces risks, it also dilutes resources. At some (future) point, a down-selection to the most promising candidate would accelerate progress on that option.
- The project seeks to make stable, mechanically robust AEMs and chemically stable ionomers for AEM fuel cells. Chemical stability is achieved through non-polar backbones and advanced cations. New ionomer dispersions are being developed for electrode integration. A modeling approach is being used to understand transport in fuel cells and operational parameters.
- The approach of using alkyl amide, phenyl guanidinium to enhance the stability of the amide linkage is a good way to increase the stability of AEMs. The modeling approach to understand the performance is also a good approach.
- The rationales for the chemistries and structures are presented on slides 7 and 8. The technical and cost targets and their bases are inadequately discussed. The CO_2 issue is recognized and is being addressed.

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

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

- The project has made good progress. The project has demonstrated the improved stability of the new membranes compared to the control in ex situ testing, and the team has met its milestone for stability for <10% loss after 500 hours in 0.5 M NaOH at 80°C with two membrane types. The team has demonstrated improved stability of the phenyl alkyl amide linkage compared to the phenyl amide linkage in high pH conditions via Fourier transfer infrared spectroscopy (FTIR)studies. Initial fuel cell performance tests indicate hexamethyl ammonium functionalized poly(phenylene) AEM is the best-performing hydrocarbon system under investigation. The area-specific resistance (ASR) of the "AR"-series membrane had a substantial dependence on current density, while the other membranes' ASR had very little dependence on current density.
- The team has achieved good progress in a short time period by establishing seven different membrane synthesis chemistries and finding the weakness in four of them. The team has also successfully determined the "MRH"-series membrane ionomer chemistry as one of the potential candidates for AEMs.
- The project team stabilized the ammonium group, stabilized mechanical properties, and modeled and tested CO_2 effects. It performed excellent impedance work.
- A series of rigid and flexible polymers have been synthesized. The ASR target for the year has been reached. A fuel cell at 60°C shows some promising stability. There is good integration of ionomer with the membrane for some good, improving fuel cell performance. The modeling is showing that input CO_2 amounts will need to be lower than 50%.
- Progress toward improving conductivity, alkaline stability, and mechanical properties is presented and is respectable, but targets are absent, so it is not clear if the progress is good enough.

Question 3: Collaboration and coordination with other institutions

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

- The team consists of a good mix of national laboratory, academic, and industrial partners. The interaction with Solvay, which manufactures PEM fuel cell membranes, is very encouraging.
- The project's full spectrum of team members covers the necessary expertise and project requirements. Collaboration and cooperation were necessary for the project team to have achieved this level of progress.
- The collaboration and coordination are excellent and extensive. All the bases are covered.
- The collaborations appear to be working well, especially between Sandia National Laboratories and LANL and between LANL and Lawrence Berkeley National Laboratory. Including Solvay gets an industrial supplier involved. Participation by or collaboration with commercial alkaline fuel cell or alkaline electrolyzer companies would be beneficial.
- There is good collaboration between national laboratories and one university. Industry involvement is mostly related to material supply. The project needs more fundamental university input. Including a fuel cell component supplier and an original equipment manufacturer in a relevant end-use area would also be beneficial.

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

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

- The project is relevant to the objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The activities are aligned with DOE's goal of having chemically stable, hydroxide-conducting AEMs.
- The development of AEM membranes has a large potential impact—this would be an enabling technology for alkaline fuel cells that can effectively utilize inexpensive non-platinum-group-metal cathode catalysts.

These fuel cells could have large cost savings compared to current PEM technology. The proposed work addresses the main problem with current AEM membranes—durability.

- This is needed to give a clear test of the hypothesis that alkaline membranes have something to offer.
- This is hard to evaluate because the Hydrogen and Fuel Cells Program does not yet have well-thought-out goals for AEM fuel cells. Certainly the researchers are addressing durability and performance targets that are relevant to AEM fuel cells; it is not clear whether cost targets will be addressed before non-precious-metal catalysts are integrated into AEM fuel cell MEAs.
- The relevance is clear. The impact is unclear without better definition of technical goals and the status of the project.

Question 5: Proposed future work

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

- The project is scheduled to end soon. The proposed work is appropriate for the time remaining. The work focused on the perfluoro alkyl amide polymer dispersion and AMFC testing should be the priority. Work on incorporating the gas diffusion layer and flow channels into the AMFC model is of lower priority at this time.
- The future work is aligned with the project proposal and the remaining time left for the project.
- In particular, the long-term testing comment is good; this has been missing.
- In the remaining time for this one-year project, the researchers are wise to finish polymer characterization so that papers can be finished. Most of the other tasks seem like appropriate loose-end issues that should be completed so that the project will provide the maximum useful information.
- The project is over on July 31, 2015. Cell testing is the most important aspect.

Project strengths:

- The team is composed of respectable research organizations with adequate expertise. Overall, the team is equipped with the knowledge base, resources, and industry/academia/national laboratory mix that is required for the project to be successful.
- The variety of chemistries studied should provide some valuable clues regarding what polymer structures and properties are best incorporated into AEMs.
- Project strengths include that it is investigating non-polar polymer backbone and developing ionomers.
- The project features a great team and a good approach; more of this is needed.
- This project features wide collaboration.

Project weaknesses:

- The project does not have enough resources to do justice for all of the polymer systems studied. It needs more proof that the novel cations will survive in the ionomers. There is not enough emphasis on the challenge of >80ºC and low relative humidity (RH) operation, where these cells will eventually have to operate.
- The team should focus on conducting more AEM fuel cell testing to determine the merit of its membrane in situ.
- Definition of technical targets is needed.

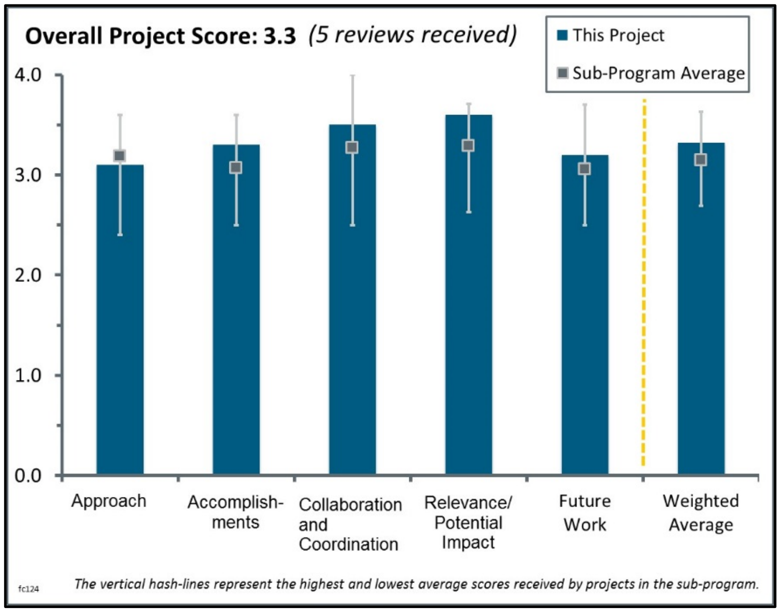
Recommendations for additions/deletions to project scope:

- It is relatively inexpensive to reduce ambient CO_2 to fairly low values; researchers should consult with industry to determine a feasible CO_2 input level instead of guessing. Researcher should also begin to think about non-precious-metal catalysts; there is no point to AEM fuel cells unless non-precious metals are integrated or more complex fuels are utilized.
- The researchers should do the long-term testing of fuel cells with the best membranes right away. If they are truly stable OH^- conductors, then these membranes may have significant use in "bipolar membranes"—a competitor to reverse osmosis for low-salt water purification. One can remove CO_2 by passing CO_2-free gas and monitoring that water pH goes from 5 to 7.

- It would be useful for the team to conduct more mechanical property testing and water uptake and swelling tests. While RH cycling may not be important in electrolyzer applications, in automotive fuel cell applications, mechanical stresses on the MEA due to swelling/shrinking may be an issue.

Project # FC-124: High-Temperature and Low-Humidity Membranes

Cy Fujimoto; Sandia National Laboratories



Brief Summary of Project:

The objectives of this project are to (1) develop a hydrocarbon (HC) membrane that can operate with minimal resistance losses (0.05 ohm-cm^2) at 120°C and humidity ranges between 30% and 50%, (2) fabricate and test membrane electrode assemblies (MEAs) at 120°C and humidity ranges between 30% and 50%, and (3) perform durability testing of MEAs at 120°C and 50% relative humidity (RH).

Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- Sandia National Laboratories (SNL) are leveraging their very well-thought-out sulfonated Diels-Alder polyphenylene (SDAPP) chemistry. An unexpected consequence of applying modified SDAPP to a redox flow battery project was the discovery that the acid content of the film could be dramatically increased. If SDAPP could be made to have high proton conductivity at high temperatures (HTs) and relatively low RHs, it would also potentially meet the cost and durability targets. In short, this is an excellent extension of previously funded U.S. Department of Energy (DOE) work.
- The work is focused on the cost barrier and the area-specific resistance (ASR) target. An HT, low-RH proton exchange membrane would decrease demands on the thermal management system and humidity management for the fuel cell, allowing for smaller balance of plant (BOP) and lower system costs. However, the membrane must be able to meet durability targets as well. In particular, mechanical durability during wet-dry cycling must be met, and this project should consider some effort in addressing this target as well. The approach to utilize block copolymers with sulfonic acid substituted polyphenylenes has a high probability of achieving high conductivity at HT and low RH. Previous DOE Office of Energy Efficiency and Renewable Energy–funded work with sulfonic acid substituted polyphenylenes resulted in high proton conductivity, but those materials had poor mechanical properties (they were brittle and had problems with swelling and strength at high RH). Utilizing the Diels-Alder reaction for the polymerization to give a distribution of polymerization at the meta and para positions, combined with the addition of a hydrophobic block, should help overcome the brittleness. The block copolymer approach may aid the swelling and solubility issues observed for the previous polyphenylenes. The project-specific membrane milestones and final targets are unclear. The project ASR milestone of 0.06 ohm-cm^2 is significantly less aggressive than the DOE ASR target of <0.02 ohm-cm^2 at 120°C and water pressure of 40 kPa (~20% RH). The team should aim at meeting all the membrane targets in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) or U.S. DRIVE Partnership Fuel Cell Tech Team Roadmap simultaneously.
- Membrane making is difficult because it involves synthesis and processing. The approach, for better or worse, was restricted to the polymer backbone to improve membrane properties. The good part is that various synthetic approaches were successfully used to develop an aromatic (polyphenylene) polymer backbone for a sulfonic acid membrane with good initial chemical thermal and mechanical stability (high glass-transition temperature [Tg]) and high conductivity. A short-term test is 2,500 hours; a full test is 50,000 hours. One-hundred hours is only an initial characterization. The bad part is that because this is a hydrated sulfonic acid membrane, this fuel cell membrane will have all the issues found in any acid membrane. It requires water (humidification and pressurized gas feeds) for acid ionization ratio and

conductivity, and water affects its performance. This kind of membrane, using water, will suffer Pt oxide formation and therefore low cathode performance (high air cathode overpotential). Therefore, although this polyphenylene fuel cell membrane demonstrates a very good polymer backbone, it is only a first step to another membrane. This specific type of membrane, itself, is not sufficient for commercialization of fuel cells.
- The approach of following the concept disclosed in U.S. Patent 8,110,636 B1 and fine-tuning it to fit the need is good. However, given the peroxide instability of SDAPP, it is very interesting that the team chose to pursue the route to have SDAPP as the ionic domain for the HT membrane. One expects that under an HT of 120°C, the peroxide degradation will be more in SDAPP.
- Hydrocarbon membranes have long suffered from poor conductivity at low RH. This approach appears to address this issue and may be a path to a competitive membrane for perfluorosulfonic acids (PFSAs).

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

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

- The project has made good progress in the short amount of time it has been active, and with the limited funds available. Conductivity at 120°C and ~30% RH is almost double that of Nafion. Performance in an MEA (at 80°C, fully humidified) is reasonable, but performance under low RH and or HT has not yet been demonstrated. The conductivity of these membranes appears to have a higher RH dependence than Nafion does at 85°C. This may suggest a larger range of water uptake and swelling, which has negative implications for durability. Minimal results for water uptake or swelling have been provided, but the uptake reported (150%) is quite high and suggests swelling may be an issue. Water uptake/swelling tests—in particular, cyclic swelling tests (using the prescribed mechanical durability protocol)—need to be done.
- The synthetic approach appears to address two issues with previous HC membranes: the rigid rod nature of the polyphenylene backbone and the sulfonic acid density. The 120°C, 30% RH conductivity is impressive. The block copolymer approach is important in overcoming the traditional shortfalls with previous HC membranes.
- One ion-exchange capacity (IEC) of the modified SDAPP has shown a proton conductivity of twice that of Nafion at 120°C and 30% RH, and the ASR is 0.06 ohm-cm^2 for a 30 µ film—a very promising result. Oak Ridge National Laboratory (ORNL) has made MEAs with SDAPP, but it has yet to make MEAs with the modified SDAPP, although this work is about to begin.
- The team has made good progress. However, the team should consider Fenton's test for its new block copolymer membrane (slide 10) to understand the feasibility of SDAPP chemistry for an HT membrane. It is good that the team is exploring the use of this membrane in vanadium flow battery technology, where the peroxide degradation is not an issue.
- By focusing on developing a backbone, the team mostly succeeded in what it set out to do.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration among the partners appears to be good. Including the Automotive Fuel Cell Cooperation (AFCC) in the team should keep the project focused on fuel cells and automotive-relevant conditions. It appears some leveraging of work is being done for flow batteries on similar membranes.
- The team consists of a good mix of national laboratory and industrial partners. Working with DOE contractor Sanjiv Malhotra is a good avenue for technology transfer.
- The team was "lean" but effective. The project features synthesis at SNL, MEA fabrication at ORNL, and testing at ORNL and AFCC.
- The project has good collaborations with other national laboratories and with AFCC.
- The collaborations are excellent and involve two national laboratories and a laboratory representing a consortium of original equipment manufacturers. It would be beneficial to add a university partner to dig deeper into the science of these new materials that might help to explain why the higher-IEC material had a lower conductivity than the lower-IEC material.

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

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

- The project is relevant to the objectives of the MYRDDP. The activities are aligned with DOE's goal of having HC membranes that can operate with minimal resistance losses at 120°C and humidity ranges between 30%–50%.
- This project is clearly geared toward meeting the performance, cost, and durability targets for membranes in the MYRDDP.
- This is excellent work, but improving a sulfonic acid membrane is evolutionary, not revolutionary, and all the problems of catalysis remain. However, polymer backbone development is one of the core issues in making membranes, and the team achieved excellent development and demonstration of a good polymer backbone that could have a place as a component in a successful fuel cell membrane.
- The project is relevant and addresses DOE area-specific resistance targets for fuel cell membranes and the desire for membranes that can operate at 120°C and under low-RH conditions. The impact could be high if successful, because a membrane that could operate at 120°C at 40 kPa water pressure would allow one to remove the humidifier and significantly reduce the size of the radiator, reducing BOP and system costs. However, the project also needs to address durability concerns with these membranes—in particular, how the membranes handle RH cycling and chemical durability.
- The performance at temperatures above 100°C could be very significant.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Testing these materials at a greater range of operating conditions will be important in order to make a complete comparison to the incumbent PFSA technology. Realistic membrane thicknesses of 15–20 µ will be important for both performance and durability assessments.
- The proposed work at HT and low RH is the right thing to do—adding time testing to evaluate durability seems needed. The workers seem to know what is necessary to reach the goals: innovation on the pendant ionic group seems essential.
- The proposed future work is a logical extension of what has been accomplished so far and should yield enough data to facilitate a decision on whether future—hopefully much larger—funding is allocated for this important work.
- The future work is aligned with the project proposal and the remaining time left for the project.
- The proposed future work still appears to focus on the ASR target. Mentions of durability consider thermal stability, as well as durability at 120°C and 30% RH under constant conditions, but the presentation did not mention the variable cyclic conditions and RH cycles found in automotive applications. Durability under cyclic operating conditions (specifically RH cycling) needs to be brought in. The team should also consider looking at supported membranes, as well as the other DOE membrane targets such as crossover.

Project strengths:

- The team is composed of respectable research organizations with adequate expertise. Overall, the team is equipped with the necessary knowledge base, resources, and industry/national laboratory mix for the success of this project.
- It is good to see work continuing in the HC membrane field. This project is thoughtful and builds on the previous work of Jim McGrath by using block copolymers and on the work of Zawodzinski and Hamrock, who identified the need for closely packed acid groups. The focus on the very difficult operating conditions at 120°C and 30%–50% RH is a good approach.
- The concept is flexible and takes advantage of previous work that showed the potential of polyphenylenes and block copolymer approaches. Initial results are promising and show the researchers can achieve good conductivity at 120°C. The work leverages ongoing work in flow battery membranes.

- The team modified the chemistry of a polymer that has been developed by SNL for a number of years. The project features a very good mix of well-known experts in the field.
- The project features a good team that is focused and has achieved its goals.

Project weaknesses:

- The data to date has been collected on very thick (~100 µ), unsupported membranes. While this is a good place to start, a realistic assessment compared to the state of the art can only be made using <20 µ supported membranes.
- The team should focus more on the stability of the membrane under HT polymer electrolyte membrane fuel cell conditions, which is the primary goal of the project.
- The project seems a little empirical; it is not really science driven. It needs many more resources to properly tackle the ionomer issues expected when constructing state-of-the art MEAs.
- The project lacks swelling and mechanical property measurements, and it is not clear these issues are being given enough consideration.
- The project is too focused; it needs to diversify to pendant ionic conductors.

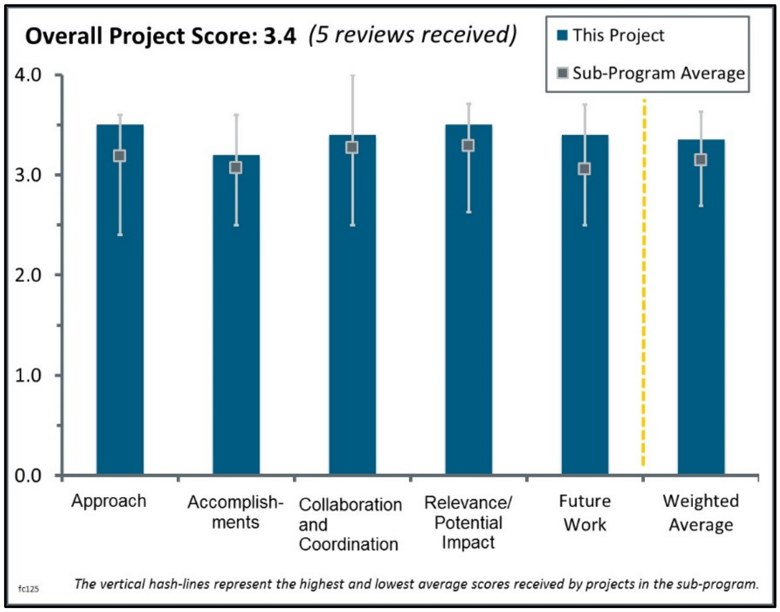
Recommendations for additions/deletions to project scope:

- The project appears to be well organized and has made very good progress. The researchers should continue to look at conductivity under low RH and durability because these are historical weak points for HC membranes.
- The team should conduct longer-term testing (at least 2,500 hours) and diversify to new pendant ionic conductors besides sulfonic acid (e.g., try mixed sulfonic/phosphonic doping in highly doped membranes).
- The researchers should include swelling tests and RH cycling testing, as well as consider including supported membranes.
- The project needs more science; i.e., a full morphological and transport study of the material so that IEC, molecular weight, and block lengths can be optimized based on a scientific approach rather than an empirical design of experiments.

Project # FC-125: Engineered Low-Pt Catalyst Layers

Mahlon Wilson; Los Alamos National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) introduce, model, and develop the materials and techniques for a new approach that focuses on an engineered ionomer topology (EIT) within the catalyst layer; and (2) attain 0.05 $mgPt/cm^2$ fuel cell performance that demonstrates the potential of the EIT approach.

Question 1: Approach to performing the work

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

- Barriers are addressed and well targeted. Clearly, reducing catalyst Pt content is critical to reduce the cost of the membrane electrode assembly (MEA). Overcoming the shortfall in performance by engineering a catalyst/ionomer interface with better oxygen utilization is a very good approach to achieve this goal. Equally important is developing the model to explain the results, and this project addresses these points very well.
- Conceptually, the EIT approach is very good because thick dispersed electrode layers must be engineered to maximize transport.
- The approach and its outcome are clear. The approach implies that the ionomer film resistance is relatively more important than other resistances. This implicit assumption should be emphasized partly because there is an absence of data on both gas/ionomer film and ionomer/Pt interface resistance values.
- The need for a better understanding of the balance between oxygen diffusion and proton conductivity for the ionomer in low-loading catalyst inks is important. LANL proposes an interesting solution to this problem.
- The proposed approach is to optimize the ionomer topology of the catalyst layer to minimize the shortfall observed with low Pt loadings and to use a two-phase approach of ionomer. This is completed by characterization and modeling. It appears to be feasible, based on the project's progress.

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

This project was rated **3.2** for its accomplishments and progress.

- The team has performed well and produced valuable results supported by complementary modeling and characterization. Ionomer characterization improvements shown this year in FC-020 might help further understanding and preparation of this two-phase ionomer approach.
- Performance results exceed the milestone target and are near the General Motors (GM) MEA reference, while EIT catalyst layer improvements are foreseen. Durability evaluations shall be the next step.
- Ionomer coverage of carbon support/catalyst could be considered in the modeling because ionomer distribution might not be uniform.
- Good to very good accomplishments were demonstrated, considering the project time frame and budget. The modeling appears to be rigorous and provides good guidance. Experimental work, while limited, achieved the performance milestones and was comparable to a traditional electrode. Ultimately, improved

performance against the traditional GM electrode is needed to demonstrate the utility of the EIT approach, but this may be beyond the project timeline and budget.
- Clearly, good progress has been made, as demonstrated by the improved performance curves at limiting current.
- The electronic conductivity of the multiwall carbon nanotubes (MWCNTs) is only important if they are not fully covered by an ionomer layer (slide 10). It is likely that the MWCNTs are not fully covered by the ionomer. This consideration should be clearly highlighted.
- It is likely that the ionomer film thickness covering the catalyst particles is uneven (slide 11). Also, it is not possible to assess the ionomer film thickness because it cannot be measured. These considerations should also be added.
- The reproducibility of the results has not yet been determined and could affect the conclusion derived from the polarization curves (slides 13 and 14). Future work should include this consideration within this project or a subsequent project.
- It is regrettable that the oxygen polarization was not measured (slides 13 and 14), because the difference between the oxygen polarization curves and the helium/oxygen polarization curve would provide a direct measurement of the performance loss associated with the ionomer film covering the catalyst.
- The modeling data suggest the proposed approach is viable, but more data ares needed to prove concept.

Question 3: Collaboration and coordination with other institutions

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

- The coordination and collaboration between the partners appear to be excellent. Involving an original equipment manufacturer (GM) is highly appreciated.
- The project work is well distributed among team members, each of which brings relevant strengths to the overall effort.
- Collaborating institutions are well integrated.
- There is good collaboration with other national laboratories, but not with industry.
- It is understood that the project is relatively limited in terms of funding and time frame; however, collaborations with an end user would be useful to establish the true viability of this approach.

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

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

- Developing low-Pt catalysts is essential to achieving the DOE Fuel Cell Technologies Office's cost targets. The modeling and initial results demonstrate the substantial promise of the EIT catalyst layer approach to overcome the low-Pt performance shortfall.
- This project has a high impact because it directly targets some of the main cost drivers—namely, high Pt loadings of the catalyst.
- The project is directly relevant to DOE cost targets, by reducing Pt content and maintaining high-rated power.
- A low-loaded catalyst that can overcome the oxygen diffusion limitations of traditional catalyst/ionomer formulations is an important area of research.
- The modeling, in combination with the experimental results, will be important in establishing the viability of this approach.
- The decrease of mass transport performance at low catalyst loadings negatively impacts cost-reduction efforts.

Question 5: Proposed future work

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

- The proposed future work is very well defined and looks good for this project. The durability of these structures will be an important metric in the future work and has been identified as such by the project team.
- The future work on the validation of the EIT concept is the most important. The focus on electrospun ionomers used with thin-film coated catalysts tested in fuel cells will be an important milestone for this project.
- The proposed future work is aligned with the goals of the project..
- The proposed future work is reasonable.
- The project team should focus on generating a wide range of constructions and comparing the resultant experimental fuel cell data to the model.

Project strengths:

- The modeling used in this project is important in identifying a solution to the oxygen diffusion and proton conductivity problem seen in low-loaded catalyst.
- The quality of the project team is a strength of this project.
- The project's strengths include a great approach and a very strong, focused research team.
- The project addresses a clear problem and has focused objectives. The team is well integrated.

Project weaknesses:

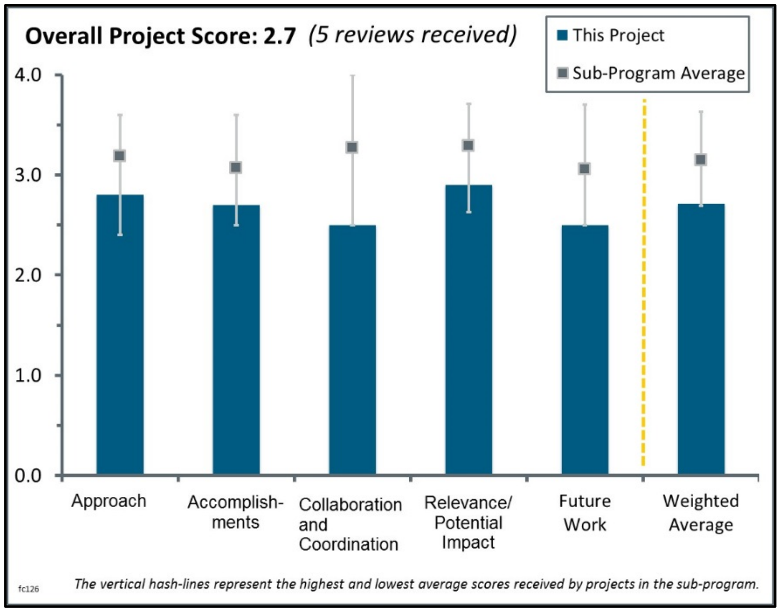
- To date, very little fuel cell data have been shared. While the idea appears to be sound, the researchers need to demonstrate that the combination of ultra-thin ionomer-coated catalyst particles with nanofiber ionomers is (1) possible and (2) improves performance over traditional catalyst formulations.
- The reproducibility of the results is currently unknown, and a direct quantification of the performance loss attributable to the ionomer film covering the catalyst is missing.
- The one-year timeline of the project is a weakness. This project should be continued to validate the promising results.

Recommendations for additions/deletions to project scope:

- This project should be continued in light of the promising obtained results and the potential impact.
- There has been a lot of work by Peter Pintauro of Vanderbilt University in both electrospinning of ionomers and the use of catalyst particles in electrospun fibers. A comparison between this approach and those already published would be helpful.
- The research team should define the results' reproducibility and measure oxygen polarization curves to calculate the difference in performance with helium/oxygen polarization curves (i.e., loss due to ionomer film).

Project # FC-126: Semi-Automated Membrane Electrode Assembly Fabrication with Ultra-Low Total Platinum-Group-Metal Loadings

Stoyan Bliznakov; Brookhaven National Laboratory



Brief Summary of Project:

The objectives of this project are to (1) develop a semi-automated system for fast and facile electrodeposition of Pt monolayer shell on non-noble refractory metal core electrocatalysts with ultra-low platinum group metal (PGM) loadings and near 100% Pt utilization, directly on gas diffusion layers (GDLs); and (2) demonstrate the feasibility of the proposed electrodeposition strategy for scaling up and fabricating membrane electrode assemblies (MEAs) with performance exceeding the U.S. Department of Energy (DOE) 2020 technical targets.

Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- In a short period of time, successful engineering, development, and deployment of an automated system for the fabrication of electrodeposited catalysts directly on GDLs has been demonstrated. The key technical advantage of the approach is that the catalyst will only be deposited at the optimal areas where a triple-phase boundary exists, ensuring high catalyst utilization percentages (this project successfully demonstrated catalyst utilization near 100%). This project demonstrated a relatively successful scale-up to 50 cm^2; however, the significant loss in peak power density in air is likely due to compositional inhomogeneity and uneven distribution of catalyst on the larger-area GDL. It is unclear whether the ionomer is incorporated into the catalyst layer—this may have something to do with the poor performance at high current density. Typically the microporous layers are impregnated with Teflon, which could limit proton transport to the oxygen reduction reaction (ORR) catalyst.
- WNi is a well-chosen and promising choice of core chemistry to allow the reduction of total PGM loading in core-shell catalysts. Development of the semi-automated processing equipment has allowed facile study of this rather complex catalyst system and expansion of testing in MEAs. Electrodeposition provides tight control of processing parameters but, in its present form, gives a too-thin catalyzed zone, which is the likely cause of the poor air performance in MEAs seen to date.
- Extending the work shown in the area of rotating disk electrode (RDE) to electrode layer is a great idea. Because feasibility is mentioned in the goals, some cost analysis should be included.
- The approach is not well thought-out. Although it may be true the proposed method can enable a low-cost manufacturing process, it is not necessary to demonstrate this with a “semi-automated MEA fabrication” process. If small, high-performance cells can be demonstrated, then MEA suppliers will be interested, and industry is much better suited to develop manufacturing processes. The fact that Brookhaven National Laboratory (BNL) is not well suited to make MEAs is clearly evident by the poor cell performance on air (which is what matters in the real world, not performance on pure oxygen). This type of work should be a collaborative effort between BNL and an MEA supplier. If an MEA supplier is not interested in working on this technology, then BNL should find out the reason(s), and then do experiments that can overcome these objections.

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

This project was rated **2.7** for its accomplishments and progress.

- The development of a semi-automated system for the deposition of complex compositional profiled catalyst materials directly onto GDLs was successfully completed, and durability, activity, and loading targets were all met for small, laboratory-scale MEA sizes. What is left is translating this procedure to larger-scale MEAs, which from the preliminary data, does not appear to be a straightforward process. There is still concern related to the high current density and air performance, especially as the MEA area increases. It is proposed that moving to a dendritic catalyst architecture will help with the high current density and H_2/air performance; however, it is unclear why this would be the case, and the preliminary performance data do not show any significant performance improvement over the primary electrodeposited catalyst structure.
- Rapid progress has been achieved halfway through this one-year project (assuming most of it was not already completed prior to the start of the project). Semi-automation of the production of the complex Pt/Pd/WNi catalyst layers has been achieved. Testing has progressed to MEAs, showing promising performance in O_2 but poor performance in air. ORR kinetic activities are good but not exceptional. The observed problems with performance at high current density in air may be intrinsic to the chosen process of electrodeposition directly onto the GDL, leaving the catalyst in a thin plane right at the surface rather than being distributed through a ~10 µ layer of optimally porous carbon, as in a conventional electrode.
- While the mass activity targets are met, the cell performance on H_2/air at high power densities is well below DOE targets. Slide 11 shows that the team does not understand the DOE targets. Specifically, both the table and plot claim 1 W/cm^2 power density on H_2/O_2. The DOE targets are for H_2/air performance. This is also the case with the voltage at 1.5 A/cm^2. There is also no evidence the team is diagnosing why the H_2/air performance is so poor, much less that it has a plan to address the issue.
- The performance achieved is low and inconsistent.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.5** for its collaboration and coordination.

- Good pathways for testing of project MEAs by outside laboratories appear to have been established. This project has been active for less than a year, leaving little time to date for collaborators to make contributions, and the presentation did not identify specific contributions of collaborators other than those within BNL.
- There is no evidence of any collaboration with anyone outside of BNL. For example, if General Motors (GM) was actively involved, it would have pointed out the misreporting of the performance targets on slide 11. This team definitely needs to collaborate with an entity that understands mass transport in catalyst layers and can help the team both diagnose and address the core issue. This could be an MEA supplier, an automotive original equipment manufacturer (OEM), or anyone who has experience in fabricating and testing MEAs.
- To this point, the work appears to be contained in-house within BNL. It appears that GM will become involved once the efforts begin for scale-up to larger MEAs.
- Evidence of collaboration is missing.

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

This project was rated **2.9** for its relevance/potential impact.

- The current project aligns well with the DOE objectives in that it has the potential to meet the fuel cell performance metrics with a process that could lead to continuous, larger-scale fabrication of MEA materials.

- The project effectively addresses the DOE goal of increasing ORR kinetic activity with reduced PGM loadings and has achieved good, if not exceptional, kinetic mass activities. The project's WNi cores provide a pathway to reduce total PGM in core/shell catalysts. It seems doubtful whether electrodeposition, even if automated, can provide a time- and cost-effective means of generating a cathode catalyst layer for fuel cells; industry tends to prefer chemical rather than electrochemical methods whenever possible. The poor performance of MEAs in air at high current density may be intrinsic to the process of electrodeposition directly onto GDLs, giving an insufficient porous, catalyzed volume to facilitate transport processes.
- It is not clear how this project will have any impact on DOE's key targets because all that is being demonstrated here is that the mass activity and stability of the core/shell catalysts are good, which has already been demonstrated.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- The proposed future work correctly identifies the high current density performance and H_2/air performance as areas that need to be addressed; however, no well-defined course of action is identified, other than trying dendritic electrodeposits. The proposed future work should also address strategies for the even, homogeneous deposition of well-distributed catalyst over larger areas to translate the performance of the small-area MEAs to that of the larger-area MEAs.
- Plans to improve MEA performance in air by growing dendritic cores rather than compact particles are directionally correct, but they likely do not go far enough in addressing the fundamental problems at high current density of a catalyzed layer that is too thin. Some of the tricks used in conformal electroplating of rough surfaces might be tried to get deposition of WNi to extend deeper into the microporous layer of the GDL.
- The proposed future work makes no sense in light of the current poor performance on H_2/air. No automotive OEM is going to be interested in testing full-size cells that do not have decent H_2/air performance. Instead, the plan should be to diagnose the cause of the poor mass transport in these MEAs and address it accordingly. Just increasing the oxidant pressure is not a mitigation strategy.
- The breadth of work proposed makes success questionable. Developing GDLs is very much different from other work.
- The strategy for improving MEA performance at high current density in air is not clear. The strategy and approach for using very low PGM and reducing cost using the chosen method are not obvious.

Project strengths:

- The strengths of this project include the well-controlled deposition of highly active catalyst directly onto GDLs, demonstrating nearly a 100% utilization of the Pt. The process shows promise for scale-up to large-area MEAs.
- Codeposited WNi is a promising core material with prospects of decreasing total PGM usage in core/shell catalysts. Electrodeposition provides tight control of metallization. The team developed semi-automated preparation techniques that improve the reproducibility of complex procedures.
- The likely positive results show the promise of the method, but the method needs to be better demonstrated.

Project weaknesses:

- The MEAs perform poorly in air, likely because electrodeposition puts catalyst only onto the topmost surface of the electrode, resulting in an insufficient volume of the (porous) catalyzed layer to support adequate mass transport. The catalyst was deposited directly onto the microporous layer of the GDL, rather than onto a carbon catalyst support layer optimized for mass transport. Even when automated, electrodeposition is likely to be a slow and expensive way of manufacturing a catalyst layer. Pt loadings on MEAs are too low to allow proper testing for optimized performance in air at high current densities and the durability thereof—the most critical remaining factor in the development of fuel cell catalysts and MEAs.

- It is unclear how high current density and hydrogen/air performance are going to be improved. There appear to be no strategies for assessing/qualifying the homogeneous distribution of catalyst with the desired composition and architecture over larger MEA areas. Incorporation of ionomer into the catalyst layer or GDL is not addressed.
- The project is unfocused. If the key work is electrodeposition, that should be the focus.
- The lack of MEA fabrication and testing experience on this team is sorely evident.

Recommendations for additions/deletions to project scope:

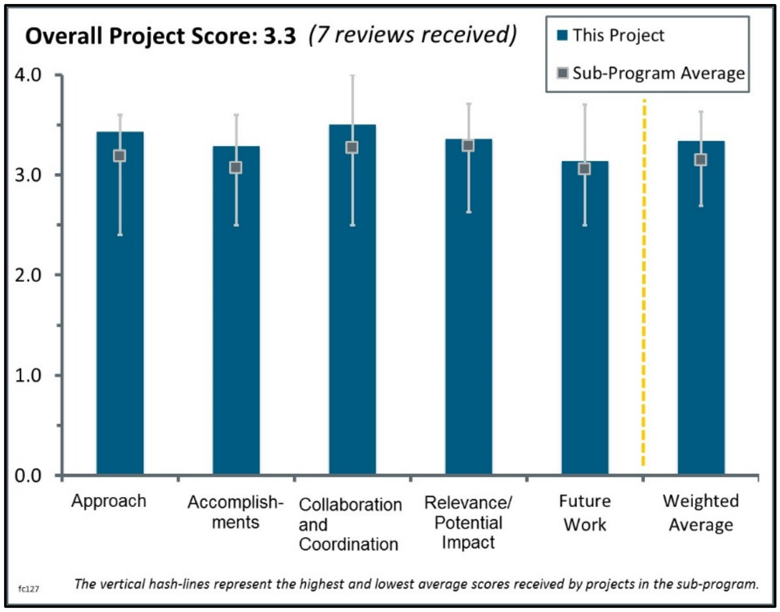
- The researchers should explore chemical, rather than electrochemical, means of depositing the WNi cores. They should deposit the Pt/Pd/WNi catalysts onto proven carbon catalyst-support particles, and then prepare MEAs by conventional methods using the catalyst powders—this is likely to be the most productive pathway toward adequate air performance. If electrodeposition is continued, the researchers should modify procedures to allow deposition of WNi particles into a greater thickness of the catalyst support layer (to improve air performance).
- The team should develop procedures for quantifying the compositional and structural distribution of catalyst on the larger-area GDLs to help improve the transition of activity from small-scale to larger-scale MEAs. It should also determine the effects of ionomer in the electrodeposited catalyst layers and identify strategies for its incorporation into the MEA catalyst layer.
- Clear proof of the concept's viability is needed before the concept is scaled.
- This project should be stopped unless the team is willing and able to get the appropriate collaborators.

Project # FC-127: Durability Improvements through Degradation Mechanism Studies

Rod Borup; Los Alamos National Laboratory

Brief Summary of Project:

The objectives of this project are to (1) identify and quantify degradation mechanisms (discern the impact of electrode structure on durability and performance), (2) develop advanced in situ and ex situ characterization techniques and accelerated stress test (AST) protocols, (3) develop models related to degradation mechanisms, and (4) explore non-system-related mitigation.



Question 1: Approach to performing the work

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

- The approach to performing this work is excellent. Carbon corrosion during the drive cycle is particularly meaningful because previous carbon corrosion studies only used simple voltage cycling. The carbon corrosion comparison for high surface area carbon, Vulcan carbon, and graphitized carbon is also very interesting. In situ experimental observations of Ce dissolution and migration during fuel cell operations have added great values; the high-resolution transmission electron microscopy (TEM) images of catalyst layers with Ce are very impressive. Combined mechanical/chemical AST tests will provide a facile and effective tool to evaluate membrane durability.
- The approach addresses key aspects of interest for the industry related to durability—particularly regarding the catalyst layer and membrane. Targeting the improvements and understanding of ASTs and durability mode quantification is a valuable contribution. Overall, the approach is consistent with existing methods and understanding on analyzing materials from a durability perspective.
- Carbon corrosion work: The approach was very systematic and focused on drive cycles, which has been less explored than start-up/shutdown phenomena. The project situated itself well to understand when carbon loss occurs by using CO_2 analysis, and to understand Pt particle size effects. Ce migration work: The project did well to focus on the "why" questions behind Ce migration. The fact that Ce migrates is understood, but the project went further to address the conditions under which this happens. AST development work: The project is correct to gauge whether protocols are too severe or whether a series of materials fails with a protocol in the same order as it does in the field. However, the project should seek to develop an AST after careful examination of the failure modes observed in the field. This may cast light on what kind of conditions to run, and especially as to whether there should be differing effects on the inlet and outlet of the cell. Perhaps the cell should not be a square serpentine channel cell. Metal bipolar plates work: This is a difficult task to address due to the complexity. Ultimately, there will have to be some interaction between the project team and developers to understand realistic failure modes and to develop an AST that addresses those failure modes.
- The researchers are doing a very good job of maintaining relevancy and performing work that can help over many material and application classes. They need better direction on their Fe work. They seem to be using the membrane electrode assemblies (MEAs) as a probe to measure whether there is any Fe release from the stainless steel plates. It would be better to determine what Fe level the MEAs can tolerate, and then determine loss of Fe into the membrane. General Motors (GM) has done the best work relating Fe to degradation rates, but there is still a lot of room for work here.

- The work presented here is very comprehensive and addresses many of the important degradation mechanisms through an optimal balance between experiment and theory. The combined use of in situ and ex situ techniques provides great clarity and unique insight into the mechanisms of efficiency and performance loss. There is no attempt to develop mitigation strategies for many of these sources of performance degradation; however, that is likely beyond the scope of this work.
- The project is addressing critical carbon corrosion and other durability issues that are barriers to implementing conventional electrodes. It features a nice combination of modeling and experimental work, although it would be advantageous to disseminate learnings to original equipment manufacturers (OEMs) for assessment at full scale.
- The fiscal year 2015 tasks are well aligned with the barriers, but they are very general and not sharply focused.

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

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

- Because the work here is more of a fundamental investigation of the various mechanisms of performance degradation associated with the many components that compose the MEA, there are no performance metrics or barriers against which the progress of this project may be directly related. However, the unique insight provided by the results presented here will have a significant impact on the design of MEA components going forward, making an important contribution to the improvement of MEA durability. This work covers a wide breadth of material degradation pathways, containing a significant amount of experimental data, much of which is included into multiscale models that could prove to be very useful to the PEMFC community at large. The accomplishments, to this point in this project, are quite significant.
- Carbon corrosion work: The results the project has achieved align very well with phenomena as they are understood. CO_2 loss was shown for potential down-transients as well as potential up-transients. The carbon corrosion trends with E, V, and EA carbons are consistent with what is known. The particle size increases with more graphitized carbons are also consistent. Ce migration work: The work involving CeZr may be a slight contribution that may assist developers, assuming suppliers have not already surveyed this composition. Ce migration trends were shown with lower pressure as well as in the direction of the cathode, which begins to answer why Ce migrates to where it does. AST development work: The project team has successfully identified protocols that are more accelerated than prior protocols (e.g., combined mechanical/chemical membrane AST and square wave cycle for Pt dissolution). Questions still need to be answered as to how well these ASTs relate to vehicle failure mechanisms, and whether they should ideally be carried out in quad-serpentine 50 cm^2 fixtures. Metal bipolar plates work: The work so far utilized uncoated 316L stainless steel. This is an appropriate prerequisite to understanding what types of stressors will cause higher interfacial contact resistance, as well as higher metal corrosion and fluoride release. The project team also needs to have a way of understanding relevant vehicle stressors.
- Analysis of the water content of the electrode related to the change of the low potential used in the analysis of the E-type catalyst would help identify the effects of the low potential effects. The mechanism effect (pathway) and reactants (i.e., availability of liquid water in the electrode) will be key in understanding the role of the low and high potential distinctions in the AST for carbon corrosion. Confirmation of whether Ce is accumulating as cations or whether Ce is still in a neutral phase is important. The team should consider confirming whether Ce deprotonates the membrane or whether it is simply a neutral molecule in the aqueous phase. Comments on the reaction pathway for CeZr and indications on what the final product of the Zr would be should be considered from both operational and environmental standpoints, considering potential washout effects on a stack or module level for automotive or stationary applications. Spatial maps of membranes via IR analysis or other methods that quantify the local thinning and divots/tearing/pin holes would be ideal to further develop the understanding of the mechanical/chemical AST. The proposed electrocatalyst AST should be considered from a mechanistic perspective; the alteration of upper potential and lower potential hold times are directly affecting the subsurface oxide dissolution, the surface passivation, and bare metal dissolution rates. The design of the potential limits and the dwell times for accelerating the test will be a direct outcome of the previously listed three processes, and means of quantification or analysis would allow targeted ASTs to be deconvoluted for various automotive,

stationary, and other fuel cell applications. In the crack propagation work, yield strengths for the catalyst layers in the simulation should be studied because the expansion of the crack into the lower regions of the catalyst layer could have performance and water accumulation considerations.

- The project has progressed very well in the past year. The durability studies almost cover all the components of a PEMFC, including the catalyst, membrane, and bipolar plates (the gas diffusion layer was previously studied), and some novel and advanced approaches have been adopted. The project has led to some new discoveries and deeper understanding relevant to fuel cell degradation. Some mitigation strategies have been proposed. A few things are noteworthy: (1) the addition of CeZr to the cathode catalyst layer improves membrane durability, (2) the developed E-carbon model is very instrumental for understanding carbon corrosion because it has incorporated parameters such as temperature and relative humidity (RH), and (3) the proposed new AST protocol tests has provided a more effective and accurate means of durability evaluation. There are two questions. Based on the project's discovery that "all types of carbon show carbon corrosion during drive-cycle testing," there is the question of whether adoption of low surface area carbon would meet DOE's ultimate durability target, or whether alternative supports other than carbon have to be developed. The other question is whether the project would investigate the stability of 3M's nanostructured thin film (NSTF) catalyst at drive-cycle testing.
- Regarding slide 9—yes, stable Pt particles on graphitized supports are needed for a durable catalyst, but it is unclear what constitutes an acceptable level of particle growth to be able to achieve durability metrics. Regarding slide 17—the team needs to more clearly define the capabilities of the small-angle x-ray scattering/wide-angle x-ray scattering methods and how the data are interpreted. Regarding slides 21 and 22—the metal bipolar plate corrosion data are interesting, but it is unclear whether they are relevant. With low membrane fluoride release rates, 316L stainless steelshould be durable enough for 5,500 hours. It should be assumed that any metal plate will have some kind of coating to reduce contact resistance, and therefore these experiments should be conducted with a "baseline" coating (e.g., thin gold) and then a representative low-cost material that meets the target for total ohmic loss at beginning of life. Perhaps collaboration with Treadstone is warranted.
- The team should start putting error bars on its experimental data. There are very strong conclusions made based on the trends, but the variability is missing. A lot of work was focused on Ce and concentration changes, but it is unclear whether a lower concentration of Ce has been linked to membrane failure.

Question 3: Collaboration and coordination with other institutions

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

- This project has had outstanding collaboration. It is led by a national laboratory, but its collaborators include other national laboratories, universities, and companies (e.g., GM, IRD Fuel Cells, and Ion Power). The industry participation is very meaningful. All the participants have complementary experience.
- This project is a model for how the national laboratories can work with industry. It uses multiple industrial suppliers and multiple site visits. This project represents a really good effort.
- The project features excellent collaboration between experimental MEA testing, data modeling, and post-mortem microscopy analysis. Each partner has contributed greatly to the success of the project to date.
- The project features a strong and diverse group, and now it includes more involvement from automotive OEMs to enhance the applicability of the research outcomes.
- Five different organizations (i.e., IRD Fuel Cells, Ion Power, Gore, 3M, and GM) provided MEAs, but there is no evidence of these organizations participating in the data interpretation or in directing the project. In the particular case of GM, it would be expected that GM would have some greater say in project activities, but that was not evident from the presentation. Collaboration with Lawrence Berkeley National Laboratory (LBNL) is evident through the Ce migration modeling work, as well as in the measurement of membrane crystallinity. The project team likely collaborated with Argonne National Laboratory (ANL) in order to provide data for ANL durability models, but there is no work shown here that indicates the ANL model returned assistance to this project. Like with many projects, Oak Ridge National Laboratory provided TEM assistance. With the possible exception of LBNL, the collaborations more closely resembled provision of service, whether this included materials (e.g., MEAs) or analysis (e.g., TEM). There was little collaboration outside of Los Alamos National Laboratory (LANL)/LBNL in terms of providing the project

direction, and in terms of interpreting data. The project needs much more expansive collaboration with fuel cell stack and system developers.
- The project obtains materials from a variety of industrial vendors, ensuring a broad selection of materials; however, additional MEAs from other vendors should be considered because of the variety of other support materials used (i.e., lower surface area, highly graphitized supports). Evaluation of the AST cycle proposals should be done in collaboration with a cross-section of automotive and stationary fuel cell developers, with some consideration for the link to an accelerated durability test or field return behavior.
- The main collaborators are only national laboratories, and this may limit the materials and fabrication methods being studied. There has been much advancement through developmental research toward mitigation of degradation mechanisms in PEMFCs, and this project has poor linkage. This is likely due to the secretive nature of OEMs and suppliers. However, it is captured in patent applications.

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

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

- Improving fuel cell lifetime and durability is arguably the most important target of the Hydrogen and Fuel Cells Program (the Program). There are clearly numerous mechanisms by which the lifetime of a PEMFC may be shortened, and the work presented here and in previous years of this project addresses a large number of these mechanisms in great detail, providing significant insight that may be readily used to develop mitigation strategies for each degradation mechanism.
- The impact of this project is significant because this project directly addresses one of two major barriers to fuel cell commercialization—durability. This project aligns well with Program and DOE objectives. It has a great potential to help advance fuel cell durability progress toward DOE and research, development, and demonstration goals. The principal investigator of this project has been well recognized in fuel cell durability/degradation studies and made significant contributions in these studies.
- Durability is one of the primary focal points of fuel cell commercialization, and the work in this project directly addresses both industry-level targets and the long-term targets set out by DOE. Further, the work done in the project is consistent with the state-of-the-art methods for quantification, analysis, and testing of fuel cell materials from the perspective of durability and performance.
- The project team has done a good job of adjusting as materials and challenges change. Carbon corrosion efforts can be scaled down. NSTF does not have it, and automakers seem to be content with current solutions.
- The project team generally performed solid, fundamental work, but it needs to ensure that the problems being studied are relevant at full scale, using material sets that are common in current application hardware.
- This year’s project presentation has essentially four sections: (1) carbon corrosion, (2) Ce migration, (3) development of ASTs, and (4) metal bipolar plate corrosion. The study of carbon corrosion on various carbons has been covered internally within OEMs, often in association with particular operating strategies. While it is fair to say that many of this data remains unpublished, the assistance that a DOE-funded study provides to many developers is limited to being a confirmation of phenomena already acknowledged. Furthermore, some patent literature (e.g., US Patent 7,887,963) already points to how OEMs have already studied the role of operating conditions in mitigating carbon corrosion. The study of Ce migration has a similar overlap with OEM work, but it may overlap more strongly with membrane supplier work. Some suppliers have extensive history with Ce cation or Ce oxide additive packages. The development of ASTs may be most relevant to the DOE projects themselves, but there is some value if this project can improve upon some tests that are far too lengthy (e.g., RH cycling). Studies of metal bipolar plate corrosion are relevant and have not been as commonly done by the industry because of the wide variety of substrates, coatings, forming methods, and approaches to joining.

Question 5: Proposed future work

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

- The proposed future work is effectively planned and addresses all of the possible suggestions one could make for the next step.
- The proposed future work is very comprehensive and crucial to further understand fuel cell component degradation and improve fuel cell durability. One example is ionomer/electrode stability and structural changes, which would be meaningful, if successful. The concern is whether the project has sufficient funding to perform the proposed future work.
- The National Renewable Energy Laboratory project on system-borne contaminants approached its topic by first asking a developer what materials would be used in a fuel cell system, and then systematically figuring out which contaminants to test in response. This project could use a parallel approach, where a developer becomes closely related to the project, so that the project has a reference point to use. Instead, the project team presumes that it already knows for certain what degrades during fuel cell system operation. Perhaps literature is used as justification, and in some cases, perhaps an experiment is done to show that degradation is possible. However, neither should be interpreted as an assurance that such degradation is truly limiting to a practical fuel cell system's lifetime. Many of the items listed in the future work slides do appear reasonable for further study. In particular, these include catalyst layer ionomer durability (especially in low Pt loaded layers), alloy catalyst durability, metal bipolar plate durability, and membrane crack propagation. However, each of these activities needs to be addressed from a perspective that has some knowledge of what is really happening in real-world systems. It is not sufficient to say that an experiment says that something might degrade, and then allow that to be the basis for continuing work.
- The work continues to address areas relevant to the industry and fuel cell adoption. The project should include work with system/unit cell modeling efforts to provide either validation data or directed testing to further improve the model mechanisms or predictions.
- The future plans seem reasonable, but the ongoing bipolar plate work plan needs to be revisited.
- There are a lot of open questions around Ce; everyone is using it or another mitigant, and the researchers seemed to have raised more questions than given answers, but this is nowhere in their future plans. Better/faster ASTs are needed, and it is great that they are focusing on this.
- More specific metrics would be helpful in evaluating progress.

Project strengths:

- The full degree of national laboratory analytical capability is available to support the project. Project collaborators have a deep level of experience in fuel cells. The project has provided a good set of AST data on baseline MEAs, which serves as a useful guideline for how materials will respond to ASTs. The project has done a good job of understanding what stressors can possibly accelerate degradation. The project has improved from showing Ce migration to attempting to understand what causes Ce migration. The results of the carbon corrosion study align with other data.
- The project is performing comprehensive degradation and durability studies on the most important components of PEMFCs. Drive-cycle testing was used for durability studies that can better mimic fuel cell vehicle driving conditions. The combination of experimental data with effective modeling can provide more insights and information. The work related to carbon corrosion and membrane durability (e.g., the addition of CeZr to the cathode) has produced significant information. The collaboration with industries (e.g., GM, IRD Fuel Cells and Ionomer Power) is greatly appreciated and valuable.
- The strength of this work lies in the breadth of topics covered with a high degree of detail, providing significant insight into each mechanism of performance degradation. The effective integration of in situ analysis, process, and component modeling and ex situ post-mortem analysis has helped this work to be very successful to this point.
- The project's strengths include its comprehensive analysis; consideration of a variety of state-of-the-art fuel cell materials; and continued focus on the key durability areas of supports, catalysts, and membranes.
- This project has world-class resources that are being utilized in an effective manner. The investigators are inviting the key stakeholders to help steer the deliverables toward relevant experiments and modeling.
- The project features a diverse, collaborative team that is applying innovative experimental methods.

Project weaknesses:

- There are no obvious weaknesses.
- The project often presumes to know what failure modes are limiting the lifetime of fuel cells (particularly in an automotive context) without having enough contact with a developer to really be able to say what is actually responsible. The project needs the ability to cast off any or all committed tasks in order to open itself up to what the true issues may be. Getting insight on realistic failure modes from a stack developer or MEA supplier is something that must be done carefully, given the confidential boundaries that often govern the development of new fuel cell technology. However, with good relationships with developers and suppliers, useful work can still be identified and executed. This is observed in some of the other projects led by national laboratories. This project needs to develop better relationships with developers and suppliers in order focus on the areas that are still problematic for stack durability.
- The project team should pursue more direct collaboration with other fuel cell developers and direct collaboration with model developers on both system and unit cell/MEA levels.
- Development is moving faster than this project. As a result, state-of-the-art materials and operating strategies are not integrated in some cases. The team should focus on patent literature.
- The carbon corrosion data would be more corroborating if delicate TEM images after degradations could be shown. The strategy to mitigate Ce migration from the membrane should be proposed.
- It is not clear that all the components being studied are relevant in actual automotive systems.

Recommendations for additions/deletions to project scope:

- The proposed future work addresses all of the possible suggestions one could make.
- The team should delete the carbon corrosion studies, development of freeze tolerance protocols, and development of any protocols that do not stress materials in a fashion consistent with how materials are stressed in a vehicle. The team should add much deeper collaboration with a developer (or multiple developers, if multiple types of applications are of interest) to understand real-world failure modes first—before durability studies follow. The team should also add a survey of different chemistries used for membrane additive packages. There are other peroxide and radical scavengers beside Ce cations or Ce oxide.
- The team should add further collaboration activities and consider further work on assessing the mechanistic aspect of changes proposed to the AST cycle.
- The team should consider expanding the bipolar plate work to include low-cost coatings to reduce contact resistance.
- It is not clear whether the project has sufficient funding to perform all the proposed future work. If funding is limited, the emphasis should be on how catalyst layer morphology affects durability.
- The researchers should link Ce concentration to a membrane failure.

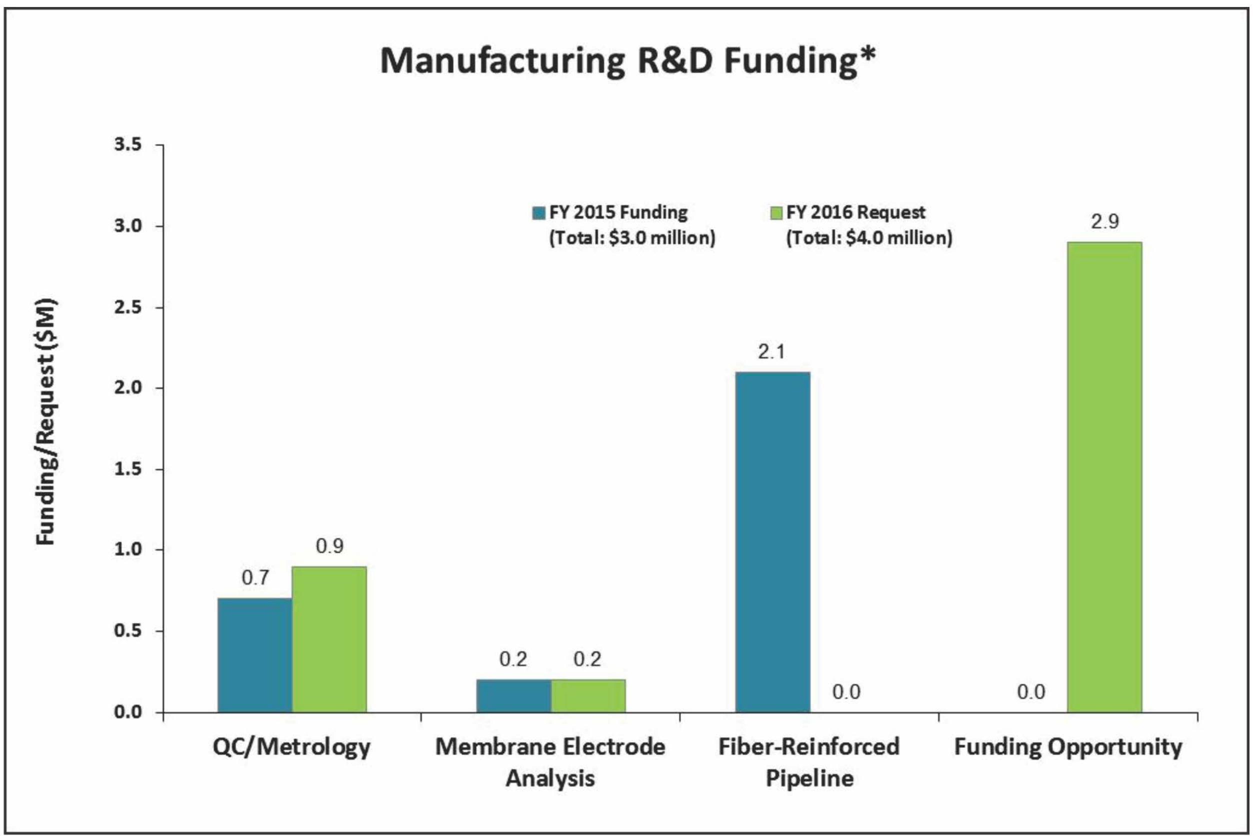
2015 — Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

Summary of Reviewer Comments on the Manufacturing R&D Sub-Program:

The sub-program is addressing the broad problems and barriers facing the U.S. Department of Energy's Hydrogen and Fuel Cells Program (the Program), and these barriers are well matched to the needs of the industrial sector. According to reviewers, the objectives of the Manufacturing R&D sub-program were clearly presented and prior successes were described. Furthermore, reviewers stated that the sub-program is well managed and effective at addressing these barriers. The reviewers found that the sub-program has done a good job of engaging appropriate stakeholders and collaborating with them effectively. In fiscal year (FY) 2015, one manufacturing project, which addresses fuel cell stack in-line testing, was reviewed.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was $3 million for FY 2015, and $4 million was requested for FY 2016. FY 2015 funding includes a continuation of existing Manufacturing R&D sub-program projects for quality control (QC)/metrology and membrane electrode analysis, as well as fiber-reinforced pipeline projects from the FY 2015 funding opportunity. The FY 2016 request-level funding will continue existing Manufacturing R&D sub-program projects for QC/metrology and membrane electrode analysis, as well as provide funding for new projects through a competitive funding opportunity announcement, subject to appropriations.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

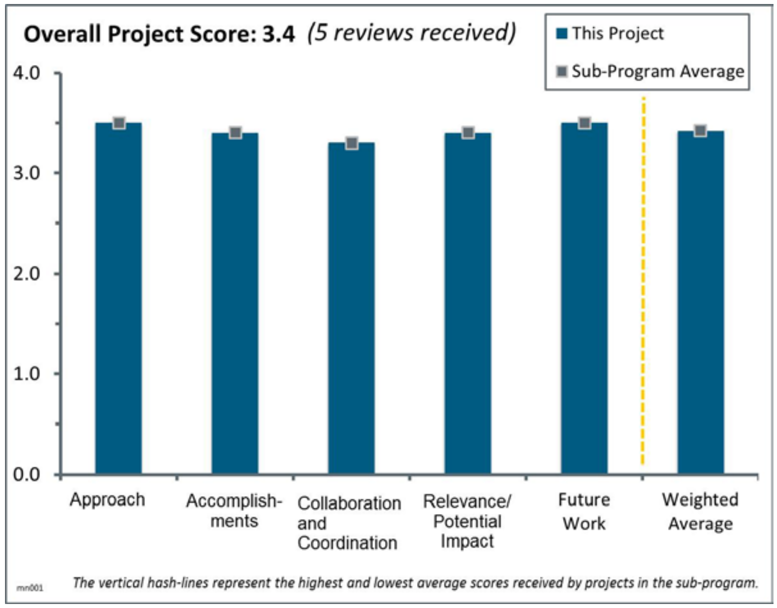
Majority of Reviewer Comments and Recommendations:

One Manufacturing R&D project was reviewed, earning a score of 3.4. Reviewers judged the project to be highly relevant to Program activities and to feature an excellent technical approach. They noted that project progress and accomplishments are very good. The project team was judged to be strong; participation and contributions from industry partners were identified as useful and coordinated.

Fuel Cell Membrane Electrode Assembly (MEA) Manufacturing: One project was reviewed in the area of fuel cell MEA manufacturing, receiving a score of 3.4. Reviewers noted that the project's approach is very good and that its collaboration with industry and other partners has been, and continues to be, very good. Reviewers also noted that the National Renewable Energy Laboratory (NREL) has made significant progress this year in further developing the reactive impinging flow technique and demonstrating the technique on a continuously running web-line. The reviewers encouraged NREL to conduct a greater number of trials to get statistically meaningful results for each approach, as well as to improve its focus on correlating defect size (as detected in a web-line) with fuel cell performance.

Project # MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh; National Renewable Energy Laboratory



Brief Summary of Project:

The objectives of this project are to (1) understand quality control needs from industry partners and forums, (2) develop diagnostics using modeling to guide development and in-situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Question 1: Approach to performing the work

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

- The project is investigating in-line detection of membrane electrode assembly (MEA) manufacturing defects. The approach is appropriate and should be the path followed. The techniques of reactive impinging flow (RIF) with IR thermal imaging appear to be appropriate for on-line detection. Modeling has been initiated to determine the impacts of defects and to determine the defect resolution needed for the on-line equipment. Experiments with segmented cells are planned to help validate the model. The modeling will be key to determining a correlation between defect size and impact on performance and/or durability. It is not clear that a two-dimensional (2D) model will be sufficient for some of the defects (i.e., it is not clear how a 2D model will appropriately differentiate between scratches and a bare spot). From the work presented, it seems that the second and third steps in the approach are coming before the first step (i.e., developing techniques for defect detection before knowing what the requirements for defect detection are). It is not clear that the resolution needed for defect detection is known or that the correlation between defect size or type and performance is known. Perhaps this is commercially sensitive information and the National Renewable Energy Laboratory (NREL) has this information and cannot disclose it, but that information is critical to the success of this project.
- It is very timely that the U.S. Department of Energy (DOE) is addressing quality control issues in fuel cell manufacturing. This task, development of useful tools to access quality control, has to be done just once, if done well. The result offers high return on investment because many manufacturers can build collectively on these results rather than individually reinventing them. The NREL activities impress, and there were some novel approaches. There remains some uncertainty. For example, the hardware shown was required rolled goods, and assumes that, for example, one can acquire a “roll” of membrane. Clearly the membrane vendor has responsibility to provide in-specification products, and thus there will be various stages of quality control, probably beginning with the chemicals needed for membrane synthesis. There has been no suggestion yet of sensible ways to distribute the various quality control measurement tasks. There was also no appreciation that the manufacturing procedures might result in the creation of failures, say, the introduction of the ink might result in membrane degradation, etc. Therefore, the early and interesting NREL quality measurement technologies are just the beginning—but a good, solid beginning.
- The approach includes stakeholder input, technical development, and (more recently) validation. This is very good. It would be nice to see a thrust toward gauge repeatability and reproducibility. An effort to run large lengths or areas of materials for each of the inspection methods with “normal” materials is needed to demonstrate the robustness of the measurement methods and to determine the rates of false positives, false negatives, repeatability, etc.

- The approach is very good and is broad-based and covers a number of defects that can appear in different manufacturing processes for MEAs and gas diffusion electrodes (GDEs) using a role-to-role technique.
- Incorporating industry input, modeling, and validation testing, this effort's approach is well designed to evaluate various quality control techniques.

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

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

- The RIF method was improved by utilizing laser-drilled holes in the gas knife. Modeling suggests that by using a GDE backing, the resolution can be improved further. Optical reflectance detection of defects was demonstrated at 10 fpm, and algorithms for automated detection were developed. The algorithm development is key to implementing this at industrial speeds. Results are needed from a statistical validation of the algorithm with percentage of defects missed and percentage of false positives detected. It is still not clear what detection limits are needed for quality assurance and what the correlations between defect size and frequency and performance are. Modeling of the impact of defects has been continuing. It is not clear what the sizes of the defects being modeled are, and validation of the model has not been completed.
- NREL has made good technical progress in measurement technology, and good progress is assembling a quality project team. The modeling results, to date, seem modest. Perhaps that is the necessary gate for beginning the modeling tasks. The thermal data technique, "hot spot," seems highly useful and novel. It makes sense to commence with simple tasks, finding "holes," etc. Measurement of spatial mechanical properties will be the necessary eventual focus. Certainly, because a wide variety of PEM fuel cell systems are now in the global marketplace, there are many parallel "quality control" activities underway. It would have been interesting to have NREL investigate those competing measurement techniques and prepare a document that describes what is known as the 2015 state of the art (SOA) for fuel cell component quality control. The interactions with "industry" were not described well enough to make any conclusions about "worth." Even so, clearly there is necessity to develop quality tools for the control of fuel cell manufactured products. Importantly, it is equally important to use such quality control (QC) tools on any system that will be utilized for durability testing—it is important to understand fully what is being tested and not to expend resources to evaluate fuel cell systems that come assembled using poorly defined, non-reproducible components.
- Scale-up of the IR/RIF gas knife was a good accomplishment, with further improvements identified and modeled. Modeling of defect sensitivity is an important contribution.
- Good progress has been made for the IR/reactive flow-through (RFT) technique in an open environment with very high moving rates of 30 fpm.
- The project is aligned with DOE's goals for fuel cell commercialization.

Question 3: Collaboration and coordination with other institutions

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

- Collaborations between Lawrence Berkeley National Laboratory's (LBNL's) modeling efforts and NREL appear to be working well. More input from General Motors, Ion Power, and W.L. Gore on the correlation between defects and performance would improve the project immensely (especially information that can be shared publicly).
- The project is well coordinated and has excellent cooperation with relevant industrial partners and institutes.
- The project has a good mix of industrial, national laboratory, and academic collaborators providing valuable contributions.
- More collaboration is always nice. However, it seems that the project has been able to maintain a healthy and continuous rotation of partners.
- Collaboration is complicated in that it involves teaming with many industrial partners with significant differences in market position and in technological competence. In some ways, fuel cell manufacturing

today already involves "assembly," the collection of various parts from a number of parts suppliers, and then using manufacturing steps that result in the desired hardware. The quality of the final step, component engineering to assemble a fuel cell system, is necessarily limited by the quality of the various components used to get that result. It makes sense to collaborate with various component suppliers and understand the challenges and opportunities they face as they strive to improve their products. It is important that cost implications of future, probably tighter, values become understood. An example might be that more rigorous specification of uniform membrane thickness might be doable, but only for higher cost, and the irregular membrane might perform well enough, etc. It seems that NREL needs to create some ongoing "sensitivity" study that explores such issues. A beginning step would be to acquire a number of starting components and evaluate them to understand the existing variations in current components. Such a study, of course, must necessarily include all system components, not only those that reside in the stack. It would be good to add quality manufacturing firms as part of this QC effort, as that makes sense.

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

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

- DOE has invested significant funds in fuel cell technology—indeed, planting "seeds" that have sprouted into a huge global enterprise. The challenge now is to include U.S. manufacturers in these emerging markets. This activity seems pivotal—and essential for success in that direction. However, the NREL effort to date is just one small advance in what needs to be a large, continuing activity. Although today the emphasis is on "voltage degradation" or "low RH performance," the necessary emphasis needs to be long-term performance and durability of fuel cell systems. In most published studies, the observed fact is that the balance-of-plant components turn out to be responsible for about 75% of fuel cell system failures. Moreover, at times "stack failures" are also the result of balance-of-plant failures, e.g., a sensor in the thermal management system fails, and the resulting out-of-control temperatures ruin the active fuel cell components. Therefore, this NREL activity is an essential, timely first step. However, in the absence of a far larger scope that works to understand the fuel cell system, this effort cannot have much impact. In summary, the project is highly relevant and clearly necessary, but not sufficient.
- Maintaining relevance in manufacturing issues is particularly challenging, as it requires a great deal of industry disclosure. Considering this challenge, the project seems to have made great efforts to maintain engagement with industry. Perhaps there are innovative approaches to encourage further openness and participation from other industry stakeholders. Relevance could be improved if it were possible to pool statistical data from a larger group of industry partners (very challenging). It would be great to compile a Pareto of defects by frequency, or weighted ratings of frequency, severity, and detectability (failure mode and effects analysis [FMEA]). Perhaps it would be possible to confidentially gather and pool data (not opinions) to ensure program relevance. This would be very valuable.
- The project is targeting the main challenges of quality control in fuel cell manufacturing. Identifying the impacts of the imaged defects on fuel cell operation is an excellent approach to verify that the defects will influence the local and overall performance.
- The project is relevant to DOE goals and has potential to have a significant impact on fuel cell cost by increasing yield and reducing waste.
- A number of Program goals are being addressed by this effort, and it is enabling the transition of QC technologies toward industrial adoption.

Question 5: Proposed future work

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

- The project has clearly responded to past reviewer comments. The efforts to link defects to performance are not easy tasks. Perhaps leveraging results of similar efforts in the literature would help in efficiently gathering more data. The continuous nature of the program is a positive, as it allows the project team to shape future efforts based on feedback.

- Every task of the proposed future work is good and important, especially the study of impacts of the relevant defects on fuel cell performance and failure onset.
- The proposed future work to predict the performance effects of defects is very important to this work. The correlation between "defects" and performance is needed to make sure time is not wasted improving resolution beyond what is needed or looking for blemishes that have no impact on performance or durability.
- Future work has been planned appropriately, most importantly the effects of defects.
- The challenge remains: there are many quality control concerns in fuel cell system manufacturing. Clearly this NREL project provides value, and the proposed future work will expand that worth. A robust stack is a sensible goal, and NREL should move into tasks that address stack engineering, the art of making MEAs into useful machines. A robust fuel cell system is the necessary goal. It makes sense to purchase commercial stacks and, as possible, explore the existing SOA in manufacturing quality control in hardware already in the global marketplace. NREL seems well established for making such measurements. One needs to understand the starting point, where we are today. (This could be accomplished without revealing the manufacturer, but the results would serve well as a benchmark of the 2015 fuel cell technology.) There need to be considerable new efforts in the optimization of the "system" and in the evolution of a fuel cell stack that results in a robust and reliable product.

Project strengths:

- The project team has clearly responded to past comments with real actions in a timely manner. The work is in many ways thorough, particularly with the incorporation of performance response and modeling. The project has overcome challenges of industry collaboration on a sensitive topic.
- This project is well designed and well executed and follows methodical approaches to quality control technology development.
- The project team has done excellent research and has good cooperation with industrial partners.
- Certainly the skills, abilities, and experience of the NREL staff and the DOE-sponsored existing quality facilities at NREL are strong project attributes. The timing of the project is, perhaps, a little late. However, the team is clearly well focused and is making significant progress.
- A project strength is NREL's experience in MEA fabrication and manufacturing and analytical capabilities.

Project weaknesses:

- There seems little indication that fuel cell quality control measurement technology is a global challenge and that others may be well ahead of the United States and its national laboratories in this area. There are operational fuel cell trade organizations around the world. The one in British Columbia (teamed with a world-class automotive OEM, the ones built around Japan's Ministry of International Trade and Industry, the three in the United States come to mind. It seems necessary to associate with this existing global community and to acquire data about what particular measurements provide the highest value for quality control in manufacturing. This focus on global market issues would strengthen the project.
- Manufacturing quality control involves statistical significance. These QC techniques would be further validated by continuing to run project systems with larger samples. Donation, purchase, etc. of "known" good material for testing would be very good. The project could determine how much the background noise varies, how environmental perturbations impact performance, and whether certain electrode compositions are better or worse for each approach.
- The correlation between defect type, size, frequency, and performance/durability is lacking. This information is critical to ensure effort is directed toward appropriate techniques and not wasted looking for or detecting blemishes that have no impact. More input from industry in this area would be invaluable.

Recommendations for additions/deletions to project scope:

- This project needs to be expanded to cover the entire inventory of parts in fuel cell systems. The emphasis on the fuel cell components is a fine, appropriate place to begin. However, as in a chain in which one bad link is all it takes for failure, one needs to understand durability from a system perspective. The proper project scope needs expansion to this system level. Indeed, one suspects that the largest, early opportunity for U.S. manufacturers will be in components such as blowers, valves, hydrogen pumps, gaskets, etc., and learning the art of manufacturing acceptable mechanical components seems critical. There are some component “standards” in place. Such a project might involve the U.S. Departments of Commerce and, perhaps, U.S. Department of Defense and “trade associations.” DOE needs to participate in building a well-defined set of manufacturing guidelines that serve as metrics for those involved in fuel cell component manufacture.

- The project should add a high run aspect to determine the statistical performance of each approach. The program could be duplicated to include other volume components, such as plates.
- The researchers should try to apply the diagnostic tools on MEA components also catalyst coated membranes (CCMs) and GDEs for PEM water electrolysis.

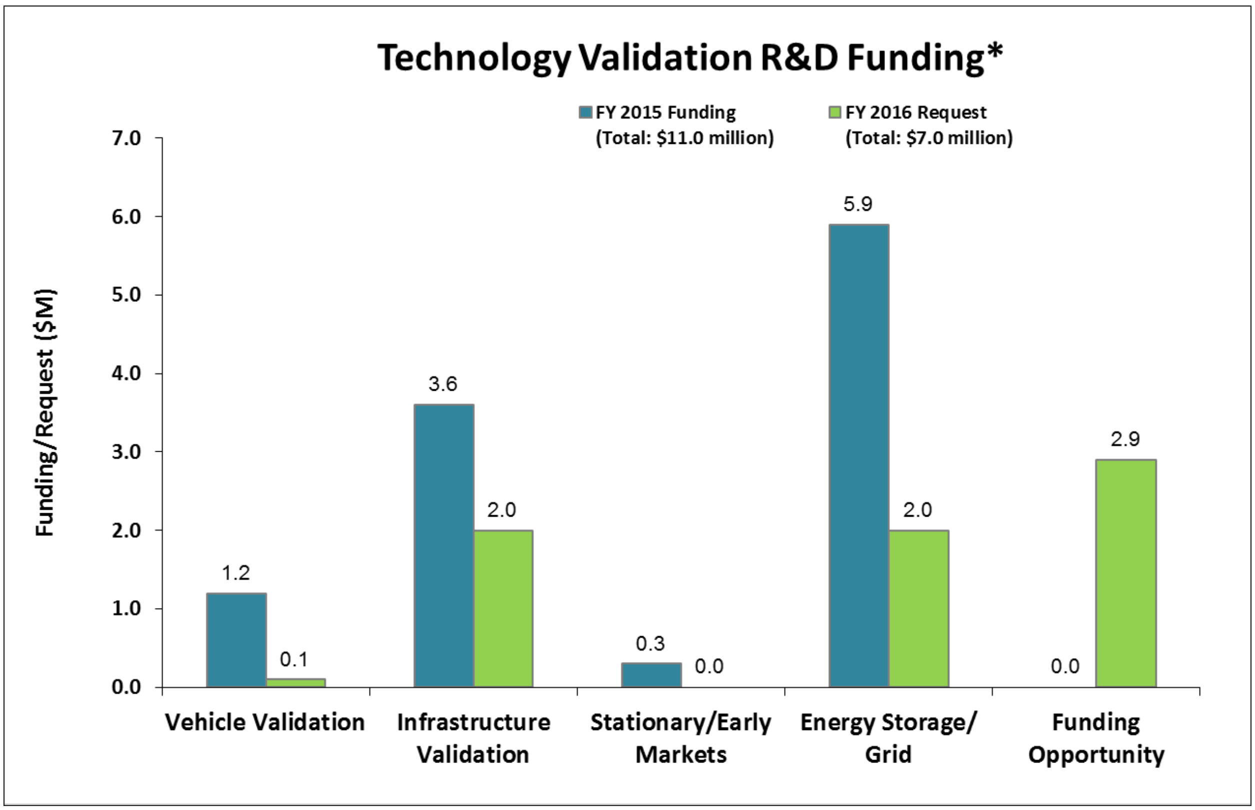
2015 — Technology Validation
Summary of Annual Merit Review of the Technology Validation Sub-Program

Summary of Reviewer Comments on the Technology Validation Sub-Program:

In general, the reviewers believed that the objectives and metrics of the Technology Validation sub-program were clearly stated, and that the role of the sub-program within the structure of the Fuel Cell Technologies Office was clearly identified. They believed that effective collaboration with partners and successful management of large amounts of data were key strengths of the sub-program and furthered its goals and objectives. Reviewers stated that progress related to projects and near-term plans of the sub-program were adequately presented, but they suggested increasing the emphasis on longer-term plans and comparison of recent progress to that of the previous year. Reviewers also suggested that the sub-program focus more attention on cost data and consumer acceptance.

Technology Validation Funding:

The Technology Validation sub-program's funding portfolio will enable it to continue to collect and analyze data from fuel cells operating in transportation applications (e.g., light-duty vehicles, medium-duty trucks, and buses), stationary and early market applications (e.g., material handling), and hydrogen infrastructure activities (e.g., fueling stations and components). In coordination with the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy and Office of Electricity, a key focus in fiscal year (FY) 2016 will be hydrogen-based energy storage and grid integration activities. The FY 2015 appropriation was $11 million. The FY 2016 request of $7 million is subject to congressional appropriations.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

Majority of Reviewer Comments and Recommendations:

The reviewer scores for the 11 Technology Validation sub-program projects that were reviewed had a maximum score of 3.9, a minimum score of 3.0, and an average score of 3.4. Key strengths identified by reviewers in all of the Technology Validation projects were (1) the collaboration involving key partners and (2) the potential for the projects to contribute valuable data to allow stakeholders to gain enhanced insights and successfully deploy hydrogen and fuel cell technologies. Reviewers also observed that the National Renewable Energy Laboratory's (NREL's) approach for collecting, securing, and analyzing data is well established and trusted by project collaborators.

Fuel Cell Electric Vehicles (FCEVs): Reviewers stated that this project has served as the main global source for reporting on the status and progress of FCEVs, and that the project has been conducted with well-defined goals and methodologies. Reviewers praised the project team for maintaining the cooperation of several automotive companies, and they suggested that these automotive original equipment manufacturers continue to provide data during increased rollout and commercialization. The reviewers also offered some suggestions for improvement, including segmenting data based on vehicle model year, disaggregating vehicle classes, collecting data for fuel efficiency at one-quarter and full power for newer model vehicles, looking more closely at fuel cell stack vintage, and evaluating the effects of climate on vehicle performance.

Fuel Cell Electric Buses (FCEBs): Reviewers found this project to be valuable for a variety of stakeholders, and to feature consistent data collection and evaluation efforts. Reviewers noted that consistent, long-term collaboration between NREL, data providers, and data users has proven to be very effective. Reviewers suggested that the project team compare FCEBs with more technologies and under different circumstances, explore the potential application of a Technology Readiness Level–like concept for maintenance personnel's level of experience, and consider combining the different results to date into a bigger-picture evaluation.

Material Handling Equipment: Reviewers viewed this project as having the potential to identify optimization for the commercialization of fuel cells in key early markets, and as providing insights into user behavior, which in turn helps guide design requirements. NREL staff's background knowledge and practical experience with the material handling equipment industry was seen by reviewers as a key strength. The reviewers noted that steady cooperation of industry has allowed a significant data set to be built.

Hydrogen Refueling Stations: Reviewers noted that data collection and evaluation efforts for hydrogen refueling stations have provided a long history of reliable information, and that the maintenance data was especially valuable and relevant in deriving preventive operations and maintenance schedules. Reviewers recommended that the researchers start identifying next-generation "open" retail stations in data reporting separately from previous generation non-retail stations, as well as evaluate the correlation between station usage and compressor failure events. Reviewers noted that the Proton hydrogen station project has provided useful insights that help stakeholders assess whether advanced hydrogen production technologies will advance efforts to reach DOE hydrogen cost goals. Reviewers articulated that the GTI hydrogen station project involves capable partners, and that good progress has been made to date. They noted that having data from five stations will help validate the technology, and that project partners should document lessons learned to aid the industry in overcoming barriers for future hydrogen station installations.

Compressor Performance Evaluation: Reviewers viewed NREL's compressor performance evaluation project as important in the deployment of commercial hydrogen stations. While they acknowledged the project has generated useful data and made significant progress in the evaluations, they also noted that there has been limited operational data and run time. Reviewers suggested performing more hours of compressor testing, evaluating other compressor types, investigating the impact of start-up mode and frequency on compressor performance and failure modes, and adding a separate mass flow sensor to confirm the calculation of the mass flow.

Cryogenic Hydrogen Storage and Liquid Hydrogen Pump: Reviewers remarked that this project has the potential to boost hydrogen density to meet DOE targets. They found the safety analysis conducted by the project team to be very thorough and capable of serving as a model plan. Reviewers commented that the project partners possess complementary expertise and are well chosen for their ability to contribute. Reviewers suggested that the project team obtain further input from vehicle manufacturers, more fully specify performance benchmarks, identify the cost of the system, and analyze the economics and pressure excursions during dormancy. Reviewers also noted that more emphasis should be put on collaborating with institutions outside the consortium.

Station Operational Status System (SOSS): Reviewers found the SOSS interface to be well designed and functional. They noted that integration with all stations is essential for the success of the project. They suggested that it would be useful to include (1) customer feedback on the app design to gauge customer satisfaction and obtain feedback for enhancements, and (2) a count of app usage and daily visits to measure its effectiveness.

Hydrogen Station Equipment Performance (HyStEP) Device: Reviewers found that this project effectively links the DOE research and development objectives related to the Safety, Codes and Standards and Technology Validation sub-programs, accelerating the validation process of hydrogen refueling stations. They noted that the mobile device is well engineered, and they praised collaborations with various organizations involved in the project. Reviewers encouraged caution with the potential changing of standardization requirements (e.g., CSA HGV 4.3 – Test methods for hydrogen fueling parameter evaluation) and the revision of SAE International J2601 (Hydrogen Fueling Protocol), and they remarked that it may be prudent to synchronize completion of this project with the publication of the revised standards.

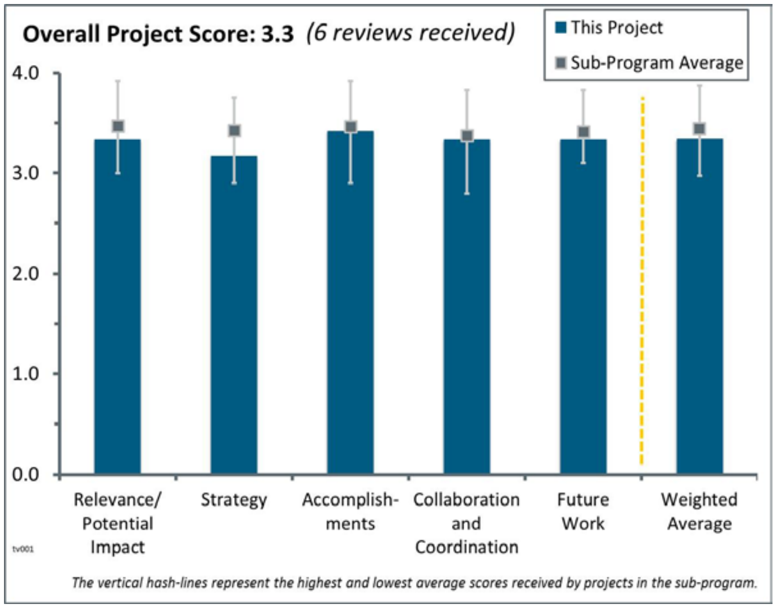
Hydrogen Energy Storage/Grid Integration: Reviewers stated that this project has demonstrated how both hydrogen and fuel cell technologies are part of a broader clean energy system and linked to a very current topic of global interest. They noted that project results have the potential to stimulate clean energy expansion. They commended the amount of progress the project has demonstrated in a short time frame on both electrolyzer technology and communications. Reviewers advised that the project could be enhanced by including utilities and Independent System Operators in order to obtain feedback on their experiences in incorporating renewables and their needs.

Project # TV-001: Fuel Cell Electric Vehicle Evaluation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate hydrogen fuel cell electric vehicles (FCEVs) in real-world settings and to identify the current status and evolution of the technology. The analysis will objectively assess progress toward targets and market needs defined by the U.S. Department of Energy (DOE) and stakeholders, provide feedback to hydrogen research and development, and publish results for key stakeholder use and investment decisions. Fiscal year 2015 objectives focus on analysis and reporting of FCEV durability, range, fuel economy, vehicle specifications, and driver experience.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- One cannot manage what one cannot measure. This project is one of the most critical for the Fuel Cell Technologies Office (FCTO) because it measures progress against DOE targets in real-life conditions. This project can determine when a project can be shelved in favor of something more promising. The project will also help determine when DOE programs are not supporting pre-commercial technologies anymore.
- Continuing to validate the current state of fuel cell vehicle technology durability and overall performance compared to technical targets remains essential to the FCTO Multi-Year Research, Development, and Demonstration Plan. The aggregated data are useful to policymakers, as well as fleet managers, manufacturers, and other potential consumers. It is exciting to see that one of the vehicles has 6,500 hours on a single fuel cell stack and that the average on-road vehicle economy is 51.4 miles/kg.
- Data collection to measure progress toward goals is always important. When original equipment manufacturers (OEMs) start commercialization, there should be a consideration about not including/collecting data anymore for specific OEMs.
- The project aligns well with DOE Hydrogen and Fuel Cells Program goals and objectives.
- Grading this project is tough; the material is a very necessary requirement, but the presentation of the material could have been improved greatly. The project is critical, but actual performance is tough to assess. The National Renewable Energy Laboratory (NREL) states that an objective is to validate FCEVs in a real-world setting, but little is presented beyond some limited refueling data, when other data exist and are regularly provided to users (e.g., monthly data about General Motors FCEVs are provided to the U.S. Navy and Marine Corps).

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.2** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project is well designed and is being conducted according to plans.

- There is a need to aggregate data, given confidentiality issues, but it would be very useful if the aggregated data could be provided in an Excel spreadsheet and if the results were categorized by vehicle class. It would be much more useful to get the actual numbers instead of trying to guess. It would be interesting to test vehicle range on partial fills, particularly at p-50.
- The presenter recollected no problems encountered during the project; a quick review of the hard copy does not find a similar discussion. If the project is integrated with efforts beyond the efforts of OEMs to place FCEVs onto the roadways, it was not discussed. The project presentation seemed limited to a presentation of highlights.
- The current data set appears to be a bit limited, with between 28 and 48 vehicles, whereas the funding is for up to 90. With the expansion of vehicles in California, it is important to have firm plans for the Office of Energy Efficiency and Renewable Energy's participation in data collection and analysis.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project is not finished. Reporting is outstanding at this point in time. Work needs to continue at this same high level, addressing the issues outlined in the project thus far.
- Significant accomplishments have been achieved in assessing FCEV on-road performance. Some key caveats, assumptions, or key points, if any, may need to be included with composite data products (CDPs).
- The number and variety of CDPs provide for easy historical trending. Also, the data show much progress toward meeting the DOE targets.
- There are more vehicles being tested every report period, which is a great accomplishment.
- Because the focus is on meeting stack targets, slide 11, which describes improvements in on-road fuel economy, should be considered—i.e., whether the reported improvements in fuel economy also included hybridization improvements. (Miles per kilogram may not be due to the fuel cell [including improvements] only.) There was a good point about looking into peaks of onboard fuel pressure at the end of fills. Perhaps analysis of the results shown in the graph on slide 15 could also be an indication of other observations with regard to the temperature limit.
- Apart from collecting and promulgating data, the project seems like an administrative requirement.

Question 4: Collaboration and coordination with other institutions

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

- Maintaining the continued cooperation of six automotive companies is no small feat.
- Collaborating with U.S. partners is great. It would be even better if the data could be compared with data from other OEMs outside of the United States.
- This project is based on collaboration with six OEMs and industry working groups.
- It appears that NREL performed all the work for this project. The partner activities listed were conducted by the automotive OEMs. Once they manufactured the car and their FCEV hit the road, it is not clear what they did for this project. There was one partner that assisted NREL, but that partner was not listed in the presentation. Otherwise, it seemed that all project work was performed by NREL and nobody else.
- It is unclear what the expectation is going forward regarding OEM involvement in providing data during commercialization.

Question 5: Proposed future work

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

- The proposed future work is consistent with plans and schedules.
- The elements for future analysis work look fine. However, it would be nice to substantially increase the number of vehicles in the study by establishing contracts with the automotive OEMs and the state of California for data collection and analysis services for the rollout of the commercial vehicles, especially

those that will be purchased as part of the state fleet. It would also be good to include collection of data for fuel efficiency at one-quarter and full power for newer-model vehicles. Also, there should be some data segmentation based on model year so that the performance of later models can be fully appreciated.

- The project is underway. The team has a great handle on what needs to be reported, has a great relationship with the OEMs, and is adjusting subtask focuses as needed to address areas that need review as they surface from the data collected.
- It is not clear whether the data is being fed back to U.S. DRIVE Partnership Technical Teams to adjust model assumptions.
- It is not clear whether NREL/DOE is communicating with potential new OEM market entrants.

Project strengths:

- This project represents the main global source for benchmarking and reporting status and progress of FCEV durability.
- Data collection and analysis remains strong and relevant.
- Fill pressure anomalies were captured as something that needed explanation.
- The project has been conducted with well-defined goals and methodologies.
- Stakeholder engagement and project planning are strengths.

Project weaknesses:

- There are no significant weaknesses.
- The fill data metrics appeared to show that the market has a conservative approach to the fill process. Those data were reported to the safety side for possible changes to the process. The question is what can be done to show the changes in benefits due to reduced fill time and range.
- The vehicle configurations, the extent of hybridization, the size of vehicle, etc. are unclear.
- If the number of vehicles gets to a certain minimum, then the usefulness of the data collection effort should be reconsidered.
- The format of results is not very useful for analysis.

Recommendations for additions/deletions to project scope:

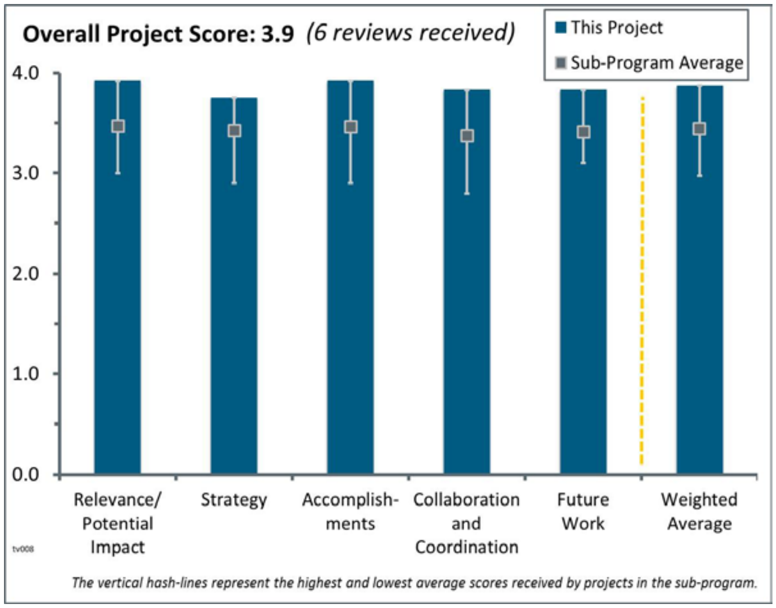
- DOE should recommend that presenters include references to posters on the same topic from previous years. A one-letter difference in file names of documents made available to reviewers (in this case, 2014 and 2015 file names) could cause confusion for reviewers and possible negative feedback.
- Stack vintage within a car's manufacturing cycle should be somehow included in the project. Most stacks are still somewhat handmade. As stack production improves, consideration should be given to how to capture that repeatable process to evaluate life changes. Early cars were demonstration platforms used at shows, ride and drives, and other events. As such, distance between refills should be low compared to cars actually placed in service with fleets and consumers. Segregating those data will go a long way to showing the actual user experience versus the demonstrator experience. When reporting the miles per gallon gasoline equivalent (MPGe), the project should look at whether drivers used the onboard displays to adjust pedal movement. Driving an FCEV the same way one would drive a gas car results in lower MPGe. Retraining the driver's pedal actions using the display can result in significant MPGe improvement. As more cars deploy, a note on the ambient environment will become appropriate—cold-weather climate versus warm-weather climate, southern California versus the Northeast. Another metric to consider will be the impact the mechanic will have on the vehicle: his training, his tools, etc.—i.e., considering who is taking care of the car and whether the mechanic is at a factory location or a dealer.
- The project should improve public reports to disaggregate vehicle classes and provide numbers in spreadsheets. International OEMs should be engaged.

Project # TV-008: Fuel Cell Bus Evaluations

Leslie Eudy; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate fuel cell electric bus (FCEB) performance and cost compared to U.S. Department of Energy (DOE)/U.S. Department of Transportation targets and conventional technologies and to document progress and lessons learned on implementing fuel cell systems in transit operations to address barriers to market acceptance. Annual FCEB status reports will compare results reported from transit partners and assess progress and needs for successful implementation of FCEBs.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.9** for its relevance/potential impact.

- This project has been funded in one form or another for 13 years. The results of the project speak for themselves. These are the only data collected from public transit buses using fuel cells, electric batteries, and diesel engines. The impact on the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) has been revealing.
- Because buses are important to DOE and are a DOE target for fuel cell deployment, it is necessary to measure the deployment of fuel cells on buses, and the National Renewable Energy Laboratory (NREL) team appears to be doing a thorough and complete job of gathering, measuring, interpreting, and providing the necessary metrics.
- Third-party validation is important to setting standard protocol to assess where technology really is and how it compares to conventional/commercial technologies. Studying fuel cell buses individually is important because they have different potential models from light-duty vehicles (e.g., depot model and specific range).
- The project enables learning from early adopters for larger populations of transit agencies and the Federal Transit Administration.
- The work is most valuable for different government agencies and is being used accordingly.
- The project clearly and directly supports the Hydrogen and Fuel Cells Program's (the Program's) goals and the objectives delineated in the MYRDDP by analyzing the performance of in-service fuel cell transit buses.
- The activity reports on components, service programs, and performance metrics to show the interconnection between them. It is not perfect, but it identifies the issues and areas that should be addressed to allow the technology to meet and exceed long-term goals.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The strategy is excellent and aimed at analyzing and summarizing in-service performance data supplied by fuel cell bus operators. Results are compared to DOE targets. It is a very useful technology validation project.
- The project has outstanding evaluation and coordination with transit companies to collect and evaluate key data on real-world performance and maintenance of fuel cell buses. The design of this project has not varied from the beginning and provides consistent data collection over time.
- Analysis was across several different metrics. Some could be better tied to conventional vehicles, although samples may not be available in all cases, while others are directly tied. Regarding the discussion of baseline vehicle selection, the presenter did a good job of describing the challenges (e.g., the team would like to have at least five vehicles but cannot always get them from the transit agencies) and approaches to overcome limitations. The project team talked to vehicle drivers to learn anecdotal things a data sheet cannot provide. On a similar note, passenger surveys were performed. These activities are very important because technology adoption is not solely about cost and performance—if the customers do not like something, they still will not buy it.
- Consistency in data collection and analysis is a great strength.
- It is difficult to suggest improvements to the NREL presentation, which appears complete and thorough.
- To the extent that bus users allow, comparisons between the types of bus technologies are good. Data collection is good. Additional reporting should extend to show the effect that larger numbers of fuel cell buses at a single site can have when compared to a two- or three-bus user site.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The presenter provided a good description of the caveats around the analysis and why differences are expected (e.g., comparing Technology Readiness Level [TRL] 9 conventional technologies to TRL 6–7). It is good to see that in the assessment of power plant life, AC Transit exceeded the 2016 target (>19,000 hours). There was a good breakdown of downtime to explain the delta between actual availability of 70% versus the target of 85% (which was mainly due to bus issues, not the fuel cell, which only accounted for 10%–15% of the reason for unavailability). In addition, it is important to point out that propulsion is the most costly, even if it occurs less often (but again, this is typically not due to the fuel cell but mainly because of cooling issues). The fuel analysis is good as well; it shows the fuel economy is significantly better than the diesel equivalent and has passed 2016 targets on miles between fuel cell service.
- Much progress has been made since the project started in fiscal year 2003. A large amount of data has been received and analyzed relative to near-term and ultimate DOE targets. While most of the targets have not quite been met, the results seem to be quite promising relative to standard diesel and compressed natural gas (CNG) vehicles. This project has gone a long way in convincingly showing that fuel-cell-based bus operating performance will ultimately be competitive with present fossil-fueled buses. The principal investigator is also getting some important verbal input from drivers. Fuel cell buses are very popular with drivers and riders.
- The Program can rest easy knowing that valuable data are being collected on public bus transits in a consistent manner and evaluated with transparent and accurate methodologies to evaluate the Program's technical targets. The project clearly shows the reliability targets of miles between road calls (MBRC). Cost of maintenance per mile is just one of the ways to evaluate the data collected, and this metric was explained well. Maintenance cost per mile by system is another example of how to evaluate the data collected. DOE reaps the benefit of the detailed data collected.
- It is impressive that the 2016 target is exceeded by one FCEB and that the average hours for most FCEBs is beyond 8,000 hours. The presentation included a solid explanation of the graphs and data, including reasons for observed changes in data. Maintenance cost per mile is an incredibly valuable parameter for

transit operations, so inclusion of this in the reporting is very valuable for DOE. It would be good to know how much of a propulsion system can be considered "shared" with other technologies from buses with the same manufacturer. In response to a 2014 reviewer comment/question, the presenter made a good point about bringing up the average MBRC number for the transit bus industry.

- Data collection does identify spare power plants. The reporting of spare power plants in combination with in-service power plants offers a challenge in interpreting what the real stack life is.
- It would have been nice to know whether NREL had difficulties with the project. NREL did a nice job of detailing the challenges that bus service providers faced, but it did not really describe the challenges, if any, it faced while performing the project. This category grade was almost a 3.5, and it would not be difficult to change downward from the grade assigned.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- DOE is fortunate to have someone like Leslie Eudy establishing such excellent partnerships with so many bus transit companies over the years. This consistent long-term collaboration has proven valuable to evaluating the performance of fuel cells in real-world conditions.
- Collaboration and coordination with other institutions has been excellent. Collaborations include data from fleet operators, drivers, bus and fuel cell manufacturers, and fuel suppliers. In a few cases, data flow has been interrupted when there are management changes within the collaborating organizations. This is unavoidable and has not been a major problem.
- Working with transit authorities in different regions is challenging. This group has done an outstanding job with that effort.
- Given the nature and scope of the project, NREL did a very commendable job of working with collaborators, such as transit agencies, manufacturers, or other agencies. The project is doing a nice job.
- The collaborations are excellent, and the project should keep it up. The team could potentially include hybrid diesel technology buses, where possible, for comparison.
- Interaction with transit agencies (input and output) and manufacturers (testing consistency and realism) was clear. Feedback from/connection with state and international organizations, other than data sharing, was not as clear.

Question 5: Proposed future work

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

- This excellent work should continue and expand according to the future work outline. It is very important to add battery-electric buses to diesels and CNG for comparison. Battery research and development (R&D) is probably exceeding fuel cell/hydrogen R&D at the moment. The great future technological battle in electric vehicles will be fuel cell versus battery.
- Because it is necessary to monitor and measure deployment activities, it is very difficult to find/determine improvement.
- Other geographic areas could be considered. Other fleets with various power configurations should be considered, as the presenter suggested. These potential transit companies should be included in the future. This would help broaden the data collected.
- The proposed future work is mainly the completion of reports—this section went by pretty fast. Perhaps there is a way to tie together the different reports and draw bigger-picture conclusions once there is more of a critical mass, or perhaps this is just more of the same, or perhaps one can draw conclusions on advancements based on studies of later versus earlier buses. It is not totally clear what the additional data were going to provide.

Project strengths:

- This project represents the only consistent source of FCEB data in the United States. The analysis and conclusions are neutral.

- There is good context and knowledge around bus maintenance—the project is clearly not just mining data from a computer.
- The project has outstanding data collection and detail in all areas. It is very easy to start drilling down on those areas that will contribute to life goals.
- This is excellent real-world operation analysis.
- The consistent data collection and evaluation is a strength.

Project weaknesses:

- Comments from transit operators, the bus operators themselves, the maintenance people, and the riders should be added to the project, allowing for comparison between the various technologies. Climate impacts—hot versus cold, wet versus dry—were not evident.
- It would be better to also include the average on the right of slide 12. It is somewhat misleading to have only high and low versus CNG (and it is not clear how the information ties to slide 13).

Recommendations for additions/deletions to project scope:

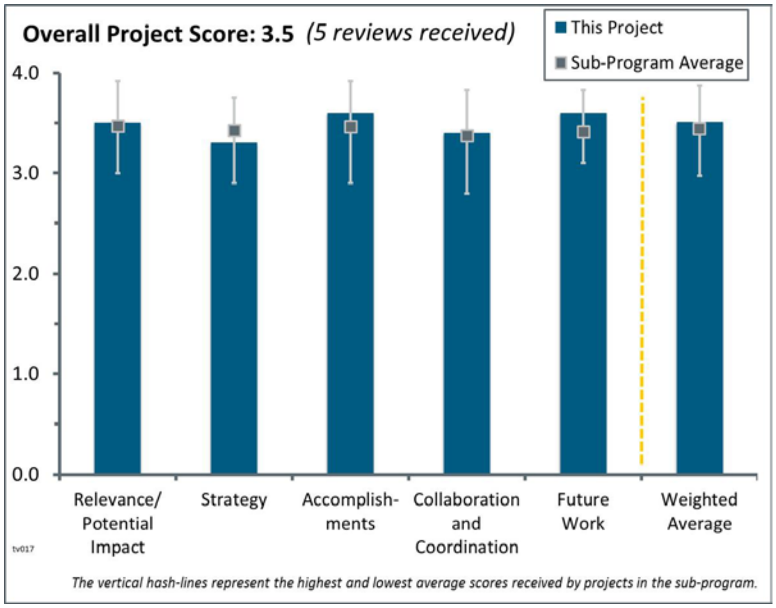
- Road call values are increasing toward the target, but it is not clear why (e.g., whether it is better preventative maintenance programs that are preemptively solving problems or better parts being used for the fix). It was noted that quick change batteries have improved and may start to give fuel cell buses a run for their money. Climatic comparisons should be considered. Battery buses in the Northeast have been reported to have range issues during the winter, causing some rerouting (e.g., in Worcester, Massachusetts).
- A comment was made that the key driver is policy (zero emissions). How this can be leveraged further should be considered. (This is not really in the scope of the project, but we should consider what recommendations can be made to other groups to drive policy.) The scope could be expanded to include the impact of regulations on the number of fielded buses.
- Additional funding should be provided to increase data from the baseline fleet vehicles. The project should explore the application of a “TRL”-like concept for maintenance personnel’s level of experience to maintain FCEBs and its relation to the availability of FCEBs.
- The project should add new transit companies in different geographies.

Project # TV-017: Hydrogen Station Data Collection and Analysis

Sam Sprik; National Renewable Energy Laboratory

Brief Summary of Project:

The goal of this project is to evaluate hydrogen infrastructure performance, cost, utilization, maintenance, and safety through independent analysis. Data analysis will support validation of hydrogen infrastructure, identify status and technological improvements, provide feedback to hydrogen research, and provide results of analysis for stakeholder use.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- The project supports the Hydrogen and Fuel Cells Program in the area of hydrogen refueling stations (HRSs) by collecting useful data on station capacity/utilization, fueling, maintenance, costs, and timing. Such data collection is worthwhile, and resulting analysis brings significant knowledge to HRS players (e.g., owners, utilities, and users) to focus on critical elements so that HRSs are more reliable and easier to operate.
- The National Renewable Energy Laboratory (NREL) team is doing a very good job in working to meet U.S. Department of Energy (DOE) goals and requirements.
- These data are essential for evaluating station performance, following the previous NREL endeavors in collecting and analyzing data from fuel cell electric vehicle (FCEV) field testing.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.3** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- This is an extremely complete performance by the NREL team to address critical barriers and advance fuel cell vehicle fueling; the work could be valuable to improving infrastructure deployment.
- The bundled data (manually and automatically collected data) are delivered quarterly to the NREL researchers, who process the data and return both internal and public data products every six months around nine categories of interest (e.g., maintenance and refueling). Despite the fact that templates were produced, the level of details and harmony of data between stations is having an impact on the conclusions that follow from the NREL analysis. One can sometimes regret that the analysis is given with no indication of the data set's representatively.
- Ideally, data are collected automatically and not entered manually by station operators into the forms described. The project should (1) start identifying next-generation "open" retail stations in data reporting separately from previous-generation non-retail stations (e.g., behind fence, non-retail, and non–SAE International J2601 compliant) and (2) consider using the "open" definition as developed by the California

Fuel Cell Partnership and California infrastructure stakeholders (e.g., vehicle original equipment manufacturers, station providers, and state government).

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project managed to gather data from 7–9 HRSs, which accounts for nearly all public HRSs in the United States. Significant results were obtained for the benefit of the involved parties. Maintenance data are particularly relevant to deriving preventive operations and maintenance schedules so as to maximize a station's availability and reduce the operating expenses.
- This is outstanding. The collection and presentation of fueling data provides an interesting and useful story.
- It would be good to know whether composite data products (CDPs) will have separate data for 70 MPa fills colder than -30°C in the future. Based on collected data, NREL should evaluate the correlation between station usage and compressor failure events, because compressors have fewer issues when running continuously.

Question 4: Collaboration and coordination with other institutions

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

- All HRS stakeholders (e.g., state agencies, institutes, and HRS operators) are contributing to the project. A wider benchmark including station data from other continents would astutely complement the landscape of the data set.
- Without collaboration, there are no data to share, so collaboration is an essential aspect of this project. It is good to have a memorandum of understanding with the California Energy Commission (CEC) for collection of data from CEC-funded hydrogen stations. The question is whether data collection will continue after the first six months the station is operational and/or after the first three years of funding (the required operational time to receive funding).
- Collaboration appears to consist mainly of partner organizations providing data rather than an effort to develop a greater role for partners.

Question 5: Proposed future work

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

- The project was successful in demonstrating its technology and economic value. Its continuity is mandatory; continuing the data feed without DOE funding is under consideration.
- The project and the work performed are necessary, and NREL did a commendable job of presenting the data as well as the challenges and issues that can be addressed in the future.
- The project should keep up the good work.
- There is no indication as to whether NREL can manage, or needs to prepare for, data processing and analysis for reporting from 40+ additional California hydrogen stations and 10+ Northeast stations.

Project strengths:

- This project has a long history of reliable data collection, analysis, and report-out activities. A large amount of data are included in CDPs. The data collection process is anonymous.
- NREL has excellent experience in collecting and analyzing data from the hydrogen and FCEV space.
- The knowledge of HRS characteristics has greatly progressed.

Project weaknesses:

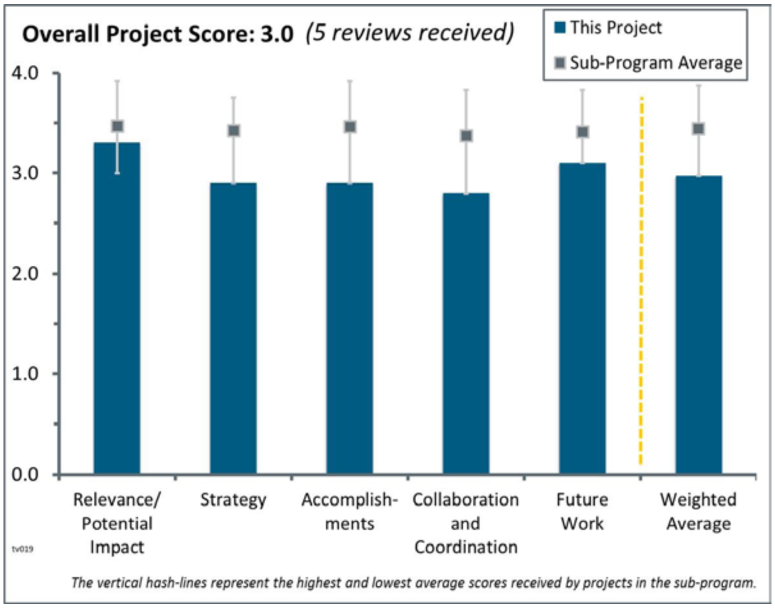
- The project sometimes contemplates its CDPs, and the value of its conclusions is delivered with limited recommendations on exploiting the data for research and development policy or seeding other projects. For example, the maintenance analysis allows prediction of an estimated duration of HRS downtimes as a function of the type of issue and parts to repair. Such dynamic information could be used in project TV-027 Station Operational Status System,(SOSS) in which the application currently shows only static information about HRS status (i.e., offline, online, or limited) with 15-minute refresh; the application does not tell when the station would work again in the case of offline status. TV-017 has the potential to tell that.
- No collaboration is equal to no data or fewer data.

Recommendations for additions/deletions to project scope:

- Products should start distinguishing between data from early generation stations and currently implemented next-generation stations, of which a larger number of the same design are built. This is especially important for understanding the new generation of compressors (where data indicate there is a high failure rate). The following should also be added to the project scope:
    - Expand the project to collect data for fuel cell bus refueling, measuring fueling time, state of charge, average fill, etc.
    - Indicate which stations fill other vehicles (medium and/or heavy duty) and devices, which will affect data if included.
    - Collect more detailed information about reported downtime/failures/issues with compressors.
- A workshop should be organized with all projects using HRS data so that better links and deeper exploitation of the data would emerge.

Project # TV-019: Hydrogen Component Validation

Daniel Terlip; National Renewable Energy Laboratory



Brief Summary of Project:

The goal of this project is to generate data and study compressor operation to determine common failure modes (approximately one-third of maintenance hours at stations) and performance in variable conditions. Through data collection and analysis, the project will provide information to help improve compressor operation and reliability, highlight compressor failures and consequences, and assist original equipment manufacturers (OEMs) in improving design and increase reliability.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- Small-scale hydrogen compressors are relatively new, and reliable data on their performance and failure modes are not widely available. This project aims to gather operational data on failure modes under different conditions, which is critical for the deployment of commercial hydrogen stations.
- The project is highly relevant because compressors remain high-cost items with poorly documented maintenance requirements. On one level, the industry partners should have done this long ago. The fact that they have not (at least not adequately) shows that this project is necessary.
- The main hydrogen component validation effort in this project is commercial mechanical hydrogen compressors. This is certainly one of the objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- This project aligns well with Hydrogen and Fuel Cells Program goals and objectives.
- There is a clear need to better understand and improve compressor reliability; however, the approach used by this project will not significantly add to the body of knowledge.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.9** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project has been well planned and well performed to date.
- The National Renewable Energy Laboratory (NREL) approach is to acquire a number (four) of commercial hydrogen compressors (diaphragm and piston) and to monitor their operation on the NREL site. In particular, failures and downtimes are quantified, and attempts will be made with manufacturers to redesign for improved reliability. All this is obviously useful for the validation of compressors within hydrogen fueling stations. Mechanical hydrogen compressors are well known to be problematical. There must be significant literature and anecdotal information that can be added to this operational study.
- This project gets detailed operating data into the public forum, but it is limited in the number of operating run hours, especially on those higher-pressure compressors.

- The approach is straightforward: test compressors to understand failure modes, time repair, and identify potential design improvements. It is not clear how much cost share the industry partners are contributing. A separate mass flow sensor should be added to confirm the calculation of the mass flow.
- Although there is a need to better understand the performance of compressors, this is not the way to do it. First of all, at a real station, the repairs will be done in a timely fashion by individuals who have the time and are well trained at repairing the parts. The amount of downtime due to the NREL principal investigator simply not having the time to work on the issue is unacceptable and badly skews the results.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- Significant progress has been made in the evaluation of compressor failure.
- Useful data have been generated so far—but not as many as could be expected so near to the end of the project. Reliability and downtime results seem to be somewhat discouraging. There is a need for increased interaction with compressor manufacturers to solve some obvious reliability problems. It would seem that industrial hydrogen compressors (e.g., in oil refineries) cannot be so troublesome.
- It took too long to complete readiness verification—six months, or a quarter of the project time. There may not be enough time to gather meaningful data on DUT 2–DUT 4 before the projects ends in October.
- There is not much to see in terms of accomplishments. The operating hours are low as a result of a lack of time to do necessary repairs. The failure modes may be due to the person doing the repairs as much as the actual compressor, especially because the time between failures seems to be excessive. What is attempted here could have been better obtained from the technology validation station data. There are also no notable changes made by PDC Machines Inc. as a result of the findings in the study to date.
- The project has only one of four compressors operating continuously. It is not clear how the other compressors, marked with a duty cycle of "as needed," are being used.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- Industry cooperation is vital to the project because any identified suggested changes have to be implemented by the manufacturer. The participation of NREL and industry is a good marriage of modeling and industrial process.
- There is excellent collaboration with several companies/organizations.
- There are a few good collaborations, but there should be more with compressor OEMs and industrial users (e.g., refineries).
- Collaboration is limited to only one compressor manufacturer. The lack of extensive collaboration could potentially introduce some bias toward the partner's equipment.
- It does not appear that PDC Machines Inc. plays a role beyond being a supplier of the compressor.

Question 5: Proposed future work

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

- The proposed future work on the impacts of contaminants is appropriate.
- The proposed work is sound, although the scope will require renewal of the current project.
- All suggested work is needed, but the project is nearing its end. It is not clear that much more can be done to solve the compressor reliability problems.
- Comparison of several different types of compressors would be quite useful. It is not clear what types of compressors the project team has in mind.
- In general, this project should be re-thought.

Project strengths:

- Unbiased, clear data collection always expands understanding.
- The project is well planned and has been conducted according to plans.
- The relevance of the project objectives to current operational challenges is a strength.
- The project provides important in-house test data.

Project weaknesses:

- There are no significant weaknesses.
- The project needs to put results in broader terms, such as mean time between failures, listing of failure modes, approximate time for repairs, and expected annual downtime.
- There is not enough survey of industrial operating data and not enough effort on practical solutions of the operational problems unearthed.
- The limited operational data and run time is an area of weakness.

Recommendations for additions/deletions to project scope:

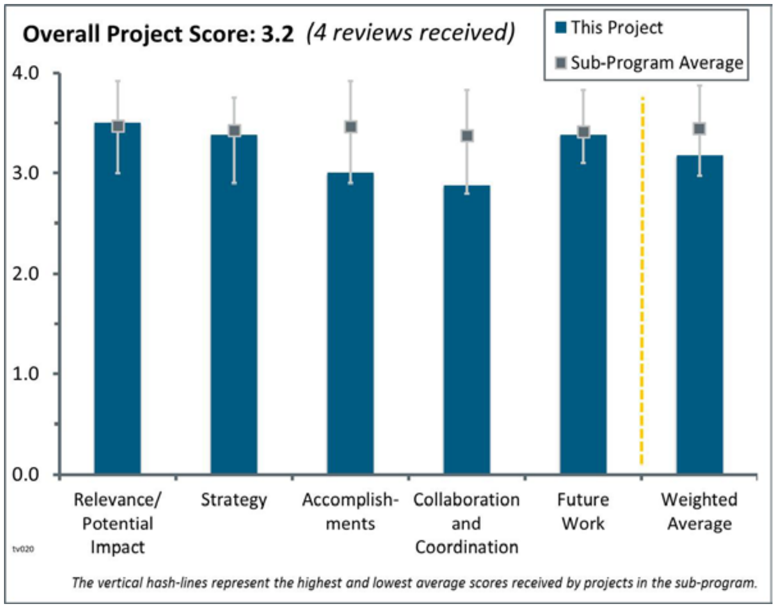
- The hydrogen flow rate should be measured directly as a check on the computed value. More hours of compressor testing and more compressor types should be added. The project should consider testing ionic compressors and Hydro-Pac piston compressors. The team should also reveal efficiency maps for the compressors to enable realistic projections of performance.
- This project must be continued, with acceleration, beyond the project end date. The problems discovered do not bode very well for fueling stations.
- The impact of start-up mode and frequency on compressor performance and failure modes should be added to the proposed work.

Project # TV-020: Validation of an Advanced High-Pressure Polymer Electrolyte Membrane Electrolyzer and Composite Hydrogen Storage, with Data Reporting, for SunHydro Stations

Larry Moulthrop; Proton OnSite

Brief Summary of Project:

The goals of this project are to meet (1) pricing targets for delivered hydrogen through developing advanced polymer electrolyte membrane (PEM) membrane electrode assemblies (MEAs) and water electrolyzers; (2) hydrogen storage targets with advanced composite containers that double usable storage per unit volume; (3) codes and standards requirements for safety, location, footprint, and costs; and (4) performance data needs through collection and reporting of 24 months of SunHydro station performance data.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- It is well known that electrolysis is a more expensive hydrogen production pathway than steam methane reforming at this point in time, but electrolysis has the potential to reduce life cycle greenhouse gas emissions, depending on the source of electricity and the energy requirements. Electrolyzer performance at medium-large scale is a showstopper for this pathway, so it is necessary to transition from research and development (R&D) to commercial scale. However, it is well known that this technology is expensive and will not meet the Fuel Cell Technologies Office's (FCTO's) cost targets. It will be interesting to see whether the new storage tanks make a difference. The project directly tackles four major FCTO challenges for the electrolyzer pathway, which will provide interesting data to engineering models that focus on near-term market penetration.
- The project is well aligned with U.S. Department of Energy (DOE) objectives. Lowering the cost of hydrogen is extremely important to furthering the commercialization of fuel cell technology in various applications. Depending on the application, the high cost of hydrogen is a huge barrier to adoption of fuel cell technology.
- The goal of the project supports the need to build hydrogen infrastructure and explore better, more cost-effective ways to build electrolyzer-based stations that can generate hydrogen on-site and potentially do so renewably.
- It is good to have actual station experience.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project includes several advances to potentially lower hydrogen cost. The project is well designed to meet objectives.

- The strategy was good, although the proposed system for hydrogen generation did not meet the energy savings demonstrated in the laboratory. However, the project did validate fabrication of the MEA.
- The project has a very long timeline, which is understandable given its size and scope, but the timeline does raise the concern that the industry or the technology will move beyond the solutions being developed during the course of the project. It is also not entirely clear how broad the benefit of this project will be, beyond helping one company build two stations.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.0** for its accomplishments and progress.

- Over the last year, the project team has made excellent progress toward meeting goals. The project has contributed considerable data to show improved station performance (for SunHydro station #1 [SH1] with 57 bar hydrogen input).
- It seems that Proton OnSite was able to fabricate, install, and test the proton exchange membrane (PEM) without major glitches. The fabrication and installation of the storage system took longer than expected, but the project seems that it is now on target. Buffer tank optimization was not in the plan because it was not initially identified as a bottleneck in the process. It is good that the team identified the issue. It remains to be seen whether improving the buffer tank will really increase efficiency.
- The project has made progress overall, but the cost projections are still a concern, and it looks like the project will not demonstrate significantly lower-cost hydrogen generation. That is a legitimate outcome to a project, but it will be interesting to see whether any further progress is made with the second station. The development of the composite tubes seems to be a useful outcome.
- There seems to be good progress, but it would be good to have estimated hydrogen costs now, as well as projected costs for higher station deployment levels.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- The collaboration with Air Products and Toyota is essential to test actual vehicles, but Proton OnSite/ SunHydro have all the in-house expertise to carry out this demonstration project.
- The collaborations with partners are as expected for this project.
- The industrial partnerships seem appropriate. It would be good to see additional collaborations with U.S. DRIVE Partnership technology teams, including Codes and Standards and Hydrogen Production. Also, the data collected from this project should feed into engineering models such as the Macro-System Model (MSM) and Hydrogen Analysis (H2A) model to provide early market cost and performance data.
- It would be good to see discussion of how the project is supported by, and will support, automakers that are introducing fuel cell vehicles on the East Coast—at the very least, to show that the stations will be used and will not remain demonstration projects.

Question 5: Proposed future work

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

- The project plan for future work is reasonable. The presenter reports that the second station might be moved from the original planned location to the Washington, DC, area. That could be good for increasing station use and providing a source of hydrogen for new projects in that area. The move could increase public awareness of hydrogen and fuel cell technology by demonstrating applications in an area with a high number of visitors.
- The proposal to build the next station in Washington, DC, rather than Braintree is an interesting one. It would be good to see more detail about the plan for this to ensure that the station will be effectively utilized and will not go the same way as the Shell station that closed down. The reporting on the station activity, especially on costs, will be a critical outcome of this project.

- The proposed future work seems appropriate.

Project strengths:

- This is a good project team with a solid plan to reduce the cost of hydrogen through a combination of increasing efficiency and standardizing packaging of station components.
- The project has been able to overcome some challenges with the technology development and stay on track, and the work has provided useful insights into whether those technologies will make progress toward DOE hydrogen cost goals.
- The project team already has experience from the operation of SH1. Fabrication and installation of components have provided the team with significant experience to transfer R&D to real-world conditions.
- The team has excellent real-world experience in building stations and dispensing hydrogen.

Project weaknesses:

- The project’s weakness lies in the possibility that these stations and the technology developed will not end up moving the hydrogen infrastructure market forward when the fuel cell vehicle market is at a critical juncture and needs to find pathways to deploy stations cost effectively and quickly.
- Collaborations with U.S. DRIVE teams could improve. The concept of PEM electrolysis for hydrogen generation is an expensive proposition, which is no surprise.
- The project provides little or no detail about station costs, nor is there a roadmap on how to drive costs down to the $4/kg range.
- The project could benefit from increased station usage to more fully test capabilities.

Recommendations for additions/deletions to project scope:

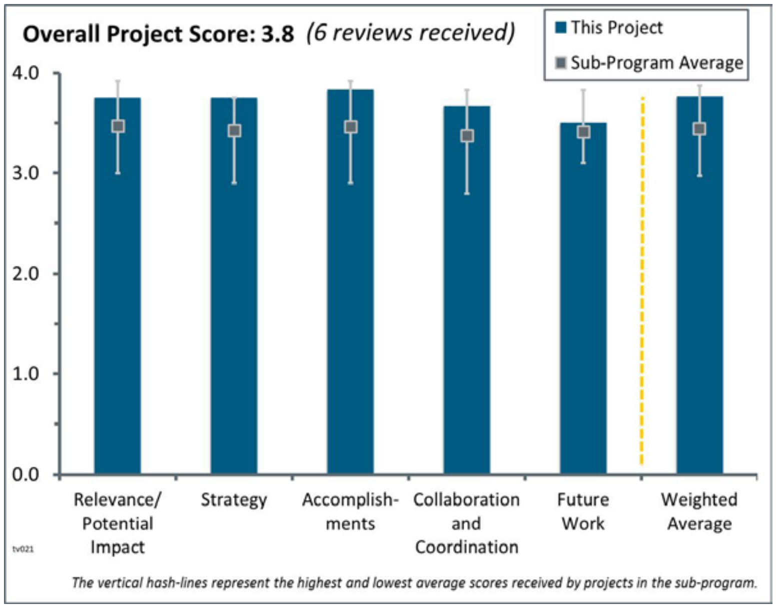
- It would be good to see a scale-up plan for how this technology could meet the need for an application with a larger throughput of hydrogen (e.g., material handling equipment or buses). It would also be valuable for the team to document the lessons learned with siting and approvals to leverage accomplishments and aid the industry with future station deployments.
- The project should add a task to estimate station costs for “N” stations and determine how many stations must be installed to reach hydrogen cost targets.
- There should be additional collaborations with U.S. DRIVE Partnership’s Technical Teams.

Project # TV-021: Material Handling Equipment Data Collection and Analysis

Chris Ainscough; National Renewable Energy Laboratory

Brief Summary of Project:

The overall objectives of this project are to assess fuel cell and hydrogen technology status in real-world operations, establish performance baselines, report on the technology, and support market growth by evaluating performance relevant to the markets' value proposition. The National Renewable Energy Laboratory (NREL) will perform an independent technology assessment in real-world operation conditions and performance and report on technology status to fuel cell and hydrogen stakeholders.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- This project demonstrates the success of U.S. Department of Energy (DOE) programs and the real-world performance of systems in different operating environments. It includes measurement of hydrogen infrastructure usage and showcases the first commercial-scale fuel cell vehicle (forklift) and hydrogen infrastructure deployments. The project establishes technology baselines in the field and represents a valuable use of public funds.
- NREL's data analyses, composite data products (CDPs), and detailed data products have significant benefit for fuel cell providers, investors in fuel cell technology, and anyone else with an interest in the progress of fuel cell technology. Specifically, this project provides information that is valuable to any organization that uses material handling equipment (MHE) and desires to investigate the value proposition for equipment powered by fuel cells.
- While the analysis projects do not directly advance technology toward DOE objectives, the projects provide third-party validation, which is very important in convincing decision makers. This project also provides insights into user behavior, which can help guide design and requirements. Chris Ainscough, in particular, brings a good deal of context to the analysis, which increases the value.
- This project has advanced the collective understanding of real-world performance for the fuel cell used for transportation purposes. The data collected in this project will become more valuable as they are referred to and utilized repeatedly going forward.
- The project fits well with DOE's goals and can help to identify optimization potentials for commercialization of fuel cells in key early markets.
- Data reporting is complete, concise, and relatively easy to understand. The project provides an excellent level of detail; it can be used to identify technical progress and areas that need attention.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.8** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The commercialization of fuel cells will occur because of the data collected during this project. The data collected from fuel cell forklifts on a voluntary basis represent incredible leveraging of DOE funds to collect actual data in real-world conditions. As the project comes to a close, the value added from this project will lie in the final written reports. How the infrastructure is used and performs and the 2 million vehicle hours achieved are the heart of the accomplishments. These are very impressive accomplishments. Partners are voluntarily providing outstanding data sets for the total evaluation of data collected directly by the project. Operation times, study of fueling pressure, and fast fuel are all impressive accomplishments.
- The data sets resulting from this project have shown the feasibility of fuel cells for forklifts and the value of hydrogen refueling. The project will try to continue collecting data on American Recovery and Reinvestment Act (Recovery Act) projects that have now ended. The addition of new data sets from non-Recovery Act-funded projects will allow data collection to continue beyond the life of the project and continue to support demonstration of vehicles that are operating beyond their designed lifetimes.
- This project contains large data sets that provide opportunities for further breakdown of the data, leading to deeper conclusions about what might be happening in the field. This was presented to a degree but perhaps could be more extensive. It is difficult to tell because some of the more specific conclusions are not releasable to the general public. For example, breakdown by class would be helpful; this is done internally but cannot be presented. However, it is impressive that suppliers are still voluntarily providing data, which proves they find the compiled results useful. The metrics and interpretation have good relevance, and the project features good discussion of what the classes are and how this affects the fuel cell life, even if all the data are not provided directly.
- NREL's approach to data collection, analysis, and reporting has been continuously refined by the National Fuel Cell Technology Evaluation Center (NFCTEC). All elements of the project are logical, well tested, and efficiently executed. There is a disciplined approach to publication of reports and project results.
- NFCTEC analysis and reporting of real-world operating data of material handling fuel cell systems will contribute to the commercialization of fuel cells in early markets.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The data show clear improvement compared to batteries —one strength of this project is the people working on it and the context around material handling. It is very clear that the project is not just collecting data from a computer; there is a good deal of background knowledge and interaction in the field. Interesting observations include the fact that lumping the three classes together handicaps some of the forklifts because some are not designed for 10,000 hours, so the average lifetime for the population is decreased—but 50% are making it to 10,000 hours anyway. A full 20,000 hours is still needed for the economic case; it is not clear how many trucks have actually run that long.
- The project results have demonstrated a large payback to end users, with a refueling time of 2.5 minutes, which beats current industry standards and technologies. The inclusion of fueling times and operation times adds value to the data set. The results also show how the demands of MHE are evolving with respect to supporting infrastructure.
- The excellent continued progress in the overall project is reflected in the ninth published set of CDPs on performance, operation, and safety for MHE.
- The partners' cooperation in providing and evaluating the data is a key component for this project's great success.
- Continued updating of CDPs for fuel cell MHE and fueling infrastructure is noteworthy. The presentation slides included information about multiple metrics that are relevant in determining fuel cell progress and performance in MHE use. The substantial reduction in sites being reported on, following the completion of Recovery Act-funded projects, is a concern. The increase in total operation hours was noted. However, the

dramatic decrease in the number of operation hours being reported on per quarter seems to jeopardize the project's continued ability to provide statistically significant results for the MHE portion of the NFCTEC's work.

Question 4: Collaboration and coordination with other institutions

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

- There is some impressive collaboration with at least nine different companies, such as Air Products, FedEx, and Plug Power. The collaboration with these companies provides a high level of results and verification of data.
- The partners are clearly engaged, because they are providing data voluntarily, and they are essential to the project; there seems to be good back and forth for inputs and outputs.
- This group deserves kudos for its ability to negotiate and continue data collection past the original funding provided to MHE deployment projects.
- The project seems well coordinated and has excellent cooperation with relevant industrial partners such as users and suppliers of MHE.
- The project has shown excellent coordination with a variety of partners. The steady cooperation of industry has allowed a significant data set to be built. Other institutions could have been involved toward the end of the project to create new pathways of information dissemination.
- Slide 17 provides a list of data-sharing and analysis partners. It is unknown whether these organizations are all currently reporting. If they are, it is unclear why the number of operation hours being reported on has dropped so much in recent quarters. If they are not, then the appropriate metric for this evaluation criterion is whether current fuel cell providers and fuel cell MHE users return to reporting status.

Question 5: Proposed future work

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

- The project should continue collecting data on fueling behavior, including compressor performance. Allegedly the value proposition for MHE with a 20,000-hour life for a stack is important to reach. So far, the average is only 4,000 hours, with only one that lasted 16,000 hours.
- Future work includes ongoing data collection and analysis, beyond the scope and duration of the project, and a final report to showcase the project's accomplishments. Based on these data, the team could recommend a target for MHE life.
- Every task of the proposed future work is effective and important—especially the plans to access a much larger data set that includes many non-Recovery Act sites.
- Based on slide 19, NREL evidently recognizes the importance of working with industry to access a larger data set. This is viewed as critical to successful continuation of the project.
- This project goes year to year, which forces some ambiguity on future work; however, it would be good to see some kind of survey, workshop, or dialogue on what the partners are getting out of this and what they feel the gaps are—some kind of roadmap for possibilities for future analysis or ways to focus what is tabulated and reported.
- Future target areas beyond just stack life should be expanded.

Project strengths:

- NREL has developed a time-tested, well-designed, and effectively managed system for collection and analysis of fuel cell and hydrogen infrastructure data. The quality of NREL management and staff associated with the project is a project strength. The project presents excellent results and benefits for a DOE expenditure of $70,000–$100,000 annually.
- This is an excellent demonstration of DOE technology that has evolved commercially and successfully. This is a way to measure the performance and value of early hydrogen vehicles and fueling.
- Project strengths include the NREL staff's background knowledge and practical experience with the units, as well as the amount of data available to analyze.

- The voluntary data provided to NREL are outstanding and will continue to allow evaluation of critical MHE. This project does a good job of leveraging the evaluation of voluntary data collected.
- The project's strengths are the excellent research conducted and the close cooperation with fuel cell and hydrogen developers and end users.
- The level of detail is outstanding.

Project weaknesses:

- There has been a major reduction in data being reported subsequent to completion of the Recovery Act-funded projects. This results in questions about the project's ability to continue reporting on fuel cell MHE. Responses to questions following the project presentation indicated that information cannot be provided on the number of sites for which data are being reported to NREL, or on what percentage of total sites with fuel cell MHE operations are represented in the data being reported. No details were provided on DOE and NREL efforts to increase industry participation in future data reporting. Information was not provided to indicate the probability of success for such efforts.
- The project team needs to (1) provide an easy rubric to identify which report covers what topic and (2) match up in the presentation the areas of need to extend stack life.
- There is no assurance of how results will be disseminated beyond being posted on a website.

Recommendations for additions/deletions to project scope:

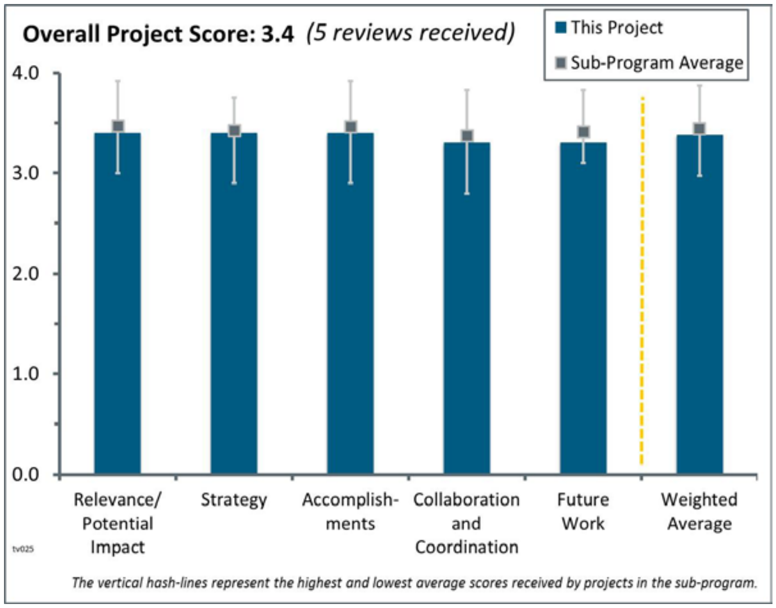
- The only recommendation is to convince companies with fuel cell MHE, fuel cell and MHE providers, and fueling infrastructure providers to participate in data reporting.
- The U.S. Postal Service would be an ideal data provider because the organization is government-funded anyway, so there should be no restriction on providing information. Also, it would be good to have a comparison of fast charge versus fuel cells.
- Continuing the data collection until 20,000 hours of operation should be considered.
- This project should consider how the resulting information will be disseminated. A partner, such as an MHE trade association or publication, could be brought in to assist.
- Technology changes have occurred on dispense pressures. The suggestion is to differentiate the old and new data and then reset the performance metrics accordingly. For example, the higher pressure may require a longer fill time, which would allow the MHE to be operated for a longer time before the next refill. It is unclear whether that combination equals what is being done today or whether the fuel cell product is outlasting the MHE equipment leases.

Project # TV-025: Performance Evaluation of Delivered Hydrogen Fueling Stations

Ted Barnes; Gas Technology Institute

Brief Summary of Project:

The goals of this project are to (1) collect performance data of real-world hydrogen delivery systems through data collection tools installed at California stations, (2) use the National Renewable Energy Laboratory (NREL) Hydrogen Station Data Templates to build aggregated data products and secure confidential data with the National Fuel Cell Technology Evaluation Center, and (3) provide useful data to accurately characterize stations' performance.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- Current and accurate data on hydrogen fueling infrastructure performance and costs is considered to be an important component of a comprehensive, complete fuel cell and hydrogen program. This project is expected to make a key contribution to the hydrogen station data sets developed by the U.S. Department of Energy (DOE) and NREL.
- This project will provide data from five stations that will help in validating the hydrogen infrastructure needed for fuel cell electric vehicles. Data from five stations is a significant addition to the current data set for validating the technology.
- Collecting actual, real-world fueling experience with liquid hydrogen delivery and gaseous hydrogen dispensing is essential.
- The project aligns well with the Hydrogen and Fuel Cells Program (the Program) barriers, namely the lack of real data availability.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project approach is straightforward, logical, and readily understood. The distribution of work to be accomplished by the Gas Technology Institute (GTI) and Linde was described well. Acquisition of data that conform with NREL's reporting requirements and templates is vital to project success. This seems to have been taken into account in the data acquisition planning. The presentation would have benefitted from a current timeline, showing the two budget periods and the go/no-go decision point.
- The project is well designed. The timing has been good to ensure that data collection will start when the stations begin operations. Further, there are enough data acquisition systems throughout the station to meet project objectives.
- The approach is well planned and reasonable for meeting goals and addressing barriers.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project has made good progress since the last Program Annual Merit Review (AMR). The charts on slides 7 and 8 are excellent and clearly show the current status of each station. Data are now being provided from the first station, and the second station is nearing completion. The project team is applying the lessons learned from the first station to improve the system and installation of the second station. This will, one hopes, speed up the process for the remaining three stations so that the data can be provided to NREL.
- The progress is on target. It seems that the communication between GTI and the stations has been very positive; the equipment has been installed without major incidents. The real accomplishment will be during the data acquisition process—ensuring that the equipment is well calibrated, works effectively, and provides reliable data without major downtime.
- The progress is good; the project seems to be a well-thought-out and well-implemented data collection regime.
- Slides 7 and 8 aid in quickly understanding the status of the five stations included in the project. However, it would have been helpful to add a date to slide 7 and to include a slide with information on the accomplishments since the previous AMR. After delays in permitting for multiple stations and commencing installation of the first station, there were significant project accomplishments: completion of the West Sacramento site data acquisition system and submission of initial quarterly data. There is evidence of real progress. However, it also seems clear that the project team needs to focus intensively on working with permitting authorities for the final three project sites.

Question 4: Collaboration and coordination with other institutions

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

- The project has excellent partners with well-defined roles.
- It is difficult as an outsider to assert that collaboration has been smooth, but it has been good enough to get the equipment installed and ready for data collection.
- GTI and Linde have significant expertise and experience that can be expected to result in a successful project. The description of the work to be done by each organization, as shown on slide 15, is helpful. Slides 13 and 14 each have some information that is not particularly relevant to the project being presented. GTI and Linde could likely cite other work in their portfolios that demonstrates capabilities more directly related to this effort. A slide showing the partnership/linkage with NREL would be appropriate for inclusion in the package and presentation.

Question 5: Proposed future work

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

- The future work plan is reasonable. It would be good to see all five stations up and running by the end of 2015. The project team should apply early learnings to speed up the process.
- What remains to be accomplished during the remainder of budget period 1 and budget period 2 is clear. For this criterion, however, a projected timeline would be useful, as would a graphic describing the potential impact of continued permitting delays. On slide 18, the statement “Installation at remaining 3 station sites possible before the end of 2015” is rather imprecise. It does not seem consistent with statements made during the presentation about the challenges of getting approvals for station construction.
- The proposed future work is fine. There is not very much to it—just finish installing the equipment in the new stations and start collecting data.

Project strengths:

- Project strengths include the experience and expertise of the project partners, GTI and Linde; coordination with NREL's National Fuel Cell Technology Evaluation Center; and 50% cost share. Excellent results and benefits are anticipated for total DOE funding of $400,000.
- The project is on target, has good technical expertise, and has good communication with stakeholders. It is difficult to improve anything here.
- The project has good partners with proven ability. Data from the five stations add to the performance database and help validate the technology. The project expands the station network for better coverage.
- The project has a good, experienced data collection team.

Project weaknesses:

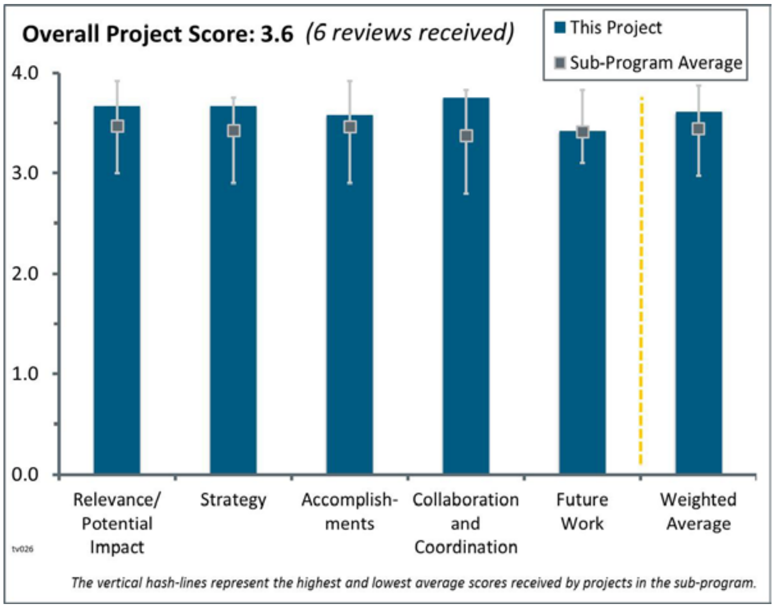
- The project does not appear to address cost barriers. Partners should document lessons learned for the industry to help with other station installations.
- Permitting issues have resulted in an extension of the project period. The project manager's attention is recommended to anticipate and resolve any issues that could result in further delays in project completion.

Recommendations for additions/deletions to project scope:

- There are no recommendations.
- The project partners should produce a report documenting the lessons learned to aid the industry in overcoming barriers for future hydrogen station installations.
- Perhaps data could be collected on liquid hydrogen boil-off rates, if the project is not already doing so.

Project # TV-026: Development of the Hydrogen Station Equipment Performance (HyStEP) Device

Terry Johnson; Sandia National Laboratories



Brief Summary of Project:

The overall objective of this project is to eliminate the need for multiple vehicle test fills by original equipment manufacturers (OEMs) to validate station performance through the use of a surrogate device operated by a testing agency. Development and implementation of the Hydrogen Station Equipment Performance (HyStEP) device will accelerate the lengthy commercial hydrogen station acceptance process and allow multiple levels of testing through a single mechanism.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- The project astutely links the U.S. Department of Energy (DOE) research, development, and demonstration objectives on codes and standards and technology validation in accelerating the validation process of hydrogen refueling stations (HRSs). The current HRS validation process is carried out in a serial fashion by the different OEMs, and HyStEP proposes to design, construct, and validate a device to measure hydrogen dispenser performance in a one-stop-shop manner for all OEMs, saving crucial time. In addition, the device is mounted in a trailer and can thus be moved as new stations are constructed.
- There is sound rationale for government support of this project. Objectives that contribute to the project's relevance include the following:
    - The design, prototype development, and validation of a device that can be used by government and independent testing organizations to ensure compliance of hydrogen stations with codes, standards, and protocols.
    - Achieving a reduction in the time required to measure hydrogen dispenser performance and complete requirements for acceptance of commercial hydrogen stations.
    - Assuming project success, a mobile device such as the one being developed could also be utilized for periodic checks on the performance and standards compliance of operational stations.
- This project addressees a critical barrier to successful deployment of fuel cell electric vehicles (FCEVs): readily available hydrogen infrastructure that can meet the needs of an FCEV fleet. While the project is quite limited in scope, it is addressing a key piece of the puzzle for the FCEV market. Indeed, the limited scope is somewhat of an advantage because it makes it easier to judge the project's success.
- If successful, the project will help shorten station acceptance and commissioning time. By aligning with SAE J2601 and CSA HGV 4.3, the project will also help standardize dispenser testing procedures.
- The project aligns very well with DOE Hydrogen and Fuel Cells Program goals and objectives.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.7** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project approach/work flow, as presented on slides 5 and 6, is straightforward, logical, and easy to understand. National laboratory personnel, government agencies, hydrogen fuel providers, and a fuel cell vehicle manufacturer are all contributing to the design of the test equipment. The one-year schedule for completion of project work, from equipment design through validation testing at the National Renewable Energy Laboratory and field testing in California, seems demanding (which is positive). However, a case could be made to hold off validation testing of the device until revision of the CSA HGV 4.3 test method is completed later in 2015.
- The project follows a logical sequence of tasks, starting with design development and review (go/no-go decision), fabrication of the device, and testing and final validation in two HRSs (one identified). The team did a good job of analyzing the critical issues and thinking through ways to overcome those issues. The future of the project after funding from DOE expires is advanced; a task force for technology transfer was put in place, and the final trailer will validate stations in California for two years starting in the fourth quarter of 2015.
- This project seems to have been very well designed to tackle this issue in a very short time frame. The timeline has been very aggressive but appears to have mostly been successful, although it seems highly unlikely the project will meet the August milestone. If anything, the schedule should be allowed to slip a small degree if needed because of delays from the fabrication stage, rather than rushing through the milestones needed to prove out this design.
- The project has a well-defined approach. The project shows good flexibility for ease of system modification as new standards evolve.
- The project has been well planned and conducted.
- One challenge is the CSA HGV 4.3 is not finished, but the MC Formula fill is going to be part of SAE J2601—they do not have to be identified separately, but can be.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- A good amount of work was accomplished in the first six months—project halftime. Initial specifications, components and equipment lists (mechanical and electrical), and the software development are progressing quickly, in accordance with a rather ambitious calendar. The robustness of the hardware is key for the mobility of the device. The team is developing a user-friendly and highly automated software interface so that its operation by technicians is simple. Scheduling may become an issue. The team must catch up quickly following the two-week delay or the final validation at HRSs will be at severe risk. In addition, the concurrent definition of the standard may lead to last-minute adjustments to the device, and there is limited cushion time in the project Gantt chart.
- The accomplishments, as presented in slides 7 through 12, indicate that design considerations, safety issues, equipment options, components, and software have all been thoroughly and efficiently addressed. Backup slides provide additional evidence of significant accomplishments in a relatively brief time period. In compliance with an aggressive schedule, the go/no-go criteria for moving on to device fabrication were met in March 2015.
- The project's milestones, schedule, and status checks are clear and show it is on track. The team has made good use of failure mode, effects, and criticality analysis to identify risks and mitigation options.
- The project has been well designed, and progress overall seems to be very impressive.
- Significant progress has been made, especially on the design and safety evaluation of the device. It is not clear how much progress the team has made on acceptance criteria.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The project partners have significant expertise and experience, which can be expected to result in a successful project. The description of each organization's role, as shown on slide 14, is helpful. Powertech Labs seems well qualified to accomplish fabrication of the HyStEP device. Slide 27, a reviewer-only slide, notes that ultimate success of the device will require its acceptance as a "surrogate FCEV" by hydrogen station providers and FCEV OEMs. DOE and the project team are encouraged to engage other stakeholders as soon as possible, as also indicated on that slide. Minimal cost share is provided for this project by industry stakeholders.
- The project includes partnerships with all actors involved with HRSs: an OEM, utilities, an HRS constructor, a regional agency, and a tank manufacturer. That gives reassurance on the project's soundness and continuity beyond the formal contract duration. The design will be public and available at no cost so that similar teams can replicate and use the device.
- The project features an excellent mix of national laboratories, state agencies, OEMs, standardization groups, and private funding.
- The project features excellent collaboration with appropriate organizations/companies.
- Overall, the collaboration and coordination appear to be good. It was concerning that it was not clear if all the automakers were engaged with this process, because only Toyota was listed as a partner, but from subsequent conversations, it appears the other OEMs are involved. Obviously having OEM buy-in is critical.

Question 5: Proposed future work

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

- Slide 16 succinctly and clearly summarizes the steps required to complete the project, the month associated with the completion of each step, and the responsible organizations. In a reviewer-only slide and in his presentation, Mr. Johnson noted that making the remaining go/no-go decision by August 31st is an issue; in response to a question, he stated it will probably occur at the end of September. As long as an extension is at no cost, it may be prudent to synch completion of this project with publication of the revised CSA HGV 4.3 test method. A task force is working on a plan for acquiring and operating the HyStEP device in California beginning in the last quarter of 2015. There is no indication in the presentation that funding will be requested from DOE to support this continuing effort.
- The project team is well aware of the challenges ahead, which mostly relate to the schedule and software. However, the uncertainties on the final version of the standard may push the project outside the initial calendar. The contingency plan is so far to keep the tool "flexible" so that the final development of the standard will be quickly exchanged to the project, because some of the partners are members of the CSA committee. A project extension for a few (maximum of two) months may be needed to get a functional and updated device.
- The project timeline is very tight and is likely to slip. It would seem wise to allow some small slippage rather than rush the testing and validation. Also, there is a need to ensure this device will indeed be accepted by the parties responsible for the safety of the dispenser. Work is being done on this, but it would be helpful to know more about the proposed pathway to having this device used and accepted as stations are being built out. In addition, it is not clear what the plan is if the device simply fails to work in the predeployment testing. It is not clear whether there is funding to go back to work out why, and to possibly make some tweaks with the design or refabricate the device.
- It is not clear whether the project team has a backup station for testing the device at a hydrogen station. Station implementation is typically delayed—Anaheim may not be an exception. The device can also be used for medium-duty FCEV testing with capacities up to 9.3 kg—a DOE-funded vehicle class.
- Completion of the remaining proposed tasks is important, although it may be difficult to meet the tight schedule.
- The team understands the risks with the aggressive schedule.

Project strengths:

- The project team has done an excellent job of utilizing the appropriate standards to design this device and appears to have done a good job of ensuring the device being built will work and be accepted by the OEMs. It has also kept on a very tight timeline, apparently without affecting the quality of outcomes.
- A project strength is that a well-engineered test device for station performance is being worked on by a collaboration of stakeholders. In addition, the design of HyStEP will be made publicly available.
- The experience, expertise, and varied perspectives of the project partners are areas of strength. The project team has a track record of on-time project accomplishments to date.
- Strengths include the project's clear goal and outstanding collaboration. The project team appears to have the right people and skill sets in place.
- This project has been well planned and features an excellent and experienced team to design, manufacture, and test the HyStEP device.
- Project strengths include the excellent consortium and ownership and a good technical approach.

Project weaknesses:

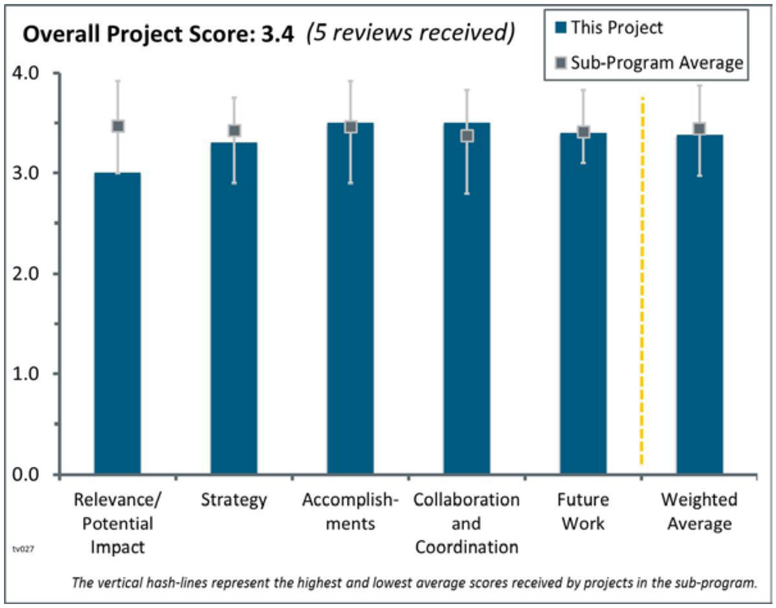
- The project has no significant weaknesses.
- The biggest remaining concern is that it is not clear who bears responsibility for anything that goes wrong with the dispenser at the station. This is important because the responsible party must be comfortable with whether the HyStEP device is acceptable as a means to validate the station. This is being addressed by stakeholders in the FCEV sector, but it does leave open the possibility that this device will not be accepted, no matter how valid it appears from the project tests. The other major weakness involves what would happen if the fabricated device fails in predeployment testing. It is not clear what the plan is if the device simply does not work.
- There is no commercialization plan for the HyStEP device. It is not clear what the demand for such a device is or who would buy it, besides maybe the California Air Resources Board.
- Weaknesses include the potential changing standardization requirements (CSA HGV 4.3) and revision of SAE J2601 with the MC Formula fueling protocol.
- Minimal cost share is being provided by industry stakeholders.
- The schedule is a weakness.

Recommendations for additions/deletions to project scope:

- Funding should be considered toward the building of a second HyStEP device—with one on-road accident, there is no station performance testing device available in the United States. The team should consider how this device can be used without equipment modifications to test stations for fill performance of medium-duty FCEVs with capacity of up to 9–10 kg.
- A case could be made to hold off testing until revision of the CSA HGV 4.3 test method is completed later in 2015. Mr. Johnson stated, however, that completing the project in advance of final determinations on the test method should not be an issue, because personnel working on the project are also involved with the test method development. A reviewer-only slide indicates that flexibility will be built into the device's software. No additions or deletions to the project scope are recommended.
- It would be good to see the plan for ensuring this device is in fact used in station deployment once it is handed over to state agencies.
- This project should be given a contract extension to ensure the delivery of a functional and updated device.
- The team should ensure other OEMs are in the loop regarding project progress, perhaps through SAE.

Project # TV-027: Station Operational Status System (SOSS) 3.0 Upgrade

Ben Xiong; California Fuel Cell Partnership



Brief Summary of Project:

The overall objective of this project is to upgrade the Station Operational Status System (SOSS) data system to improve user interfaces and data quality and to increase data transmission intervals between stations and data sharing capabilities. The SOSS will enhance access to hydrogen fueling station status information as well as the frequency and quality of the data available, ultimately to allow real-time access to stations' operational data.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The project supports the Hydrogen and Fuel Cells Program in the area of hydrogen refueling stations (HRS) by making the fuel cell electric vehicle (FCEV) refueling a better experience for the drivers by informing them of the station status (i.e., online, limited, or offline) at both 350 and 700 bars.
- The project addresses the barrier of public acceptance. A mobile app makes it easier to plan for fueling vehicles, which is extremely important for customer satisfaction. The data is consistent across all stations, which makes it easier for a customer to understand where to go for fuel.
- As the number of operational FCEVs grows, the value and importance of readily accessible information on hydrogen refueling availability will increase. This initiative could have a key role in development and refinement of a system that provides accurate and current information for FCEV users. In the overall context of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, this project will not contribute to achieving FCTO targets and goals for fuel cell and hydrogen infrastructure technologies. However, it could contribute to the more rapid acceptance of developed technology by vehicle consumers, particularly early adopters. It seems that the potential impact of this initiative may be competing to some extent with activities being undertaken in parallel by other organizations (e.g., individual original equipment manufacturers [OEMs]) that have similar and/or related objectives.
- The project will help improve the customer experience when refueling, but this does not seem to be non-commercial work. Automotive manufacturers and hydrogen station owners should be paying for the development of the system. The role of the U.S. Department of Energy (DOE) is to accelerate the introduction of alternative vehicle technologies, but at the point when users need a system to tell them where they can refuel their vehicles, it seems that the vehicles and the stations are already at the commercial stage.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.3** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The approach is reasonable and steps up to add more functions as each phase is completed. The SOSS is well designed and easy to understand—it uses colors and shapes to help users identify a station's status quickly. Integration with all stations is essential for the success of the project. The consistency of the reporting and definitions is excellent.
- The project approach is good. With time passing, the first HRSs are now equipped with data loggers/transmitters to make the app active and representative of the HRSs publicly available (90% of all public HRSs adhere to the project). The project is now focusing on early planning and integration of the additional equipment from design and construction of the new HRSs deployed in the territory.
- The phased approach to the SOSS project is logical and straightforward. The overall objectives of the current Phase 2 (e.g., reporting interval of 15 minutes or less) are clearly stated on slide 4. The presentation did not include details associated with a Phase 2 work plan, a list of work elements, or a time line for completion of project activities.
- The system does address the barriers outlined by the presenter—namely, integration of complex systems and the lack of hydrogen refueling infrastructure performance and availability data. However, much of the information still needs to be put into the system manually.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- Noteworthy accomplishments are documented in the slides and were discussed during the oral presentation. These include the (1) improved user interface (slide 7) and (2) additional information on hydrogen station operational status (slide 8). During his presentation, Mr. Xiong stated that 90% of the operating hydrogen stations (presumably those in California) are providing data to the SOSS. This was confirmed in his response to a question.
- The project managed to gather data from nine HRSs, which accounts for nearly all public HRSs in the United States. All FCEV manufacturers have opened their customer interface for onboard screen integration. The app is functional, easy to use on phones, and includes location features with Google Maps.
- The project is making excellent progress with the development and improvements of the SOSS. Each improvement builds on the base and adds functionality. The team is working with most stations to add real-time data that is automatically updated. This is critical to make the tool useful for drivers.
- It is good that the principal investigators (PIs) were able to get >90% of station owners to participate in the program. However, with so few stations out there, it is important to get everyone on board. That is the only way this project can be effective, particularly for people who live or work near one of the stations that is not participating. The other issue is that the PI mentioned that some car companies will develop their own status system—this indicates that the issue is no longer pre-commercial, and that perhaps station owners will be asked to choose one system over another or to implement more than one reporting system.

Question 4: Collaboration and coordination with other institutions

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

- This project is supported by members of the California Fuel Cell Partnership. As indicated on slide 11, many are providing inputs—such as criteria, requirements, and definitions development—for SOSS design and improvement.
- All HRS operators and FCEV car manufacturers collaborated in the project. The app has the potential to cover all HRSs worldwide, acting as a unique repository.

- The team is working closely with fuel providers, station owners, and customers to develop the tool. Using customer feedback to further improve functionality is a great feature of the project.
- The stakeholder engagement seems adequate.

Question 5: Proposed future work

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

- The project features an excellent plan for future improvements to the SOSS. Real-time reporting is essential for the accuracy of information on station status. Moving to an actual app should also improve functionality.
- The project was successful in demonstrating its technology and economic value. Continuing the project should be mandatory, and continuing the data feed without DOE funding should be considered.
- Slide 13 suggests that significant additional work (Phase 3) will be required to fully achieve SOSS objectives.
    - Slides 14 and 15 outline a number of future work elements and activities. However, specific information is not provided on project duration (for the remainder of Phase 2 and Phase 3) or projected costs.
    - Evidently, the portion of Phase 2 work supported by DOE funds has been completed (see slide 2). During the presentation, there was no mention of additional DOE funds for continued activity.
- The proposed future work includes the logical steps to continue the project—engage new stations, improve the software, etc. The project should also include getting the OEMs and station owners to pay for the system.

Project strengths:

- The project has been supported, through both financial resources and partner inputs, by the members of the California Fuel Cell Partnership. Results from the project should provide useful information for FCEV operators, leading to reduced anxiety about the availability of hydrogen fuel. DOE's expenditure of $155,000 is reasonable, given the expected benefits.
- Creating a mobile website or app to provide real-time station status data is an excellent way to increase station use and customer satisfaction, and to help the industry commercialize FCEVs. The project lead is committed to gaining access to all public stations.
- Project strengths include the system's adaptability to different HRS configuration and its integration to existing HRS equipment, as well as the project's early planning for HRSs under development.
- The project features good engagement of station owners, although this could be improved by integrating 100% of station owners because there are so few stations.

Project weaknesses:

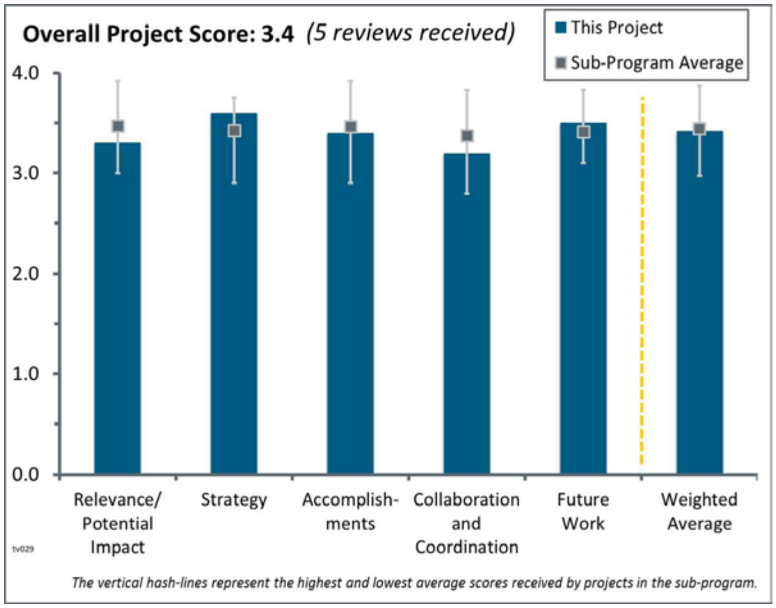
- A project weakness is the lack of specificity (e.g., work plans, work elements, or timelines) associated with the project approach and proposed future plans. The project could potentially be duplicating, or at least insufficiently coordinating with, other initiatives. (This observation is based on a brief discussion after the presentation.)
- To fully reflect the hydrogen coverage available in the area, all public stations should be included. The team needs to do everything possible to gain access to all stations. There may be difficulties in doing this that are beyond the project scope (e.g., adding equipment to a station to allow real-time monitoring).
- The project is focusing on getting real-time data, whereas other interesting information on waiting time for hydrogen availability or the typical busiest refill times may help drivers decide where and when to refuel.
- The system still relies on a lot of manual input.

Recommendations for additions/deletions to project scope:

- The team should include customer satisfaction feedback on the app design, the level of information, and the assessment of new data to be included (customer satisfaction and recommendations). The project should also include a count on app usage and daily visits to allow the app's effectiveness to be measured.
- In the event that funding from DOE is requested for further SOSS development, such as Phase III, FCTO should consider funding no more than 25% of the requirement. DOE is one of many California Fuel Cell Partnership members; future SOSS funding should be divided more evenly between government and industry members.
- The project team should address any issues with stations that cannot be added. If new equipment is needed, the team should reach out to funding organizations to cover these expenses.
- The project should get OEMs and station owners to pay for the development of the system and develop an app.

Project # TV-029: Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump

Salvador Aceves; Lawrence Livermore National Laboratory



Brief Summary of Project:

This project is testing a new generation of cryogenic pressure vessels equipped with liquid hydrogen pumps to develop compact, lightweight systems with long-term durability and high refuel density. Cryogenic pressurized storage has the potential to meet challenging U.S. Department of Energy (DOE) goals for improving long-term hydrogen storage while building infrastructure performance data.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- The project certainly supports the Technology Validation sub-program efforts, Hydrogen and Fuel Cells Program goals, and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP). In particular, the effort supports research and development on high-pressure gas storage. The project is “hybrid” in nature because it is a combination of efforts supported by technology validation, storage, and delivery.
- Advances in cryogenic pressure vessels that can increase 700 bar (liquid) hydrogen storage for increased driving range while decreasing overall weight are part of the MYRDDP goals.
- This project has the potential to boost hydrogen density to meet DOE targets.
- The project fully supports progress toward DOE goals in terms of onboard hydrogen storage. The MYRDDP targets 5.5 wt.% hydrogen by 2020, while the system under development aims for 9%, thus surpassing the 2020 target much earlier. The impact is hampered because this accomplishment is shared with ST-111, which has roughly the same scope and achievements.
- The project is a logical extension of a storage concept that has been under development for many years. The goals of the project are relevant but may be obsolete if industry (beyond BMW) does not pick up the technology.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.6** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- This approach is a very useful attempt to obtain higher tank volumetric capacity than commercial ambient temperature tanks by using cryogenic gas containment. The effort centers on building, testing, optimizing, and validating a newly designed working tank. Work will also be done on an innovative liquid hydrogen pump. In summary, the approach and project results will be useful to DOE and fuel cell electric vehicle (FCEV) manufacturers.

- All the right steps have been taken to ensure the safe development and testing of both the cryo-compressed tank and the refueling facility. The innovative liquid hydrogen pump has been developed outside the project and is being integrated in the dispenser and tank system in the context of this project.
- The project approach is good. Coupling the performance test of the high-pressure vessel and the liquid hydrogen pump makes good use of resources and expertise.
- The project features a nice approach to designing and applying high stress to the thin-lined cryogenic pressure vessel.
- The project approach is logically laid out and has an excellent chance of successful completion.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project team deserves praise for all of the work it did to get the approvals for the cryogenic hydrogen pressure vessel test facility with the American Society of Mechanical Engineers (ASME)-rated containment vessel for non-certified vessels.
- The project is well advanced in surpassing DOE goals. Important testing facilities have been built and are ready for operation for this or future tests.
- Results from testing the 700 bar vessel with liquid nitrogen shows the team has made progress. The team made good use of the mass flow meter with the pump to get data on boil-off rates.
- With the project halfway through its three-year planned duration, the team has made much useful progress and generated a substantial amount of operational data. Cryogenic storage offers 10% volume and 20% weight improvements over conventional compressed hydrogen storage. A very nice test facility has been built at Lawrence Livermore National Laboratory (LLNL). It will surely be useful for other DOE tank testing activities. The safety analysis of the test facility has been very thorough and is a model for the required DOE safety reporting. It would be desirable to have estimates of the increased cost of the cryogenic tank and data on dormant retention time. In response to a question, the principal investigator indicated that a full tank would start venting in about one day (worst-case scenario).
- The achievements to date are good but should be accelerating now that the safety plan and (some) of the project has been completed. While a 100-page safety plan may be comprehensive, there is a possibility that it can create an unnecessarily high bar for others seeking to do similar work. While one cannot be too safe, one can be too cautious and unnecessarily costly.

Question 4: Collaboration and coordination with other institutions

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

- The project features an excellent mix of partners representing vehicle, industrial gas, tank supplier, and national laboratory entities. The Safety Plan review by the DOE Safety Panel, resulting in a request for use as a sample plan, demonstrates the quality work done by the project team.
- The work clearly demonstrates that all of the partners (e.g., Spenser Composites, Linde, and BMW) are working closely together with LLNL. Also, all or most of them were represented at the presentation.
- The collaborative partners on the project are very well chosen for their relevance and ability to contribute.
- There are three important partners: Spencer Composites, Linde, and BMW. They seem to be contributing very well to the overall effort. More vehicle original equipment manufacturer input would be desired, in particular to answer the question of whether the increased volumetric hydrogen density is really worth the added cost and complexity of a cryogenic system.
- No information was provided in terms of any collaboration with institutions outside the current consortium.

Question 5: Proposed future work

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

- Cryogenic cyclability is key and will be tested for 1,500 cycles. Also, the durability of the liquid hydrogen pump will be tested and verified. The proposed future work includes a clear list of valid milestones.
- The future tasks are well defined and have a clear go/no-go decision point.
- The future work outlined is fine and certainly needed. There are some desirable additions that can be made to the planned future work.

Project strengths:

- The project team appears to have a good understanding of the challenges and the tasks needed to overcome these challenges.
- A project strength is the complementary expertise of the project partners that work closely together.
- This is an excellent hands-on testing and safety effort.

Project weaknesses:

- The present effort is to establish hydrogen refueling stations dispensing gaseous hydrogen at 350 or 700 bar. The dispensing of liquid hydrogen would need additional investments that would be difficult to expect in the short term. Niche markets within the hydrogen FCEV (already) niche market would need to be found.
- The convincing demonstration for the need for cryogenic storage is not evident. It is not clear whether 10%–20% is adequate to justify the additional cost and complexity of cryogenic containment.
- A project weakness is the lack of a broader liquid hydrogen research community and stakeholders to share and build knowledge to advance the technology.

Recommendations for additions/deletions to project scope:

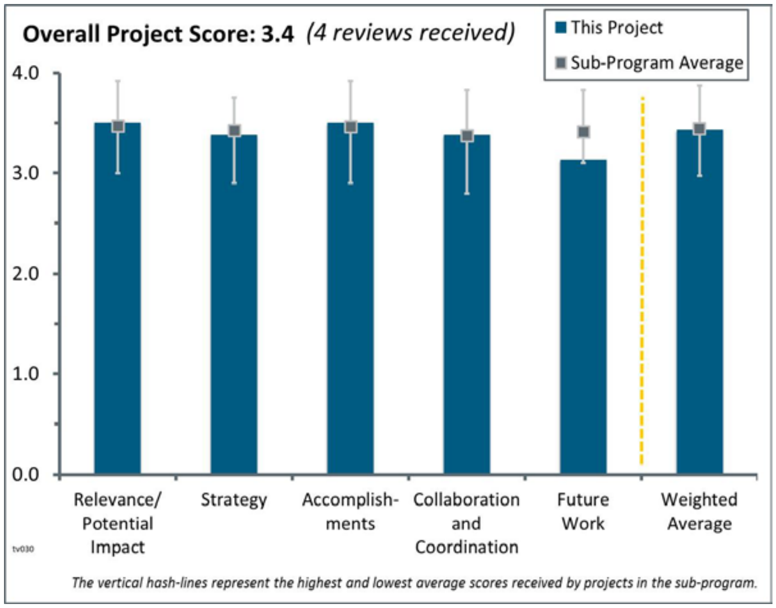
- The differences in scope and achievements of this project and ST-111 are not at all clear; a number of them appear in both PowerPoint presentations. DOE should make sure that work performed is not charged twice (i.e., in both projects). More emphasis should be put on collaborating with institutions outside the consortium.
- The specific performance benchmarks can be more fully specified. For instance, cryo pump degradation over a time period is not specified, and acceptable/anticipated heat leaking into the thinly insulated vessel is not specified. In addition, the cost of the system is not addressed.
- As long as the vessel the project team is preparing to test is not certified by any independent method, standard, or known body, any references to a vessel not certified by organizations such as ASME, the U.S. Department of Transportation, and the International Organization for Standardization should be removed.
- There should be more detailed analyses of economics and pressure excursions during dormancy.

Project # TV-030: Fuel Cell Technologies Office INTEGRATE Stack Test Bed and Grid Interoperability

Kevin Harrison; National Renewable Energy Laboratory

Brief Summary of Project:

The Integrated Network Testbed for Energy Grid Research and Technology Experimentation (INTEGRATE) project studies megawatt-scale electrolyzer systems that can provide hydrogen for numerous end uses as well as energy storage and grid ancillary services. The goal of the project is to improve grid stability and enable higher penetrations of renewable electricity sources.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- Analysis of the new grid that incorporates distributed generation and renewables is very relevant both to the Hydrogen and Fuel Cells Program (the Program) and other U.S. Department of Energy (DOE)/Office of Energy Efficiency and Renewable Energy programs. New communications protocols can significantly advance the United States in this area. This project is also timely because many public utility commissions are rethinking the way that power is generated and transmitted, and they are considering distributed generation, stabilization, and efficiency. The project has the potential to create better understanding of how different systems perform in the new grid environment.
- This short project clearly supports progress toward the Program's goals and the objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. In particular, it represents a unique effort to adapt large electrolyzers to the grid in an efficient and synergistic manner, thus paving the way for better utilization of time-variable renewable energy sources (e.g., wind and solar).
- The project aligns well with the Program—especially with the research, development, and demonstration (RD&D) needs, which was pointed out at the 2014 Electrolytic Hydrogen Production Workshop—and it has the potential to advance progress toward DOE RD&D goals and objectives.
- This project aligns well with the Program's goals and objectives.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The approach is well thought-out. The main idea is to construct a testbed for large electrolyzers (open to industry) and to test electrolyzers relative to variable performance and regulation to the grid. The ability to achieve long-distance communication and monitoring is studied via a connection to Idaho National Laboratory (INL).
- The approach to build up an accessible, open, megawatt-scale testing laboratory seems to be an effective tool for testing the next-generation electrolyzer stacks and for optimizing balance-of-plant components.

- The approaches to performing the work are well conceived and defined.
- The project integrates electrolyzers into grid technologies to enable higher penetration of renewables, grid optimization, and efficiency improvements. It also seeks to improve communications for better controls and data, bringing together electricity, fuels, thermals, and data. While the information passes through utilities, there is no utility partner directly involved to enhance the project's focus and provide feedback.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The team made excellent progress by building up an electrolyzer stack testbed and establishing a real-time digital simulators (RTDS)-to-RTDS communications network between the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility and INL.
- The testbed was completed in a relatively short period of time, and large (i.e., 120–250 kW) Giner, Inc. and Proton OnSite electrolyzers were tested relative to the variable requirements for grid integration. Long-distance, rapid communication and monitoring were clearly demonstrated via a wide-area network. Many other useful details (e.g., hydrogen purity) were studied.
- Considering this is the first year of the project, it is impressive that the researchers have already demonstrated results in both electrolyzer technology and communications.
- The team has made excellent progress, especially in the development of a communications network.

Question 4: Collaboration and coordination with other institutions

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

- The project seems to be well coordinated and has excellent cooperation with relevant industrial partners and institutes.
- There have been excellent collaborations with Giner, Inc.; Proton OnSite; and INL.
- The project features excellent collaboration with two companies and one national laboratory.
- The project has some current partners within the industry. The researchers will interface with other programs to continue testing RTDS. The researchers could enhance this project by directly including a utility and an Independent Systems Operator to obtain feedback on what these entities are currently experiencing regarding incorporating renewables and what would be useful to them.

Question 5: Proposed future work

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

- The establishment of the communications network and data architecture, as well as the service analysis, potentially has the greatest value outside DOE. While the presentation slides focused on the future electrolyzer work, the presenter described additional RTDS work linking to other DOE projects and a utility.
- The proposed future work is good and important—especially the establishment of a megawatt-scale testbed for polymer electrolyte membrane (PEM) electrolyzer stacks.
- The proposed demonstration of control of the 120 kW electrolyzer stack testbed is appropriate for this project.
- The future work list is fine. It is not clear, however, whether that work can be completed with the remaining contract time. It is perhaps time to get other industrial organizations (e.g., utilities) involved in using the test facility.

Project strengths:

- This topic is closely linked to a very current topic of global interest—how energy is produced and delivered. It therefore has great potential impact. It also demonstrates how both hydrogen and fuel cell technologies are part of a broader clean energy system.
- The project features good, practical orientation. The results should help to stimulate the incorporation of variable alternative energy sources into the grid.
- The project features excellent research and good cooperation with industrial and institutional partners.
- The project has been well conducted and has achieved several significant accomplishments.

Project weaknesses:

- The project has no significant weaknesses.
- It is not clear the extent to which future funds will focus on electrolyzer technology versus data and communications.

Recommendations for additions/deletions to project scope:

- The project scope should include a utility partner and perhaps other entities outside DOE involved with energy generation and distribution. The scope and funding of the project should be increased to provide a broader impact.
- DOE should provide support to NREL to increase the opportunity of the test platform for large-scale testing in the real megawatt scale.
- It would be of value to continue the contract beyond the project's October 2015 close.

2015 — Safety, Codes and Standards
Summary of Annual Merit Review of the Safety, Codes and Standards Sub-Program

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

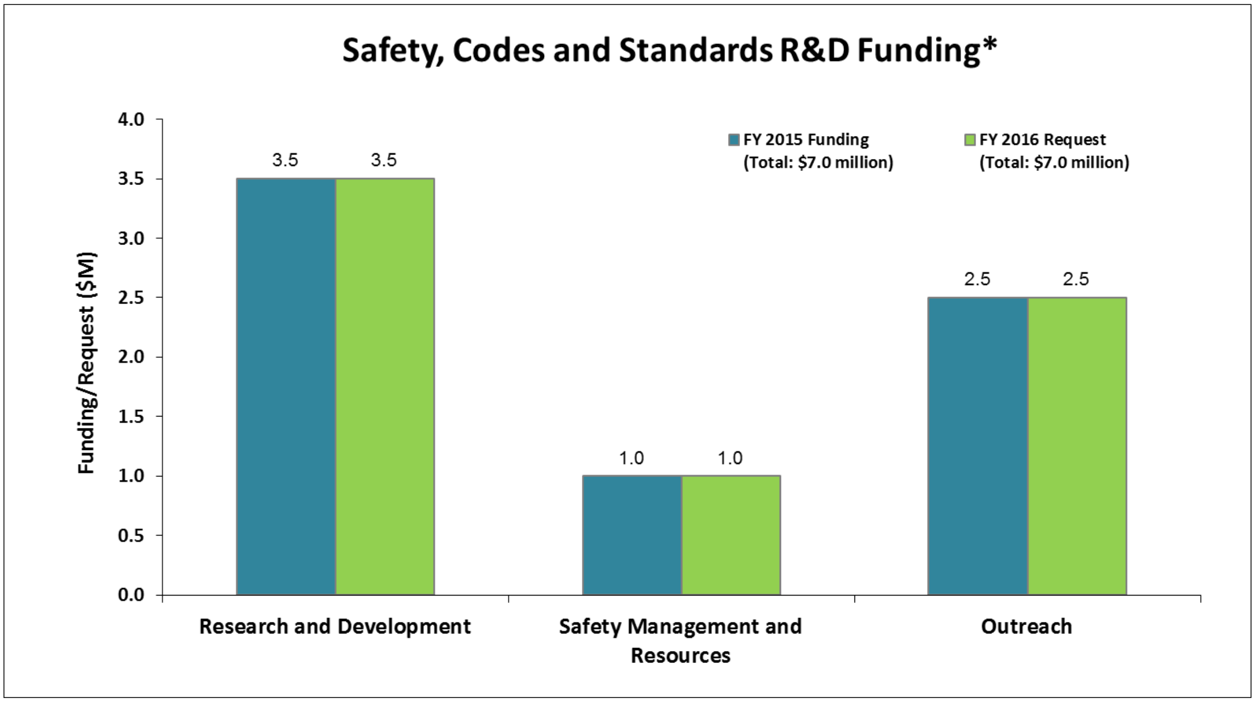
The Safety, Codes and Standards sub-program supports research and development (R&D) that provides the critical information needed to define requirements and close gaps in safety, codes, and standards to enable the safe use and handling of hydrogen and fuel cell technologies. The sub-program promotes safe practices among U.S. Department of Energy (DOE) projects and develops safety-related information resources and best practices. Reviewers stated that this sub-program is essential to the overall development of hydrogen and fuel cell technologies. Reviewers praised the sub-program's overall approach of starting with fundamental science, using that knowledge base to develop models and tools, and disseminating those resources to end users. They observed that the sub-program has transitioned to a more comprehensive and balanced approach from an R&D-focused effort.

As in prior years, reviewers praised the sub-program for its balanced and effective coordination with a wide variety of organizations, including national laboratories, standards development organizations (SDOs), and code development organizations (CDOs). Reviewers also commended the sub-program for its comprehensive approach to domestic and international issues, and especially for its international collaboration efforts. Reviewers agreed the sub-program appropriately prioritizes codes and standards and field validation, along with other critical issues. They commended the timeliness of the sub-program's efforts, especially with respect to outreach and information resources, and they credited this timeliness to the partnerships the sub-program has built with key stakeholders. Reviewers also applauded the sub-program's adaptability to the changing field, pointing out the Continuous Codes and Standards Improvement (CCSI) effort, as well as the long-term goals for alternative compliance methods. Several sub-program successes were also praised, including the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project, a new DOE Hydrogen and Fuel Cells Program record demonstrating a 50% reduction in separation distances, and a commercially ready hydrogen sensor.

Although reviewers commended the sub-program for its balanced work with both national laboratories and the private sector, they recommended better defining the roles of partner entities with similar capabilities. Reviewers also recommended the sub-program place a greater emphasis on hydrogen metering and indicated this is a key area in need of significant improvement. Other focus areas recommended by reviewers include advanced refueling protocols, stationary applications, coordination with the U.S. Department of Transportation on standards for bridges and tunnels, and other applications such as medium-duty or heavy-duty vehicles. In terms of outreach, reviewers recommended the sub-program seek new ways to report training data to allow for better evaluation of the impact of projects. Finally, reviewers commended the sub-program's vast international collaboration efforts and encouraged the sub-program to seek further international engagement at the R&D level.

Summary of Safety, Codes and Standards Funding:

The sub-program's fiscal year (FY) 2015 appropriation was $7 million, as shown in the chart on the following page. FY 2015 funding has allowed for continued support of codes-and-standards-related R&D and of the domestic and international collaboration and harmonization efforts for codes and standards needed to support the commercialization of hydrogen and fuel cell technologies. The FY 2016 request of $7 million will continue these efforts.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area.

Majority of Reviewer Comments and Recommendations:

In FY 2015, 12 Safety, Codes and Standards sub-program projects were reviewed, with a majority of the projects receiving positive feedback and strong scores. Reviewers' overall project scores ranged from 2.4 to 3.8, with an overall sub-program average score of 3.4.

R&D: Eight R&D projects were reviewed, earning an average score of 3.5. The highest-scoring project in this category received an average score of 3.8 and was the highest-scoring project for the entire Safety, Codes and Standards sub-program.

Sensors and Component R&D: Reviewers applauded the developments by sensor projects as well as the projects' collaboration efforts. They commented that sensor work is a critical issue and praised the focus on proper deployment. Reviewers commended the newly established component testing facilities, noting the potential for developing a hydrogen component knowledge base and the use of the facilities for work such as meter benchmarking. Reviewers recommended establishing a clear benchmark for operational wear of components and suggested further cooperation with industry and third-party testing laboratories. For sensor work, reviewers supported future plans for commercialization and recommended more focus on sensor installation guidance.

Hydrogen Behavior, Risk Assessment, and Materials Compatibility: Reviewers were impressed by the significant progress that has been made by all of the projects in this category and noted the critical importance of the work being done. They also commended the projects for their collaborations with the appropriate stakeholders. The reviewers praised the projects' efforts to close knowledge gaps in materials compatibility and recommended efforts to harmonize activities with work being done through the International Partnership for Hydrogen and Fuel Cells in the Economy. Reviewers praised the application of the developed modeling tools for validating alternative compliance methods and highlighted the potential for this use to contribute to further model development. They mentioned the potential difficulty in having performance-based designs accepted by authorities having jurisdiction (AHJs) and recommended demonstrating the results of a real case to encourage adoption. Reviewers also recommended continued efforts to expand models, such as for liquid hydrogen behavior.

Hydrogen Quality: Reviewers identified hydrogen quality work as a critical task that directly addresses needs expressed by the stakeholder community. Reviewers acknowledged these projects' efforts to consider consumer needs and to strive for a commercial application, as well as the demonstrated improvements over the previous year's work. Reviewers applauded projects' collaboration efforts, although they also encouraged further collaboration with CDOs and SDOs.

Safety Management and Resources: Two safety management and resources projects were reviewed, receiving an average score of 3.3. Reviewers commended the developed training resources and safety knowledge tools for their quality and innovation. Reviewers highlighted the value of the Hydrogen Safety Panel to the greater community and to DOE projects, noting that it leads to a general "safety culture." Reviewers praised the benefits of safety knowledge resources such as H2 Tools while also acknowledging the challenge of ensuring widespread deployment of these resources. Reviewers recommended that future work focus on expanding video resources.

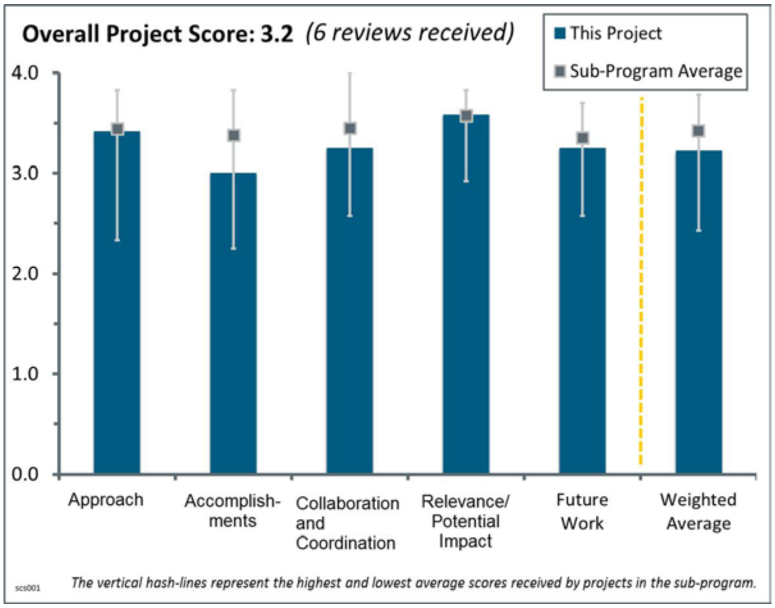
Outreach: Two outreach projects were reviewed, receiving an average score of 3.4. Reviewers agreed that the work to further codes and standards development and facilitate connectivity between stakeholders is critical. They described a forum for industry participation, such as that provided by the Fuel Cell and Hydrogen Energy Association, as relevant and providing valuable coordination. Reviewers applauded the projects' focus on domestic codes and standards, such as in the CCSI effort, as well as praised projects for acknowledging the importance of efforts beyond the completion of initial codes and standards. Reviewers encouraged further collaboration, including engagement of AHJs, to facilitate outreach and harmonization between similar code improvement projects to prevent redundancy and ensure success.

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

Carl Rivkin; National Renewable Energy Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- This project comprises two subprojects, with one focusing on development and deployment of national codes and standards and the second focusing on outreach and training for code officials and project developers. In both sub-projects, the approach is well chosen and effective— in particular the continuous codes and standards improvement (CCSI) approach as a structured mechanism for identifying and implementing needed improvements. The training approach also appears sound. For example, it is good to start from the point of view of end users in the development of the training video on hydrogen refueling station (HRS) permitting.
- The barriers are adequately addressed, and the project is well designed, feasible, and integrated with other efforts.
- The team also needs to pay attention to activities at ASME and American Society for Testing and Materials (ASTM) International. It is laudable that this team is more focused on the domestic codes, which are a critical path for the adoption of hydrogen, instead of the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) standards, which as a rule are not adopted by state governments or the federal government.
- CCSI as a specific project activity produces mixed feelings. The code process is one of continuous development and improvement accomplished through periodic revisit, review, and code modifications. It is not clear what is new and novel about this concept. This project is connected closely with the relevant code development organizations (CDOs) and standards development organizations (SDOs), and with the research and development community, at least at the national level. The principal investigator (PI) of this project is very knowledgeable about the CDO/SDO community. However, the PI can be much more successful by more broadly embracing teaming across the community. The outreach is good.
- The approach could more explicitly link the barriers with the project objectives and efforts. The intent of the project is clearly articulated, closely aligns with the intent of the barriers, and represents feasible project objectives. This project offers leadership and information dissemination on critical areas. The approach of continuous improvement acknowledges the completion of the initial code and standards development while identifying that further efforts are equally as important as the effort to initially develop these documents.
- The team takes a good approach, but it is unclear how much engagement with project developers has been accomplished. It is also unclear what the pathways are for getting feedback from this group.

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

This project was rated **3.0** for its accomplishments and progress.

- The degree to which progress has been made and measured against performance indicators is satisfactory. The degree to which the project has demonstrated progress toward DOE goals is also satisfactory.
- CCSI is a continuous process and typically delivers incremental progress toward multi-annual objectives. In 2015, important results of the training and outreach effort become tangible in a series of important documents, including the ”Hydrogen Technologies Safety Guide,” the “Guide to Permitting Hydrogen Motor Fuel Dispensing Facilities” (which is expected to be published soon), and the HRS permitting video (which is expected later in the year).
- The permitting video and the animation are very helpful references for the community. These are outstanding accomplishments. The “Guide to Permitting Hydrogen Motor Fuel Dispensing Facilities” and “Hydrogen Technologies Safety Guide” documents seem poorly executed. This reviewer has interviewed several key contacts within the hydrogen community, and none were aware of or consulted on these documents. It is very problematic to have DOE or its representatives provide documentation for public use that is not sufficiently vetted by the industry that will be affected. It is counterproductive to the Fuel Cell Technologies Office (FCTO) mission and disables, rather than enables, national and international markets by providing inconsistent or potentially incorrect regulations, codes, and standards (RCS) information. This project is frustrating in that it does some things very well, with lots of creativity, but it does other things poorly, with aligning it to needs of the community. It is unclear whether there is a publication requirement within the laboratory that is driving the need to publish documents annually. It seems every year this group publishes 2–3 poorly vetted documents.
- The HRS permitting video appears to be comprehensive and will be very valuable. The plan for effective dissemination is unclear. The CCSI approach seems to be focused on one key finding (i.e., setbacks for liquid storage). It is unclear whether there is a comprehensive analysis that identifies all necessary codes and standards that might need to be addressed by CCSI. In general, it is a little difficult to evaluate progress from the presentation, especially with respect to the goals and project plan.
- The accomplishments to date are appropriate. Care and coordination is needed to avoid redundant work with other organizations (e.g., the Fuel Cell & Hydrogen Energy Association [FCHEA] and the California Fuel Cell Partnership [CaFCP]).
- This is a list of activities. The number of concrete accomplishments, as opposed to “work in progress” activities, is weak for this level of funding. This element of the project deserves a score of 2.5 because the concrete accomplishments were not clear. The video is being shot now—it is not complete. The script is complete; contracts were put in place in “early 2015” (fiscal year or calendar year 2015?). The video will be useful, but it is still a work in progress. The “Guide to Permitting Hydrogen Motor Fuel Dispensing Facilities” is in the review stage, so it is also a work in progress. The Telecommunications Industry Association document is “well on its way to completion,” so it is still a work in progress. Regarding codes and standards training, several in-person and web trainings have been completed, which is good. These trainings have received good feedback. The “Hydrogen Technologies Safety Guide” was published in January 2015, which is good. With regard to CCSI accomplishments on hydrogen component standards, meeting with CSA to discuss test plans, presenting the issue to the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project for review (when H2FIRST itself is partially an National Renewable Energy Laboratory [NREL] project) , and prioritizing standards are not concrete accomplishments. However, the list of training activities on slide 13 does signify concrete accomplishments and represents good output from this work.

Question 3: Collaboration and coordination with other institutions

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

- The degree to which the project interacts with other entities and projects is excellent.

- The coordination and collaboration are very good. It might be time to engage the state fire marshal and building inspector trade organizations to facilitate outreach to the states' authorities having jurisdiction (AHJs).
- The project interacts with all required stakeholders, from AHJs to developers and operators. It is actively present in various standardization teams. It can also rely on the pool of competencies available in the coordinated approach to safety, codes, and standards at NREL. It is, however, not clear how the NREL supports the various improvement teams, supports the work of the HCI–H_2 Code Improvement team (HSI) team, and coordinates and prioritizes the huge number of collaborations.
- The list of domestic collaborators is impressive and relevant to this work. However, this project needs to strengthen the collaboration and coordination with international organizations such as ISO. The answer provided by the PI to the ISO question posed last year is unsatisfying. The international code development activities draw on work from other international efforts, and the U.S. efforts draw from the international code development work. Indeed, many of the same people sit on these committees (international and domestic). For harmonization, it is critical that the U.S. code efforts and this project remain well connected and contribute to these international code efforts. The comment from the FY 2014 review is still appropriate.
- NREL has a strong list of collaborators, making the lack of insight into documents much more difficult to understand. It is not clear why this project seems so resistant to collaboration with the H2FIRST and H2 Tools projects. Since they are all funded by FCTO, the program should try to resolve this. Lack of full cooperation seems to be a persistent issue within FCTO and the laboratories.

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

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

- The CCSI approach is very important and timely, now that a first (almost complete) safety and standardization framework is in place. The concept of continuous improvement of codes is something that cannot be left to the initiative of individual industry players, and in this respect, these NREL activities are exemplary.
- The degree to which the project supports and advances progress toward Hydrogen and Fuel Cells Program goals and objectives delineated in the FCTO Multi-Year Research, Development, and Demonstration Plan is satisfactory and on target.
- There is no doubt this topic and the work of this project are directly relevant to the needs of hydrogen technologies deployment.
- This is a very relevant project, given the state of the technology.
- This is a critical path activity.
- This project has had a notable impact, but it could be much more impactful if it were more aligned with the overall mission of the FCTO SCS sub-program. It seems there are disparate groups of individuals working on separate topics, while the industry needs support from a team. The potential impact is much greater than the current impact.

Question 5: Proposed future work

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

- The project will end by September 30, 2015. The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points; considering barriers to its goals; and, when sensible, mitigating risk by providing alternate pathways is satisfactory.
- The proposed work is very good. It might be time to engage the state fire marshal and building inspector trade organizations to facilitate outreach to the states' AHJs.
- The proposed future work is a logical continuation of the effort started in previous year(s).
- It is not clear whether the liquid hydrogen work is connected to other liquid hydrogen work performed at Sandia National Laboratories, or whether this is another example of independent and often competitive

laboratory activities. It was mentioned at the review that NREL should consider hosting on-site visitors for training rather than traveling to only a few key geographic areas. Sometimes the greatest influencers in the fire community are not necessarily located in the key area. The fire community is well connected and capable of relaying information, especially from internal experts and training officials. NREL could and should be an expert in networking to find those individuals, maintaining a close relationship and providing hands-on experience at a real station, rather than "death by PowerPoint" training sessions in the key areas.

- The planned future work is as expected. No really "out of the box"-type of thinking was presented, which would have been good. This project has so much potential—the team just needs to embrace a true teaming approach with others.

Project strengths:

- This PI is extremely knowledgeable in this area and brings years of experience to the table. With that, this project and the PI are very valuable in helping to navigate the code world and successfully executing necessary code language implementation.
- This is a good project that fills needed gaps for meeting barriers. It will be good to see the permitting video. Overall, NREL is well equipped to provide this important work and build on existing collaborations.
- The CCSI approach and results are very timely and an important support to reach the overarching goals of the SCS sub-program.
- The knowledge, determination, and dedication of the staff on this activity are areas of strength.
- The outreach content and outreach expertise are areas of strength.
- The project adequately addresses the states' three barriers, stated in the presentation as (1) Insufficient Technical Data to Revise Standards, (2) Enabling National and International Markets Requires Consistent RCS, and (3) Safety Data and Information: Limited Access and Availability.).

Project weaknesses:

- The concrete achievements made during this reporting period are weak. The slides list a 2002 start date. This is clearly an error. The PI is seasoned in this specific field and has years of experience. This specific program has been funded for at least two years (FY 2014 and FY 2015), for a total of $700,000. The amount of concrete accomplishments is weak; most of what was discussed here represents work in progress. One clearly would have expected some work in progress accompanied by considerable concrete accomplishments. Holding meetings to "finalize …" is not an accomplishment, but an activity.
- The ambition of the project (i.e., the CCSI concept) and the very wide field in which it moves (e.g., from codes development to field assessment) does not seem proportional to the amount of funding received.
- Weaknesses include the lack of cooperation and a cohesive team within FCTO, as well as the lack of industry vetting.
- It might be time to engage the state fire marshal and building inspector trade organizations to facilitate outreach to the states' AHJs.
- The project appears to need a more comprehensive/cohesive work plan.

Recommendations for additions/deletions to project scope:

- This project needs to develop a teaming collaborative structure with other programs and projects working in this space, both domestically and internationally. It is concerning that several projects are working in this space with little to no coordination/collaboration between them. The problem of liquid hydrogen separation distances is such an example. These activities need to be led by industry, not a national laboratory. FCHEA TWG/HCTF might be the perfect place to provide a center of activity to help coordinate efforts on this issue. NREL could team with the HCTF, providing the wealth and breadth of expertise this PI and NREL have to that industry-led activity. To be successful, this project will need to collaborate and team with a diverse set of talents.
- Slide 12 states that "NREL supports CS through active participation in technical committees..."—it is not clear what this "support" really entails. The project interfaces with many other projects in the SCS sub-program. From a 10-minute presentation, it was not completely clear how this interface is coordinated. It would certainly help the evaluation of the impact and the assessment of project efficiency if in the coming

years, some time would be dedicated to explain the relationships between the CCSI, which is an NREL specialty, and the development in the field of NFPA, the Hydrogen Safety Panel, and other related activities. It would also be good to see some examples to understand how the various improvement requirements are ranked and tackled in a prioritized manner.

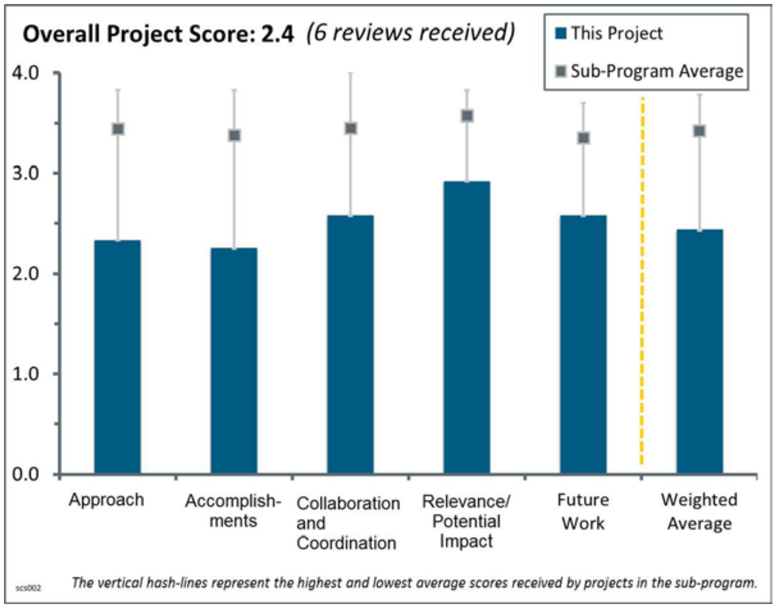
- It might be time to engage the state fire marshal and building inspector trade organizations to facilitate outreach to the states' AHJs.

Project # SCS-002: Component Standard Research and Development

Robert Burgess; National Renewable Energy Laboratory

Brief Summary of Project:

Safe deployment of hydrogen fuel cell technologies is dependent on components that are proven to perform safely and reliably as measured against new safety and performance standards. The goal of this project is to work with manufacturers, installers, and the National Renewable Energy Laboratory's (NREL's) Technology Validation program to prioritize gaps in safety and performance standards, and then work toward closing those gaps by conducting hydrogen component research and development and performance validation.



Question 1: Approach to performing the work

This project was rated **2.3** for its approach.

- The development of accelerated tests to evaluate material selection for the valve seat and seal may be useful.
- This review comments on two aspects of the project: dissemination of information to the community and methodology of obtaining failure data.
    - Iteration with the codes and standards community is important, but there was no concrete evidence where this actually has been done. It is critical to get this information out into the community; it is questionable whether technical reports are the most effective vehicle to disseminate results from this work. It would be good to also see this work published in refereed literature so it gets vetted by the community. The components workshop is very good as a communication vehicle. This work should be expanded.
    - As quantitative risk assessment (QRA) efforts are improved, data is needed on failure mechanisms and frequency (e.g., mean time between failures). This project should make sure it contributes to developing that database. The notion of "designing" components for failure in order to better understand failure mechanisms is a little curious. It is unclear how one designs for failure and still produces a component that represents the actual component used in service. In particular, one valve failure with which this reviewer is very familiar was a fatigue failure due to several factors, especially the hydrogen incompatible material. This failure is a materials issue, not a "component" issue. It is known that this was a mistake not intended by the original bill of materials. It is not clear how the components are being designed for failure in a realistic manner to provide new information, rather than simply doing so to create a failure in a domain that is already understood and/or putting the test specimen in a domain unrealistic for designed installations. Modifying a component for failure by changing the material to one that is susceptible to fatigue crack growth does not add to the understanding of failure mechanisms. However, the example given by the principal investigator (PI) of exposing a composite overwrapped pressure vessel (COPV) to a qualifying test when the COPV has been exposed to acid to see whether the qualifying test will fail the tank (as it should) is of value.
- The referenced report on pressure relief devices (PRDs) (*Pressure Relief Devices for High-Pressure Gaseous Storage Systems: Applicability to Hydrogen Technology*, http://www.nrel.gov/docs/fy14osti/60175.pdf) does not mention the current efforts at the Compressed Gas Association to remove PRDs from hydrogen and all other tube trailers. The "Unexpected Failure of

Rupture Disk on Liquid Hydrogen Tank" section on page 6 makes some confusing statements such as the "burst disk PRD ruptured prematurely when a cryogenic liquid hydrogen storage tank became slightly over-pressurized due to heating from ambient temperature. Investigation showed that the hydrogen piping was creating back pressure on the disk during manual venting, which caused the PRD to rupture below the set pressure." It is unclear how back pressure on the downstream side of the burst disk can create extra pressure on the process side. The laboratory testing of the PRD that was involved in the known valve failure is not being tested with pressure cycles and it is not clear why it is not being tested. This question was brought up, and the team seems to miss the point that these PRDs are on bank storage systems that experience daily pressure cycles.

- It is not clear why there is a need to replicate a known failure under laboratory conditions. The known failure involved improper part selection, not a misunderstanding of the underlying technical principles. The description of this project's approach is misleading. The project team attempted to fit testing of the failure into the broader suite of necessary evaluations (i.e., "Test Hierarchy" from slide 5)." It is not clear whether this effort is part of a larger hierarchy of improper part selection testing. For example, it is not clear whether the compressor check valves in the subcomponent laboratory testing use improper materials or improperly selected subcomponents, for the team just to see whether they will break.
- The test program does not appear to be vetted by the industry or correlate to real life. It would be advised that suppliers of hydrogen stations be contacted to update the plan.
- It is unclear whether the 70 MPa station was operational at the time of the presentation.

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

This project was rated **2.3** for its accomplishments and progress.

- It is nice to see the laboratory is up and running. The non-destructive inspection is good and will be valuable as this project continues. The PI also noted that destructive investigation/observation also needs to be performed to understand the failure mechanism. This project is funded at about 0.5 full-time equivalents (FTEs) for 2014 and about 0.3 FTEs for 2015. Even at this low level of funding, more concrete output is expected. However, the laboratory took a long time to get up and running, so the PI has not had a lot of time with a functioning laboratory to generate concrete output, which did not help. Regarding outreach, the component webinar is good.
- The accomplishments and progress may be appropriate; however, there is no clear goal or objective.
- It is not clear what the key performance indicators are for the project. It is also unclear how the team has reached the goals it previously set for itself. Besides some pictures of the test setup, it seems that no answers are provided. When questioned during the review, the PI had no answers or seemed too unfamiliar with the project to provide sufficient answers. This project, particularly by juxtaposition with tremendously beneficial projects such as the compressor durability work, casts a negative light on associated projects and should be considered for discontinuation. It is not clear why the metrology meeting only invited foreign private companies (e.g., Tatusuno and Iwatani), and why no U.S.-based or U.S.-operating companies participated. It is not clear how this benefits U.S. metrology efforts. The February webinar did not appear to add value. The open house seems to have provided little more than a networking opportunity. The proposed accomplishments have not achieved the stated objective (slide 3): "Successful deployment of hydrogen infrastructure will require components that are proven to meet existing safety standards."
- The purpose of slides 8–10 is unclear. The accomplishments stated in these slides seem to be that the test equipment is installed and the function and capabilities of the equipment. It appears this effort is more part of the approach for testing. It is good to see a CT scan is effective and non-destructive in identifying/inspecting/evaluating issues. When considering a relief valve nozzle, no indication or benchmark was provided for an acceptable level of operational and/or installation wear. It is unrealistic for the application environment (i.e., hydrogen fueling station) to expect no operational or installation wear for installed equipment. Regarding slide 13, the use of lower-pressure testing was attributed to the time needed to purge. However, for realistic accelerated test data, the project should consider using the pressures found in a 70 MPa station setting or explain how the resulting data correlates to 70 MPa station applications. The project team members should consider the relief valve failure reported in DOE's Safety Incident Database. The metrology collaboration event was good, but it was not clear why the California Department of Food

and Agriculture, Division of Measurement Standards was not involved. The team put forth good effort on the webinar and open house focused on hydrogen components.

- The testing of the known failed valve type spring-loaded safety relief valve needs to be conducted by pressure cycling. The thermal cycling approach currently used does not correctly simulate actual service conditions.
- Creation of a new CSA Group standard for pressure relief valves (PRVs) is advised, but this needs to be vetted with industry.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.6** for its collaboration and coordination.

- Collaboration with the National Institute of Standards and Technology and international partners on meter accuracy is a good investment of time and money.
- The team made a good effort to reach out to the right entities. However, third-party testing laboratories should be more closely involved (e.g., through joint efforts or side-by-side in-laboratory collaboration) with NREL's efforts (instead of only talking). This will build capability at these laboratories to do actual third-party testing. It will take more time before this knowledge is gained, potentially effectively delaying the process of third-party certification of components.
- The list of collaborators is impressive; however, it is not clear how the interaction with these collaborators actually works. It would be nice to understand how the talent from these collaborators makes its way into this project. The project features a good suite of collaborators, including Sandia National Laboratories (SNL), which is necessary to study fundamental material behavior. The Energy Systems Integration Facility is a designated user facility, which should encourage additional collaborators and coordination.
- There are several remaining questions concerning the project's collaboration and coordination: (1) what other institutions are participating in the PRV test; (2) what other institution has advised this team on the scientific approach it is taking; and (3) what participating industry partner will take the findings and improve products, thus "successfully deploying the infrastructure components" through the lessons learned in this project. This project is likely to succeed in failing this valve and will also, apparently, investigate an unintended valve failure. One or many reports are expected to be generated from this project. However, without industry, academic, and other collaborators providing input, this project may fail to provide information useful to industry. The team should consider stopping or reorganizing the effort before further time and effort is lost.
- It is unclear who the industry partners are on this project. The project team should speak with members of the relief valve industry. It is doubtful that the members have facilities to test at 15,000 psi with hydrogen.
- More collaboration is needed.

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

This project was rated **2.9** for its relevance/potential impact.

- The project team has done well in setting up the laboratories for testing components, and this work could provide great benefits.
- Data for testing hydrogen components is important for future third-party component certification—it supports commercialization.
- This is a very relevant project.
- With appropriate guidance to make sure the work actually provides unique information on failure mechanisms, the data generated will improve understanding of the failure mechanisms and provide data for safety, codes, and standards QRA activities.
- It is unclear how this project, as explained, would directly benefit industry. A reconsideration of the goals of this testing may be in order. As an example, this testing could be used to (1) evaluate seat/seal materials; or (2) determine the thermal cycle life for valves in hydrogen service for incorporation in the National Boiler Inspection Code.

- There are no industry participants, and there is no technical plan beyond testing PRVs. If this project is truly addressing all infrastructure components, it is not clear why the plan is not more comprehensive.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- Any successful work developing a master meter technology would be good; however, this seems like a challenging task.
- There is a short list of ideas, but there is no substance, collaboration, or basis. It appears that a similarly poorly planned test for nozzles and receptacles is under preparation. It is not clear (1) why this group did not publish a study that surveyed the most important components to evaluate and appropriate evaluation methodology(ies); (2) why this group did not consider various partners for testing the nozzle and receptacle; (3) who else might have done this work previously; (4) what nozzle modifications the stations and vehicle original equipment manufacturers (OEMs) are planning in the future; (5) what new nozzle designs are under consideration; or (6) why the researchers just assumed they could build a test fixture and take the Edisonian approach to getting some results—that is an irrelevant approach and is unfortunately consistent with this project.
- The focus of the future work needs to be on providing unique data to advance the understanding and to provide data relevant to QRA. This project has potential but attention must be given to performing test campaigns that will yield improved understanding of mechanisms, which would differentiate this effort from the fundamental materials science work that SNL performs.
- The proposed future nozzle/receptacle testing appears to be limited in scope, and it is not clear whether this is the best use of NREL's capabilities. More realistic wear-and-tear usage pattern testing or a method to do this instead may add more value for industry and commercialization in the long term.
- It is unclear where this activity might go. An end goal or interim objective is needed.
- The testing cycle needs to be representative of real-life events.

Project strengths:

- Strengths include the laboratory's testing ability and proper tooling to (1) develop and execute a thermal cycle test protocol to evaluate relief valves; and (2) test various combinations of set and seal materials for durability and functionality.
- Component reliability is important for the safe design of systems. This project has the potential to gather reliability data for use by the QRA community. It also has the potential to understand failure mechanisms to help component manufacturers improve their products.
- Component testing is important for commercialization. Other strengths include increasing hydrogen component understanding and improving the initial testing of components.

Project weaknesses:

- The approach of "designing" for failure will/could result in misleading conclusions or, worse yet, irrelevant data/conclusions. For example, replacing the material with a material that accelerates fatigue crack growth is a design change for failure, but it is irrelevant because a class of suitable materials for hydrogen use is known. In addition, this work will not yield fundamental information regarding the physics governing that phenomenon. SNL already performs that work. The project team needs to work closely with the teams already performing those investigations (SNL is a collaborator) rather than attempt to investigate that set of physics itself.
- There is limited in depth sharing of hands-on experience with testing. NREL is not using its capabilities to the full extent possible.
- The style of the known valve failure PRD should be tested with pressure cycles.
- The objective of the testing and the end use of the data are areas of weakness.

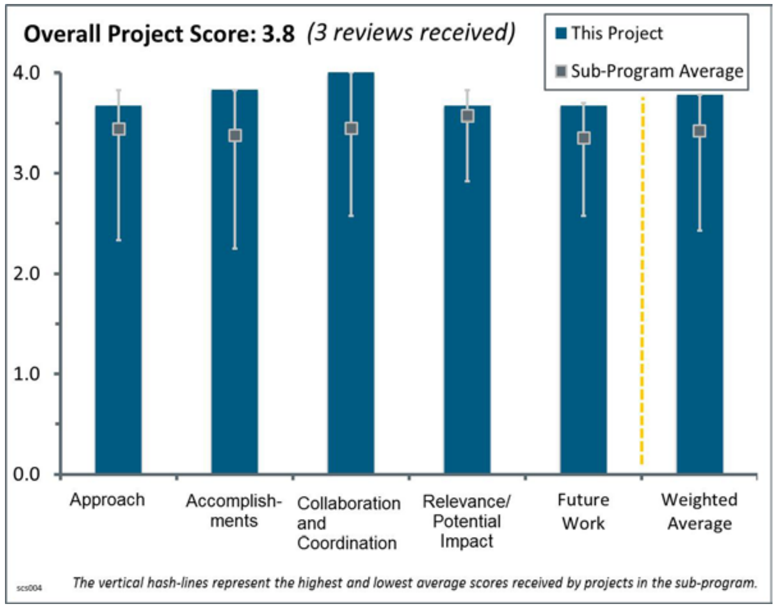
Recommendations for additions/deletions to project scope:

- The team should add an evaluation of nozzles/receptacles used in previous hydrogen station service (used at any pressure) to learn more about wear patterns in actual user environments. Examples of user environments from which to acquire nozzles/receptacles include forklift projects, fuel cell bus fueling projects, OEM vehicle testing grounds, etc. This could be a 1-to-1 exchange of equipment—one new piece of equipment for a used piece of equipment.
- It is suggested that NREL sit down with some industry members to develop a test program objective, determine specific data to collect, and identify an end-use location. The team should also include members from the relief valve industry, ASME, and possibly the National Board of Boiler Inspectors.
- FCTO should revisit the project's objectives and restart the project with a new direction.

Project # SCS-004: Hydrogen Safety, Codes and Standards: Sensors

Eric Brosha; Los Alamos National Laboratory

Brief Summary of Project:



The project objectives include the following: (1) development of a low-cost, durable, and reliable hydrogen safety sensor for stationary and infrastructure applications (extendable to vehicle protection) through material selection, sensor design, and electrochemical research and development; (2) demonstration of the working technology through performance evaluation in simulated laboratory and field test environments, rigorous life testing, and evaluation of sensor performance in relation to codes and standards with National Renewable Energy Laboratory (NREL) collaborators; (3) advancement toward commercialization by engaging appropriate industry partners, for activities such as long-term testing and development of manufacturing methods; and (4) pursuit of commercialization of the new sensor technology through industry partnerships.

Question 1: Approach to performing the work

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

- This project has been designed and executed well. During the last year, specifically, the approach to sensor packaging, field testing, and data analysis has been highly successful.
- The project has demonstrated significant improvements in terms of advancing the sensor technology and demonstrating reliability.
- This project is focused and directly applicable to hydrogen infrastructure.

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

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

- The field testing was a great success and allowed the team to identify a few deficiencies in the sensor system (mainly sensor communications). The sensor was found to be very sensitive to what was thought to be refueling leaks, which could be very valuable for new stations.
- The data supported the goal of developing hydrogen sensors with the appropriate response time, sensitivity, and accuracy for use in safety applications to reduce risk and help establish public confidence. The Safety, Codes and Standards (SCS) sub-program will develop hydrogen sensors with the appropriate response time, sensitivity, and accuracy for use in safety applications to reduce risk and help establish public confidence.
- The project team has conducted excellent work.

Question 3: Collaboration and coordination with other institutions

This project was rated **4.0** for its collaboration and coordination.

- The project had superb collaboration with government laboratories (i.e., NREL and Lawrence Livermore National Laboratory [LLNL], although LLNL is not funded in 2015) and the commercial sector, including with sensor packaging and field testing partners. The communication between the partners seemed excellent.
- The excellent collaboration between partners was demonstrated when an unanticipated need arose for additional data to support questions/concerns over sensing hydrogen and the partners were well suited to provide that data.
- The collaboration and coordination are appropriate for this point in the project.

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

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

- This system could provide a very low-cost, sensitive, and reliable hydrogen sensor for both stationary and vehicle applications, which is critical to the success of hydrogen fuel cell vehicles.
- Sensors are needed in many areas; this work shows good progress is being made to fill this industry need.
- This project is “spot on.”

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- The proposed future work is appropriate for the schedule of the project. The work involves continued data collection at the Burbank station to verify the excursions and incorporating lessons learned for sensor communications to increase data transmission reliability.
- The data gathering has shown/demonstrated the sensors are (1) responding as intended and (2) holding their calibration over a period of time.
- The next steps are toward commercialization, which makes sense.

Project strengths:

- There is good collaboration between partners. The team was able to gather and track data to identify and support sensor performance and provide confidence that the sensors placed in the field are performing well.
- The project’s successes are an area of strength.

Project weaknesses:

- A concern not necessarily related to the project, but to the sensor manufacturing itself, is that an exceptionally high percentage of sensors failed right out of the box. A general consumer would not accept this rate of failure for other products. Granted these are not “consumer” products, but the quality control for production should be higher than it appears to be based on the report/discussion.
- One weakness is the lack of funding to expand environmental testing (e.g., altitude at NREL; temperature at the Las Vegas and Ann Arbor sites which are or were Air Products and Chemicals Inc. sites). The team should try to generate interest from major instrument makers (e.g., MSA Safety Incorporated, United Technologies Corporation/Det-Tronics, and Scott Safety) regarding collaboration. The team should show these potential collaborators the field data.

Recommendations for additions/deletions to project scope:

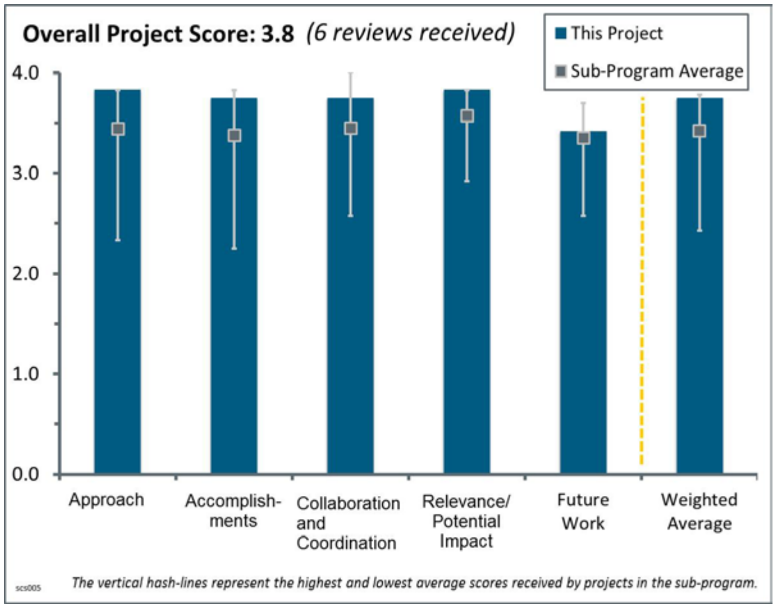
- Recommendations include adding environmental testing and discussions with major manufacturers to project scope.

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

Brian Somerday; Sandia National Laboratories

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- The U.S. Department of Energy (DOE) has engaged the best and brightest material scientists on this project, and these scientists are leading the efforts to establish new standards for measuring the hydrogen effect on steels.
- The approach is industry-approved and actively supported by ASME. The data will eventually make it into the ASME pressure technology codes and possibly the ASTM International test methods, if support for the project is continued.
- The focus on relevant data and improved test procedures to evaluate hydrogen fueling station components is timely because industry focus is currently shifting from vehicle regulations, codes, and standards (RCS) to infrastructure.
- The approach to performing the work is very relevant to revise standards and good practices for designing materials. The international partnerships have to be maintained, and this prenormative work must be promoted to the international working group level.
- The team made good use of industry input to focus the work and identify the need for work, but it is not clear how industry participation and feedback was utilized during the project (other than through the provision of materials).

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

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

- This team continues to make significant contributions to the understanding at CSA Group and SAE International regarding hydrogen effects on steels.
- The accomplishments to date are impressive and assist in furthering understanding of the impact of hydrogen on alloyed steel, which are materials used for vessels and pipelines.
- It was impressive to see the summary slides of work in progress this year, combined with the publications list and collaborations with researchers and industry.

- Excellent progression was shown with respect to the project's accomplishments and progress. Limited information was presented on the progress toward DOE goals (perhaps the progress is implicit, but it should be explicitly stated/displayed). It is important to continue low-temperature testing for pressure vessels.
- Compared with the previous work, the experimental progress is excellent.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- This team has been collaborating with international partners, specialized technologists around the world, and key standards development organizations (SDOs).
- The collaborations are wide ranging, including SDOs, researchers, and industry.
- The project is very connected and very active.
- The collaboration is sufficient and appropriate. The lack of acknowledgement of the work and collaboration with the National Institute of Standards and Technology is assumed to be an oversight.
- The collaboration with other institutions in Japan and the European Union is very attractive, but insufficient details were provided on content and coordination with initial work.

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

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

- The relevance is high, and the potential impact is great. There is a potential for industry to reduce costs by properly selecting materials and thickness to ensure safety, while also reducing excessive conservative limits.
- The project is very relevant to improving good practices with materials for hydrogen technologies.
- This basic research on the susceptibility of metals to hydrogen attack is essential work.
- The stated goals (slide 3) are a comprehensive effort to provide data-driven development of international RCS for materials compatibility and components used in hydrogen systems.
- Although this is important work, the criticality of the work was not noted. The international impact was noted.

Question 5: Proposed future work

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

- The proposed work is essential to the success of the Hydrogen and Fuel Cells Program.
- This is critical, highly focused research. It deserves funding.
- Industry engagement and input remain evident in this work. Low-temperature and high-pressure testing is a good future approach. International round-robin testing will help move this project forward.
- The proposed work is a continuation of efforts to close gaps in material and component properties, develop test procedures for industry stakeholders, and facilitate safe and cost effective commercialization.
- This is excellent work thus far, but there needs to be clear collaboration with the SAE Safety Fuel Cell Group and an attempt to harmonize the efforts of this project and work being conducted under the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). There should be a clear direction to develop plans that also include industry input, such as from the SAE Safety Fuel Cell Group. The work done by Sandia National Laboratories (SNL) at IPHE has not been well coordinated and needs to align with industry input. For example, room temperature testing of materials is not a valuable test for the automotive operating environment.
- Round-robin testing should be prioritized.

Project strengths:

- Strengths include the project's technical competence, history of tritium handling expertise, and funding for basic research on test methods.
- The project features strong collaboration and communication with knowledgeable industry members through ASME.
- The accomplishments are apparent and progressing. The team has identified logical follow-on work.
- The project's strengths include the experimental facility and team members' expertise and background.

Project weaknesses:

- There are no obvious weaknesses.
- Weaknesses include the lack of coordination to turn pre-normative work into harmonized standards at the international level.
- The industry input is apparent, but perhaps more direct engagement is warranted.

Recommendations for additions/deletions to project scope:

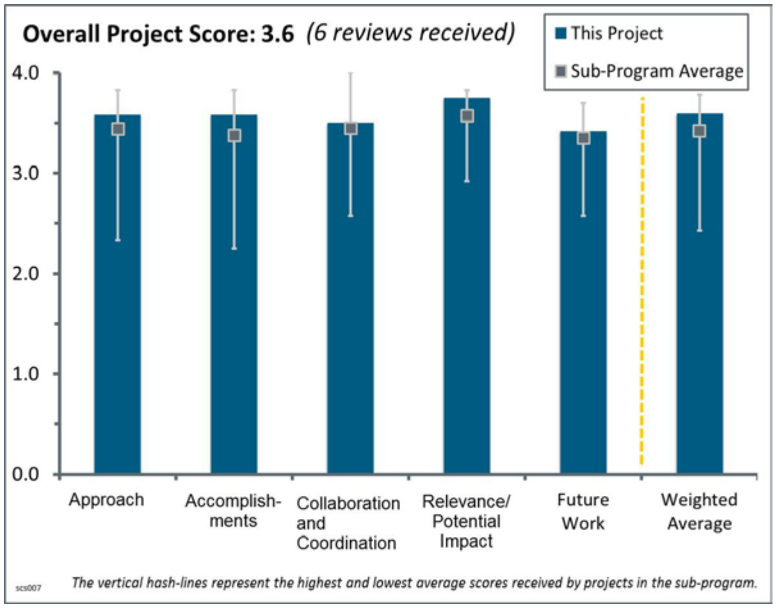
- The project should be continued. The team should consider evaluating other alloy steels and stainless steels (i.e., ferritic, martensitic, duplex, and/or series 200).
- The future work plans should align with the SAE Hydrogen Materials Round Robin, the sensitivity study, and the materials test campaign. Harmonization is needed with SAE Fuel Cell Safety Group input so that the plans for testing at SNL (and with IPHE) are aligned with the industry. There is a need to target and create an "open" materials database for automotive and stationary applications.
- The scope of the topic and the amount of gaps to be resolved are unknown, so it is not possible to make an assessment of what additional work might be warranted. There is no reason to delete anything from the existing scope.

Project # SCS-007: Hydrogen Fuel Quality

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project:

The objectives of this project are to (1) contribute to the goals of ASTM International as subcommittee chair for D03.14 gaseous hydrogen fuel efforts, (2) develop an electrochemical analyzer to detect low levels of impurities in gaseous hydrogen fuel, (3) investigate the impacts of contaminants at the levels indicated in the SAE International J2719 and International Organization for Standardization (ISO) Technical Committee (TC)197 Working Group (WG)12 documents using 2015 U.S. Department of Energy (DOE) loadings, and (4) collaborate with international partners to harmonize testing protocols and fuel cell impurity testing.



Question 1: Approach to performing the work

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

- Exerting leadership at ASTM is not an easy task, and the principal investigator (PI) is doing an excellent job of stewarding a wide range of important work through the ASTM process. This is very important work for the progress of hydrogen fueling infrastructure. The efforts to reach out to international colleagues at the Japan Automobile Research Institute (JARI), French Alternative Energies and Atomic Energy Commission (CEA), and VTT Technical Research Centre of Finland is commendable and demonstrates true leadership in a confusing and challenging area, where not all stakeholders are on the same technical page and everyone is learning a lot.
- The ASTM work is spot on and the new activity with WG24 is perfect. Development of a sensitive, in-line analyzer for a polymer electrolyte membrane fuel cell (PEMFC) is a very good approach even without speciation; the fact that there is speciation on some contaminants (e.g., CO and H_2S) is a bonus. The PI is a principal player in the international effort to define fuel quality needs with a high degree of confidence and accuracy. This activity and the PI are clearly recognized internationally as the U.S. leader in this area, which is extremely valuable.
- This presentation covers three projects: (1) interfacing with ASTM on analytical test methods to detect impurities in hydrogen, (2) in-line fuel quality monitoring, and (3) testing of the effects of impurities in hydrogen on PEMFCs. All three activities are critical tasks.
- In-line fuel quality monitoring is one of the most relevant aspects of this project as well as one of the key enablers to a successful rollout of hydrogen fuel cell vehicles and hydrogen stations. For this aspect of the project, the researcher is taking a very effective approach in trying to validate the device with two of the most critical fuel cell contaminants, CO and H_2S, to the levels defined by established standards. The researcher is taking the right approach in first obtaining a response within hours and then decreasing that to levels of minutes. It would be good to see the team start to develop a future cost analysis for this device once it is ready to be deployed in hydrogen stations, because cost will carry a lot of weight when deploying these in a major rollout of stations.
- A great deal of work is being done, and the presentation covered a lot of information. It may be worth separating out the presentations so the presenter can give more information on each subject.
- It is not clear from the presentation how chairing the ASTM subcommittee contributes to the goals, objectives, barriers, and challenges in the Fuel Cell Technologies Office Multi-Year Research,

Development, and Demonstration Plan (MYRDDP). Perhaps chairing the ASTM subcommittee makes it possible to develop the needed test methods. It is not clear whether this can be accomplished by contributing to ASTM activities rather than chairing. The presentation is not clear on this aspect. Development of the in-line fuel quality analyzer and the hydrogen fuel quality testing work seem to directly contribute to meeting expressed needs.

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

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

- The project team is sharply focused on pushing the technology forward regarding a number of critical areas, including establishing international harmony on hydrogen impurity detection methods. The team has many areas of focus, and it is making nice progress on all of these areas, including the round-robin evaluation of laboratory test methods. The progress on the hydrogen fuel cell impurity detector is very good, considering the lack of official industry partners. Ford Motor Company deserves special recognition for supporting this very important work with some advanced technology.
- Given the level of funding (~30% full-time equivalents [FTEs] for laboratory work), the accomplishments are excellent, excellent in quality, and spot-on for the needs of the deployment of hydrogen technologies. The team made great improvement in sensitivity from last year. This is starting to look promising. The response times are getting small enough that when the response time for this technology is evaluated, the sample system must be considered. If care is not exercised, this device will measure the hydrogen from a previous fill, which could be an issue as the device is applied in the field. . Regarding the JARI comparison, the team worked to get the Ion Power cell to match the JARI cell on the JARI cycle. Ion Power redesigned the cell to match JARI—this is nice, but it is not clear why it was important to match PEMFC hardware between JARI and Los Alamos National Laboratory (LANL). This internationally designed hardware will form the basis of the international round-robin on fuel quality with respect to ISO 14687, SAE J2719. Regarding the new recirculation system, the collaboration with VTT-Finland is nice.
- The team conducted excellent work in reducing the response time from hours to minutes on traces for both CO and H_2S. The project is definitely moving in the right direction.
- While this work seems to be very well coordinated and moving along, there is some urgency for the in-line analyzer portion; perhaps more emphasis can be placed on this component of the project, and perhaps this component could be better aligned with the infrastructure that is being deployed now and in the near future. The presentation from the National Renewable Energy Laboratory (NREL) on the in-line analyzer work mentioned monthly calls with LANL. There is room for improvement in that collaboration—working together more closely could expedite a needed technology/product.
- The ASTM-related accomplishments are a disappointment. SAE J2719, the fuel quality standard, was republished in 2011. At that point, there was only one open item—an analytical test method for detection of halogenated compounds. This is still an open item, and it is critical path, especially for a hydrogen vehicle rollout in the Northeast. Regarding the fuel quality monitoring work, the accomplishments on detecting CO and sulfur compounds are encouraging. Regarding the work on the effects of impurities, the data collected on the effects of CO on lower catalyst loading electrodes is needed and useful as the industry moves to new electrode designs.
- The presentation does a very good job of demonstrating progress toward the overall project goals. Improvements can be made on how the presentation describes the degree to which the project has demonstrated progress toward DOE goals.

Question 3: Collaboration and coordination with other institutions

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

- The outreach to international partners is outstanding and groundbreaking. The possibility of international round-robin testing and validation of test methods is about to come true, thanks to the diligent efforts of this team and funding from DOE. The collaborations with international partners are outstanding, and projects such as the VTT-Finland/LANL collaboration and the LANL-JARI-CEA baseline evaluation of membrane electrode assemblies (MEAs) are breaking new ground by developing international round-robin testing capabilities. Support for the International Electrotechnical Commission WG11 PEFC document on testing, which is under development, is another example of this team leading international standards development.

- This project features the right mix of collaborators—including ISO WG24 in this effort is excellent. The PI should pay attention to evolving efforts in the international standards community. The issue of fuel quality assurance is being reconsidered (including a revisit of contaminants identification and tolerance levels). This fuel quality assurance capability is critical to ensuring those new activities are successful. WG24 is important, but this effort will be superseded by a new work item proposal on fuel quality (previous WG12).
- The coordination and collaboration on the hydrogen fuel quality activity were described well. Further expansion of the relationships with the partners/collaborators shown on the Overview slide would be helpful. For example, the presentation shows the "National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee Call" on the list, but there is no further description of this collaboration or coordination. While there has been sporadic, brief reporting on the project activities by the project lead on the monthly National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee calls, this represents participation, rather than collaboration and coordination.
- Regarding the ASTM work, the collaboration is appropriate for this task. Regarding the fuel quality monitoring work, the collaboration is also appropriate for this task. Regarding the work on the effects of impurities, it is disappointing that collaboration was limited to national laboratories in several countries while the academic laboratories that generated the data used in the fuel quality standard were not included.
- The current collaboration is very good; however, more interaction with any industry partners and other laboratories working on similar/related topics seems warranted.
- The team is collaborating with key partners in this area, including ASTM, SAE, and JARI. The project team would also benefit if progress is also presented to ISO.

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

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

- There cannot be enough said about the relevance of this team and the work it is doing to establish new hydrogen impurity test methods and bring these methods through the ASTM process. There is no one else to do this work, which is critical for the success of the Hydrogen and Fuel Cells Program and DOE research, development, and demonstration goals and objectives.
- All activities this PI contributes to are spot-on regarding relevance and impact. This work is critical to understanding and ensuring that the fuel delivered has the purity needed to protect the fuel cell. The PI contributes to ASTM as a chair. The in-line analyzer is critical to the assurance of fuel quality delivered. The continued work on tolerance levels is excellent. The work related to harmonizing safety, codes, and standards is excellent. Regarding the ASTM work, the PI chairs the sub-committee work with WG24, which is excellent.
- The relevance and potential impact of the ASTM task is critical path. The relevance and potential impact of the fuel quality monitoring task is relatively high. The relevance and potential impact of the effects of impurities task is high.
- This work is critical to current hydrogen stations and even more so to future stations and those in development (all will ultimately see more vehicles). It is imperative that the fuel quality is, to the fullest extent possible, guaranteed to meet SAE J2719 and to not disrupt vehicles' performance, and hence the consumer experience.
- In-line fuel quality monitoring and the assurance of the appropriate fuel quality are essential for the development of the hydrogen fuel market.
- The relevance-related text stated on slide 4 seems to describe an approach—a means to an (unstated) end. For example, the first stated objective is "Contribute to the goals of ASTM as sub-committee chair for D03.14 gaseous hydrogen fuel efforts." This does not reflect the direct relevance to the DOE barriers, goals, and objectives. Instead, this seems to be an approach to addressing the DOE barrier ("G. Insufficient technical data to revise standards"), and to support the objective "Support and facilitate development and promulgation of essential codes and standards by 2015 to enable widespread deployment and market entry

of hydrogen and fuel cell technologies and completion of all essential domestic and international [regulations, codes, and standards] by 2020." This barrier is not shown on the Overview slide. The project contributes directly to the following Technical Challenge expressed in the current MYRDDP:

  - Test Measurement Protocols and Methods: "The key technical challenge is to perform the first principles work to develop internationally harmonized robust, validated test measurement protocols so that a system qualified for service in one country will be accepted by other countries. Test measurement protocols must be developed for all relevant pressure and temperature environments that materials are subjected to during hydrogen service and must account for relevant manufacturing variables such as welds and other process effects. In addition, measurement protocols and test methods must be optimized to minimize the time and cost of qualification and enhance the timely development and deployment of new materials, components, and systems. The cost of qualifying hydrogen components and systems can be prohibitive, and if test methods are too time consuming, new technology deployment can be delayed. Accelerated testing methodologies must be developed for materials, components, and system qualification that resolve the relevant physics and adequately emulate operational conditions. These test measurement protocols and methodologies must be documented rigorously such that they can be implemented by standards development and testing organizations."
  - The presentation would be more effective and the work would be better understood if the project team focused on the higher-level DOE goals, objectives, barriers, and challenges to address objectives and relevance, and then showed the means to achieve these (e.g., chairing an ASTM subcommittee) in the Approach section.
  - In summary, the project is relevant to the DOE goals, objectives, barriers, and challenges; however, it is difficult to determine this from the presentation as written and presented.

Question 5: Proposed future work

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

- While the presenter did not have time to talk about this slide, and left it up during questions, he did mention that other tests are in development (e.g., the current work on a [new] protocol with JP Hsu). It is not clear that a new protocol is appropriate, given the amount of future work and the ongoing work. Perhaps that protocol development is organic with the current work. The fact that the in-line analyzer will be validated at NREL is excellent; NREL gave a presentation on the in-line analyzer work being done there. The workshop mentioned on the slide is a valuable item for pulling in industry participants.
- The proposed future work is perfect and needed for the deployment of fuel cell technologies. One expects that this PI will continue to provide global leadership in this field.
- The future work is very well defined. It is good to see that the moisture effect will also be evaluated because electrolysis could be a main pathway for on-site hydrogen generation. The researcher could also consider other contaminants such as hydrocarbons, ammonia, and others on the current SAE and ISO standard. Tests at higher pressures could also be included in the future work. Once a prototype is developed, the team should conduct a cost analysis for a future commercial device.
- This team is carrying a huge load and is pursuing a wide range of active work efforts. The challenges of developing a low-cost, highly sensitive, and accurate analyzer with rapid response are significant. This subproject alone is a daunting task and includes numerous technical hurdles. The task of managing the movement of new fuel cell impurity test methods through the ASTM process is a major subproject that is very challenging due to the limited number of independent laboratories with the ability or interest in investing in the capability of performing comprehensive analytics of hydrogen at the required fuel cell quality levels of detection.
- For the ASTM work, there is no mention of the critical path test methods. For the fuel quality monitoring, the proposed work is appropriate. For the work related to the effects of impurities, the proposed work is appropriate.
- The future work may be reasonable and worthwhile; however, little detail is provided in the presentation. The decision points are not described. Risks, barriers, and challenges are not described.

Project strengths:

- The PI has some of the best personal knowledge of the relevant analytical techniques of anyone in the world, and his experience with MEA resistance to contamination has been an outstanding foundation for the work on the contaminant detector, the in-line hydrogen quality analyzer.
- The project features a world-class PI who is doing world-class research. This work is among the best in the world, and it is recognized as such.
- This project has great importance and significance to what is happening in infrastructure (and vehicle) rollout.
- The technical aspects of the project are areas of strength.
- The hydrogen in-line analyzer activity and hydrogen fuel quality efforts are making good progress.

Project weaknesses:

- While there has been progress, there is still so much to answer and more to do (e.g., the topic of performing the work at pressure) before getting the in-line analyzer out to the "real world." This is not a true project weakness; it is more of an observation on the amount of work to be done.
- The project's weaknesses are the apparent lack of urgency with ASTM and the apparent lack of collaboration with the academic laboratories that developed the initial data.
- Perhaps the project team could do more with more funding.
- The main weakness is communication, both within the presentation and through collaborations.

Recommendations for additions/deletions to project scope:

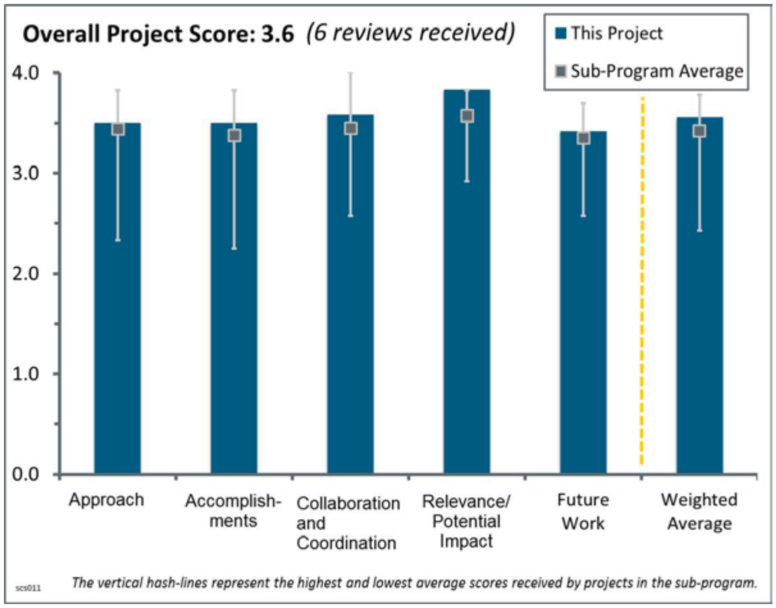
- It seems that more interaction and load sharing (of the work) is needed. Not to take away from the presenter's responsibilities, but there is so much happening simultaneously, along with parallel/similar work happening elsewhere, that all involved parties should consider how to pull all of that together to get more done, faster.
- The PI should pay attention to the emerging activities to revisit fuel quality, which would also involve embracing fuel quality assurance. The work with ASTM is also critically important, and it needs to be continued, with attention given to determining how to cost effectively get testing methods to the testing laboratories in the field.
- Completing the needed ASTM test method and more activity with the domestic academic laboratories would be appropriate. The domestic academic laboratories are where the next generation of researchers are being trained.
- The research team should evaluate the effectiveness of chairing the ASTM subcommittee.

Project # SCS-011: Hydrogen Behavior and Quantitative Risk Assessment

Katrina Groth; Sandia National Laboratories

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- The team is bringing the science behind the NFPA 2 (Hydrogen Technologies Code) setback distances into a layered risk management analysis platform and offering this to risk mitigation system developers around the world. This is a long-term project, and the team is making good progress as it reaches out to establish international partners. The mission of this project team is a critical one, and the team is doing a stellar job.
- This is an extremely timely and important approach; efforts are finally aiming at bridging stand-alone results from academia and the engineering solution needed for the deployment of hydrogen infrastructure. In addition, the integrated approach, including the probabilistic methodology, is novel and well placed. The choice of an integrated tool for the safety evaluation is also an important step toward increasing the accessibility of data for end users.
- The approach seems well thought-out, with effective use of partners and development of hardware for validation of models. The forward-looking inclusion of liquid hydrogen release modeling is commendable because this is an expressed need from industry for future RCS activities. The approach regarding the development of data and models seems sound. The implementation of the work is the subject of another presentation (SCS-025), and there must be an effective interface between the modeling work and implementation of this work into RCS.
- The approach follows from all the work performed by SNL in support of NFPA. The model should prove very useful to system designers.
- Regarding the degree to which barriers are addressed, the project is well designed, feasible, and integrated with other efforts. Barriers A, F, G, and L are satisfactorily addressed in this project.
- The approach appears sound. It is not clear how the model was validated. It is also unclear whether the model has been applied to compressed natural gas.

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

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

- This work clearly contributes toward the stated DOE goals. The effort is a long-term effort, and it has some iterative characteristics in that user/industry feedback is used to develop improvements to the models and leads to further investigation. Stakeholder validation/testing is in early stages. This, along with successful implementation of the work into appropriate RCS, will be critical for determining the effectiveness in meeting project and DOE goals.
- Excellent progress has been made and measured against performance indicators, and excellent progress has been demonstrated toward DOE goals. Also, the three SNL goals listed on slide 5 are meaningful and meet DOE goals and expectations.
- This past year, the work of this team on the International Organization for Standardization (ISO) technical committee (TC) 197 working group (WG) 24 risk mitigation task force has been outstanding, with significant acceptance and support from international colleagues from Linde, TÜV SÜD, and Air Liquide.
- The project addresses important aspects of the DOE Hydrogen and Fuel Cells Program (the Program) and will contribute considerably, when finalized, to DOE goals, specifically by enabling a science-based, validated, and harmonized approach to the design and acceptance of hydrogen infrastructure. To achieve this, however, the level of funding must remain as before for at least an additional two years.
- The accomplishments and progress are appropriate. The use in support of code changes in NFPA 2 and NFPA 55 is excellent.
- The release of the model for alpha testing is an important milestone.

Question 3: Collaboration and coordination with other institutions

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

- The SNL delegation to the ISO TC 197 WG 24 task force on risk management has been very successful in reaching out to Europeans colleagues and has been able to bridge the chasm created during the previous efforts at ISO to create an international standard for hydrogen vehicle fueling stations.
- Regarding the degree to which the project interacts with other entities and projects, there is outstanding collaboration and coordination with other institutions such as the International Energy Agency Hydrogen Implementing Agreement Task 37 (Hydrogen Safety).
- The international cast is important for gaining acceptance (and review) of the model.
- The project has a reasonable plan for engaging partners and is establishing cooperative research and development agreements (CRADAs) and other appropriate mechanisms to engage stakeholder groups. While it is recognized that not all stakeholders are created equally, it seems curious that a CRADA is in place with one hydrogen supplier directly, and that the team is pursuing a CRADA with other hydrogen suppliers through a third-party organization. It will be good to see future updates on this topic. H_2USA is a potential stakeholder group that is currently evaluating models for usefulness in planning hydrogen fueling infrastructure deployment. The presentation notes organization memberships in the H_2USA Locations Working Group and the H_2USA Stations Working Group. Consideration should be given to developing a more direct collaboration with H_2USA on this project specifically—particularly with the H_2USA Stations Working Group to collaborate on design insight activities and aid this key industry group in resolving open issues.
- The interfaces with all the players are well coordinated, extremely well developed, and guarantee the required level of input and assessment. One essential interface is the one with industry for the information on component performance and realistic failure frequencies. To this respect, CRADA or similar activities are an enabling mechanism; however, the project should pursue CRADAs with more than one major player.
- The industry collaboration is appropriate. It is unclear whether there was any direct outreach to NFPA (a research foundation).

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

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

- The project has greatly supported and advanced progress toward the Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The team has done an excellent job in terms of the relevance and potential impact of the project on these goals and objectives.
- The project will have a great impact, both in relation to the DOE goals and for the international communities. It will have an impact not only in terms of the one-step integrated tool, but also as an innovative incubator of new approaches and methodologies.
- This project is focused on developing the data and tools necessary to advance progress toward DOE goals and objectives. This work facilitates opportunities to improve RCS using science-based data and tools. This project fills significant gaps to enable performance-based compliance.
- The efforts by the project team to reach out to the international community and be an active participant in the ISO TC 197 WG 24 development team will have a significant impact on the ability to deploy hydrogen fueling stations in downtown environments. The changes in codes and standards will not happen overnight, and the ISO process will be a 3–4 year sojourn just to get the first editions of standards published. The full impact of the efforts of this team will not be complete for at least two, and maybe three, code cycles of NFPA 2.
- This activity could be highly relevant. Slight reductions in separation distances can save industry millions of dollars. Separation distances are often a major impact on the capital cost of a fueling station.
- There is a definite need for tools that can describe hydrogen behavior and predict risk.

Question 5: Proposed future work

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

- The liquid hydrogen behavior work being done this year is essential and is providing key input into the NFPA 2 task force on hydrogen storage setback distances. All of the members of this team are doing extremely important work today.
- The following aspects of the planned future work are particularly interesting:
    - Design insight: the safety impact of different designs, and which components drive risk/reliability.
    - H_2USA should be considered as a potential partner for this stage of the project.
    - The proposed work to validate liquid hydrogen releases is also very important to industry.
    - The nature of the project requires flexibility for future work. This project recognizes this need. Out-years plans are highly commendable, as there will undoubtedly be value in future validation.
- The project supports and advances progress toward the Program goals and objectives delineated in the MYRDDP by providing a good roadmap and milestones for future work.
- The proposed future work appears to be a sound path forward.
- It is absolutely important that the underlying physics and the frequencies are validated and that data is updated regularly. Regarding validations, it is not clear whether there are plans for an (international) effort—for example, in the form of round-robin tests. Regarding data updates, the use of the tool to describe real situations will deliver a source of lessons learned and reliable failure data that need to be fed back into a continuous improvement action. It is unclear whether there are plans for such continuous improvement. Some long-term funding has to be planned by DOE to guarantee continuous development—for example, synchronization with the continuous codes and standards improvement activities mentioned in other Safety, Codes and Standards sub-program projects.
- It is important that “modules” to allow similar assessments with cold gas releases are designed and tested.

Project strengths:

- The project team's engagement with industry, as well as with codes and standards activities, facilitates a well-rounded understanding of the needs to be addressed by the project output, as well as a real-time feedback loop for continued improvement of quantitative risk assessment tools. The project is well focused on resolving the noted barriers from the 2013 MYRDDP.
- The cold release laboratory is an important facility that will bring key information to the NFPA 2 and ISO TC 197 WG 24 committees.
- The strength of this project is SNL's testing ability to support this development. The experience of the specialty gas companies with field incidents could be interesting.
- This is a well-coordinated project. Also, the project is progressing very well and is focused on addressing the four key barriers: A, F, G, and L.
- This project is a novel way to link basic science, pre-normative research, and RCS efforts. It deserves great applause.
- The application is based on scientific risk modeling and data.

Project weaknesses:

- Overall, the project is very strong. The effectiveness of the work, however, will be determined based on adoption of the tools and data into RCS activities. It is not clear from this presentation how the results of the project will be fed into the RCS processes. The presentation does note this will be covered by a separate presentation (SCS-025). Therefore, it is difficult to evaluate the overall effectiveness of the project without taking this separate presentation into account. Looking at the SCS-025 materials does not actually provide insight into this issue. The adoption of the work into RCS seems to be dependent on how the tools are ultimately adopted and used. SNL is pursuing multiple avenues to engage with authorities having jurisdiction (AHJs), targeted code officials, and targeted fire protection officials directly. It would be better to see the outreach taking place with appropriate industry organizations to facilitate development of code change proposals by industry. Messaging to AHJs should be clear and coordinated to avoid mixed messaging, and it should be led by industry needs.
- The development of the cold release laboratory has been hampered by the inability to source small liquid hydrogen containers—a commodity available in Japan and Germany but not in the United States. The laboratory is not able to do release and ignition testing because of the urban site and the lack of portable liquid hydrogen containers to carry into more remote sites.
- The only weakness in this project lies in its high ambitions. If not heavily tested and validated, the tool risks remaining a toy for first-stage designers. The presentation stated that all the phenomena already considered in Hydrogen Risk Assessment Models (HyRAM) have been validated. It is highly probable that 10 minutes was not enough time to give full demonstration of this fact, but that should occur in the future.
- The weakness of this project is that ultimately the model needs acceptance by local AHJs. It is not clear how this outreach is envisioned.
- Weaknesses are not known at present; they will be revealed through testing by users.

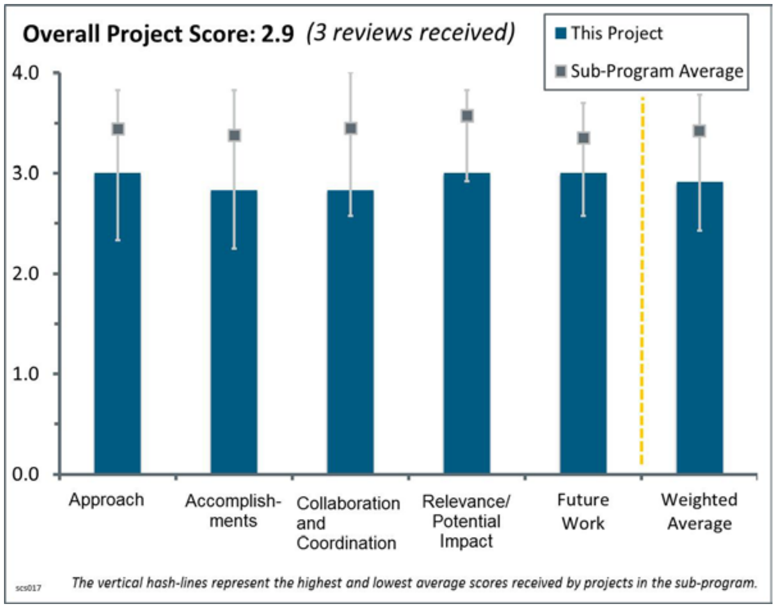
Recommendations for additions/deletions to project scope:

- Establishing CRADAs with major industries is an essential step toward realistic values, and perhaps also toward validation exercises. CRADAs are, however, only enablers. It is difficult for reviewers to evaluate the real efficacy of this mechanism to reach the desired results. Next year, the presenter should disclose additional details on how data on real component performance is gathered and elaborated in HyRAM.
    - The international collaborations are unquestionably a means of dissemination and consensus achievement, but it is not clear how effective the collaborations are with respect to the development of the project. The presenter said, for example, that selected ISO TC 197 WG 24 partners are acting as alpha testers. Entities are required to agree to so many legal conditions before receiving permission to access HyRAM that not many international players will be able to do so. For HyRAM to have a chance to become the reference tool for design, it would be better to follow a much more public distribution to allow independent verification and validation.

    - Failure or success will depend mainly on the development and dissemination strategy. The decision on whether to make the application available as freeware will be functional to this strategy. The project has not yet made a decision on the boundary conditions for the further development and utilization of the tool. It would be good to know the pros and cons underlying the decision. To really help the deployment of the infrastructure, this tool should be as open and transparent as possible.
- More effort should be made to bring portable liquid hydrogen tanks into use in the United States because that would enable release and ignition testing to support model validation and revision of liquid hydrogen setback distances. A facility should be developed to test hydrogen equipment enclosures to validate the sizing models that determine deflagration venting.
- It is recommended that this project include AHJ outreach and modeling of previously documented incidents to validate the model. The team should consider working on mitigation of liquid hydrogen releases. For example, it is not clear whether a deluge system, intended to heat the hydrogen to facilitate the evaporation of the release, would reduce or increase the risk of a fire or explosion.
- It would be good to see more direct collaboration with appropriate industry groups to utilize the tools and data to develop risk-informed decisions in codes change proposals and standards provisions, in lieu of direct engagement between research activities and AHJs.
- The project should include uncertainty analysis in the HyRAM's calculated risks: Potential Loss of Life, Fatal Accident Rate, and Average Individual Risk.
- It is recommended that this application be extended to include effects from liquid spills and overpressures due to confinements.

Project # SCS-017: Hands-On Hydrogen Safety Training

Salvador Aceves; Lawrence Livermore National Laboratory



Brief Summary of Project:

Appropriate hydrogen safety training is key to avoiding accidents. The overall objective of this project is to develop a hydrogen safety training program for laboratory researchers and technical personnel. The 2015 objective is to develop classroom materials for a hands-on training course that includes comprehensive instruction on components, system design, assembly, and leak testing.

Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- There is a good approach to performing the work and addressing the specified U.S. Department of Energy (DOE) barriers.
- The project has progressed well in working to incorporate training and lessons learned and having more people/individuals view the work/training.
- Overall, the approach is good. The project could benefit from additional focus on feedback mechanisms to improve developing training beyond the Hydrogen Safety Panel (HSP).

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

This project was rated **2.8** for its accomplishments and progress.

- The project has done good work based on the degree to which progress has been made and measured against performance indicators and the degree to which the project has demonstrated progress toward DOE goals.
- The project has progressed well in working to incorporate training and lessons learned and having more people/individuals view the work/training. The project seems to have addressed last year's comments that additional exposure is needed to get the information more into the mainstream.
- This project has accomplished very little since the last peer review. It is operating on a small budget. Funding disruptions are likely to have a significant impact on progress. In order to evaluate the effectiveness of the online training class, a chart showing scores achieved on the end-of-module quizzes with respect to class completion would be useful. A similar metric for hands-on training modules would also be useful in the future.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The project seems to have addressed last year's comments that (1) additional effort is needed to get the training information into more mainstream forums and to more individuals and (2) the training needs to include more hydrogen-specific information. It would be interesting to understand whether there is a level of "certification" that would be valuable for individuals to have. Delivering the training is only one aspect

of understanding whether the individual has "received" the knowledge being transferred and can successfully apply it.
- The partnership with the HSP is very good. The title of slide 7 indicates the training is being used as regular training for various organizations. The presentation does not cover partnerships with organizations that provide similar generalized training, such as industrial gas companies. Such partnerships could be useful to validate the training and potentially provide additional avenues to incorporate the results of this project into the mainstream. This is an important feedback mechanism for the project, and further project focus and information should be provided.
- There is good collaboration and coordination with other institutions, such as the HSP.

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

This project was rated **3.0** for its relevance/potential impact.

- Hardware training is an important aspect of safety that has not received much attention. This project does a good job of starting to address this need.
- The project's relevance and potential impact on hydrogen safety awareness are good.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed work to complete the modules is very important. Additional focus on industry validation would improve the project. Further focus on outreach to increase awareness and uptake of the training is identified as a remaining challenge. Close coordination with the Fuel Cell and Hydrogen Energy Association (FCHEA) and Pacific Northwest National Laboratory (PNNL) could aid this effort.
- This project will probably not continue beyond 2015.

Project strengths:

- The project is developing tools to educate about hydrogen and how to handle/use it.
- Hands-on training is a valuable activity that had not previously been addressed.
- The project offers extensive hands-on training in hydrogen safety.

Project weaknesses:

- The project is weak in terms of understanding whether the tools are effective in delivering the information by evaluating whether the individual has "received" the knowledge being transferred and can successfully apply it.
- Progress is slow.

Recommendations for additions/deletions to project scope:

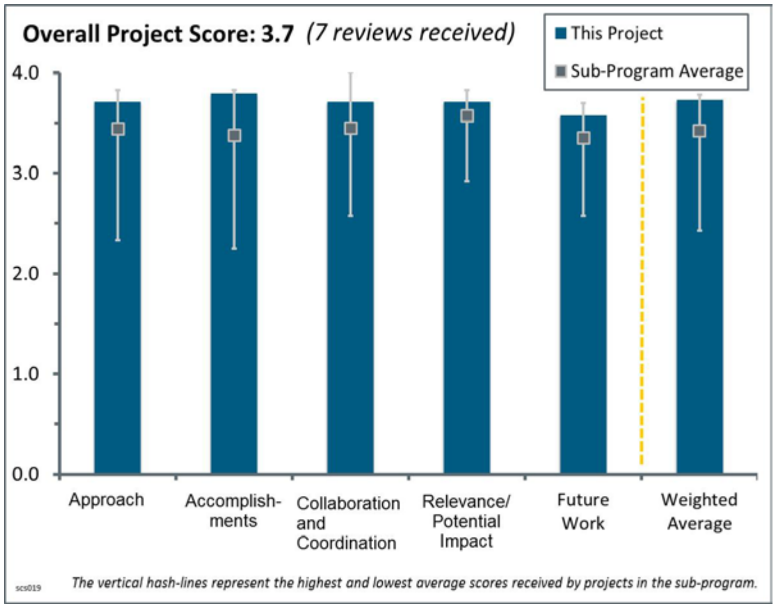
- It would be good to see some analysis of the potential for this work to be used for other audiences. These include technical colleges, industrial gas company training programs, gas utilities, etc. Future validation by such audiences could help improve the overall training and fill training gaps to accommodate hydrogen-specific information in mainstream gas safety training programs. Inclusion of the project in PNNL's Hydrogen Safety Toolkit and FCHEA's Hydrogen and Fuel Cell Safety Report is recommended to improve uptake of the training and facilitate feedback for continued improvement.

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

Nick Barilo; Pacific Northwest National Laboratory

Brief Summary of Project:

The objectives of this project affect three main areas: the Hydrogen Safety Panel (HSP), safety knowledge tools and dissemination, and first responder training. This project provides expertise and recommendations through the HSP to identify safety-related technical data gaps, best practices, and lessons learned and help integrate safety planning into funded projects. To further safety knowledge tools, data from hydrogen incidents and near-misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community. The team has developed a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.



Question 1: Approach to performing the work

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

- The presenter's approach to ensuring hydrogen safety is right on point. A centralized database for authorities having jurisdiction (AHJs) is needed. H2tools.org is the resource California has been awaiting because it simplifies information flow and provides a reliable, neutral source to recommend to AHJs. With ongoing attention and funding, the tool will continue to grow in both relevance and importance. Component listing is critical as well. The plan to level the playing field by showing AHJs and station developers how to establish comfort with station system performance is incredibly timely and important. This is a big unanswered question in California. First responder training is crucial, and more is needed. Going to videos on H2tools.org to supplement in-person training is a great way to expand the all-important reach.
- The approach is excellent. The HSP safety plan reviews bring much value to project safety. The proposed involvement at post-award kickoff is a particularly strong point. The site visits are also a great enhancement to safety. Nothing complements understanding and problem identification like having experts on site. Sometimes projects are managed from beginning to end entirely without site visits, and site visits, on the rare instances when they are possible, are extremely valuable. The other two segments of the program—first responder training and instant, easy access to learnings and best practices—extend U.S. Department of Energy (DOE)-funded project learnings out to the field. The plans for housing the tools with the National Fire Academy/Federal Emergency Management Agency are an excellent long-term solution for managing and updating the information and providing it to the broadest audience.
- The HSP component is excellent; this talent still needs to be used more broadly. Moving the knowledge tools to the portal is a very powerful move. The first responder training component remains excellent—the saying, "if it ain't broke don't fix it," applies. However, with that said, there is value in moving this activity to a more mainstream activity, possibly with the National Fire Association.
- This project is made up of three considerably different areas: the HSP, the training tools for first responders, and the safety knowledge tools. However, because these areas interface with each other, it makes a lot of sense that they are clustered in one single project. The advantage is that the competencies

developed in each of the three areas are generated in the same team and can be efficiently mutually profitable.

- The H2tools site appears to be a great improvement/advancement and is needed by industry. It is concerning that one of the initiatives is to address the lack of certified equipment, but there do not appear to be any certification agencies involved in the activities. In addition, the statement “Safety is not treated as a continuous process” is listed as a barrier. The “safety standards” have this as their primary focus, yet there is no support for standards development organizations (SDOs) or their process.
- It is difficult to remove all barriers because the scope of work is very broad. There is too much focus on AHJ approval; there should also be focus on increasing listed components and systems.

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

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

- Given the funding level, this project has achieved much very high-quality work on all three aspects. Having the notion of safety planning in the funding opportunity announcement (FOA) is a great idea. It sets the posture for a safety culture and allows the HSP to engage early in the project. Regarding listed equipment, development of a guide to assist AHJs in “approving” installations that are not “listed” will be a great asset in the early stages of development until the community gets hardware listed. Moving safety knowledge tools to a portal is outstanding! The number of “hits” is quite impressive.
- As stated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, it is not possible to evaluate the progress according to quantitative indicators for these types of activities. Nevertheless, the progress booked this year is evident and of high quality. The new H2 Tools website is an example of a successful communication effort; it is well structured and of utility for users with different goals and levels of competence.
- Safety is paramount—it is the first question that is asked in California in local communities. If anything, stakeholders need to figure out how to expand the HSP’s reach. The reviews from the HSP, a crucial, trusted third-party resource, have already shown the HSP’s benefit to the state. Education and outreach is the undercurrent that appears to feed this work. This is the state of the market in California—the more influencers are comfortable with the technology, the better. H2 Tools gets at this issue.
- There has been significant progress on numerous objectives; the project achieved many key deliverables over the year. The primary question now is ensuring widespread deployment and use of the tools that have been developed.
- The DOE Hydrogen and Fuel Cells Program seeks to increase the “safe” use of hydrogen and fuel cell technologies. The tools being developed will support industry. The review of plans for stations provides good support for the nascent industry, but it does not appear to be a sustainable solution. In addition, it needs to be stressed that the data from the incidents need to be routinely fed to the SDOs/code development organizations (CDOs) so the information can be reviewed by the technical experts to understand whether revisions to the standards/codes are needed.
- Overall, project accomplishments include broadened outreach activities and continued expansion of knowledge of safe hydrogen handling, as documented in the slide deck.

Question 3: Collaboration and coordination with other institutions

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

- Pacific Northwest National Laboratory (PNNL) has worked very well with the California Fuel Cell Partnership and state agencies (e.g., the California Air Resources Board, California Energy Commission, and California Governor’s Office of Business and Economic Development [GO-Biz]). The coordination and collaboration is fundamental to overall project success.
- The approach is excellent. The project should consider working with other federal departments (particularly the U.S. Department of Transportation) and state agencies (particularly in California) that are funding hydrogen infrastructure/fuel cell vehicle deployment projects to also include language in solicitations that

"encourages coordination with the HSP for development of Safety Plans" similar to the DOE FOAs. This has been very effective for early project involvement for DOE projects.

- National and international collaborations are excellent. Getting from the federal level to SDOs and local AHJs shows great coordination.
- The collaborators and collaborations for this work are good. While Sandia National Laboratories (SNL) is mentioned as a collaborator, during the presentation, following up on a question from the audience, it was noted that the principal investigator (PI) should work to interface with the SNL Hydrogen Risk Assessment Model (HyRAM) activity more strongly.
- There is widespread, direct engagement with many key stakeholders.
- In general, collaboration is good. However, the activity should not happen without SDO/CDO and Nationally Recognized Testing Laboratory (NRTL) involvement.
- The HSP is per se a collaborative exercise, in terms of both (1) teamwork that includes different competencies and (2) engaging many players and stakeholders.

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

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

- The relevance of all three of these activities is perfect. The HSP has proven valuable to the community beyond the collaboration on the DOE projects as originally intended. The outreach activities such as the Tools Portal will continue to grow and increase in impact on the AHJs as more and more AHJs seek to understand how to get hydrogen in their communities. The first responders training remains a powerful activity. This activity must continue; however, maybe it is time to move this to a more mainstream activity, such as with the National Fire Association. This was noted in the presentation.
- Safe operation of hydrogen resources, coupled with well-designed education and outreach, is fundamental to market success. Technological advancements mean very little if communities do not welcome the technology into their areas. Hydrogen solutions need to be safe, and they need to be perceived as safe. The HSP can help ensure the former; education and outreach (and exposure) help the latter.
- It is difficult to assess the impact of the many activities related to the deployment of the technology. This is the only reason why this assessment was given a ranking of "good" instead of a higher ranking. It is probable the impact is visible in an incremental way—in the improvements achieved in the projects that received the HSP's assistance and in the use that website visitors have made of the lessons learned from safety events. All items are difficult to assess quantitatively.
- Safety is always relevant, and a safety incident resulting in death or injury could paralyze the industry.
- The tools are ready; implementation and use are key.
- This is important to help the industry grow and move forward safely.

Question 5: Proposed future work

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

- Building out the H2 Tools portal and leveraging HSP resources are key. Both help push the collective understanding and knowledge of both the safety and community reaction. The key is for stakeholders to help PNNL ensure these tools are widely acknowledged and used. Building out video resources has the potential for broad impact. City officials do not have much time to digest new technology; if simple and short videos can be produced to create a baseline understanding of safety, they will be used.
- Part of the future plans consists of continuing and making incremental progress in the already running activities. This is perfectly fine and deserves further funding of the same level. The draft certification guide planned in 2016 is ambitious, very useful, and extremely timely.
- Continued safety performance data collection and outreach are desirable. Engaging the insurance industry with the AHJs is a necessity for safe commercialization, so it would be good to see more involvement of insurers.

- The proposed future plans are spot on in each of the three areas. However, attempting to bring other databases into the portal could rapidly become unwieldy from a maintenance perspective. Serious thought should be given to understanding how the databases can be referenced rather than actually incorporating them into this portal. This would put the burden of maintenance on the "owner" of the database.
- There are good initial plans for reaching first responders, but there do not appear to be plans for non-fire personnel or certifying personnel (e.g., second responders and maintenance professionals).

Project strengths:

- This project yields a fantastic bang for the buck! For the level of funding, the output quality, innovation, and quantity are excellent. The HSP is doing its job and has developed an outstanding resource that is quite frankly the envy of the world. The hydrogen safety tools component has grown and will continue to grow and become an outstanding resource to the AHJs and permitting communities. The first responder training has matured but continues to provide enormous value to the community as the hydrogen fueling infrastructure is rolled out. It is time this activity move to something more mainstream, such as the National Fire Association—a move recognized by the PI and in the future plans.
- Strengths include coordination, collaboration, and doing what is necessary to support a budding network. Getting the emergency responder training package into existing courses will help amplify the project benefits. The fact that the HSP exists is extremely comforting—AHJs are likely to trust the collective wisdom of the panel.
- Strong tools with strong content have been developed. There are good early adoption pathways. Partnerships and communication are strong.
- This project involves many important activities that will ensure safe deployment of hydrogen. There are many tools for industry, regulators, and the public to utilize.
- This project profits from the integrated gathering of experiences and the elaboration of them into a permanent pool of first-class experts.

Project weaknesses:

- H2 Tools is a great resource. The challenges will be getting people to use it and setting it up to capture useable lessons through time so that all stakeholders can benefit from multiple learnings. It is tough to do the appropriate level of training with limited resources. PNNL is taking a great approach in trying to integrate resources into existing training—this needs to be successful for the project to have the reach that is needed.
- No weaknesses were identified.
- It is difficult to implement all of these key initiatives under the banner of one project.
- There needs to be additional SDO/CDO and NRTL involvement.
- There is not much presented here on automotive applications.

Recommendations for additions/deletions to project scope:

- Nothing should be deleted. From the California perspective, it would be good to see all of this project's activities augmented and amplified. The more people who can be reached/trained, the better. The market is coming, and this effort is exactly what is needed. It is suggested that the project do the following:
    - Figure out how to best maximize the use of the HSP. Perhaps funding can be increased to support more reviews. Perhaps California and other active states should help establish priority reviews (as opposed to first come, first served).
    - Focus on the video expansion. A general video explaining hydrogen stations and their safety systems would be very helpful for communities.
    - Work to make sure H2 Tools collects collective lessons that can be easily accessed.
    - Explain incidents in the headings of search results on H2 Tools. Some search results can be scary for a city official new to hydrogen, so this step may be worthwhile. A search on incidents brings up a page of potential scariness; some sort of reassuring explanation could be helpful.
- The project should consider development of a simple tool/video that could be referenced on public stations either by URL link or quick response (QR) code that would provide information to public users on

hydrogen basics and safety. Most of this information has already been developed and would just need to be distilled into quick, basic, educational information that would be easy to access at point of use. This link could go to or through the Portal as well, but perhaps there could be a quick refresher for users while fueling.

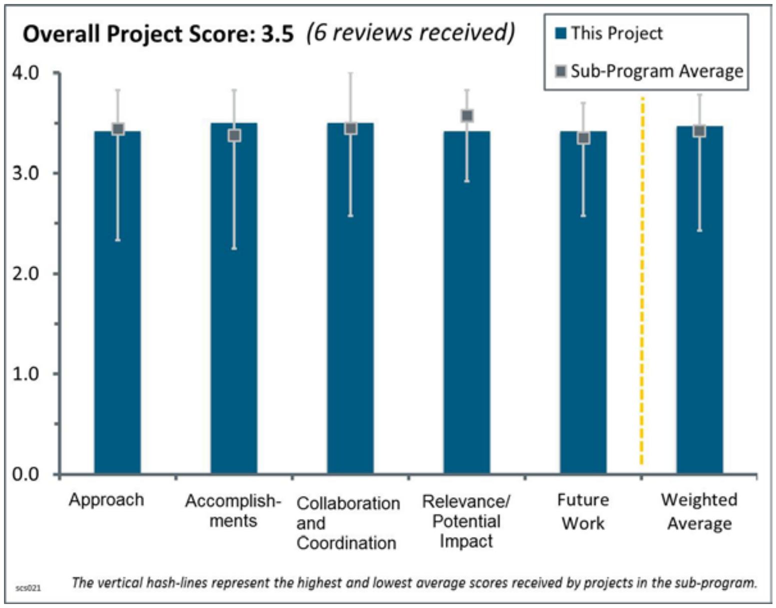
- The first responder projects should involve vehicle original equipment manufacturers. Also, the project should get involved with the SAE J2990/1 Gaseous Hydrogen and Fuel Cell Vehicle First and Second Responder Recommended Practice committee, which is working on a document that provides recommendations to vehicle manufacturers from the first responder perspective and includes recommendations for emergency response guides. Also suggested is involvement in the SAE committee to develop Hydrogen Fuel Cell Vehicle Crash Testing Safety Guidelines, which is associated with SAE J3040 and the SAE Impact and Rollover Test Procedure Committee.
- This suggestion is challenging and not easily implemented. Progress in this area cannot be evaluated simply on the basis of progress toward a few quantitative targets. However, some qualitative indicators are available, such as the numbers of downloads of a training package, the availability of guidelines where none had existed to date, or the number of DOE projects for which safety planning is a reality. However, it is not clear how to evaluate the impact of these achievements. Perhaps the project is planning some kind of "users' satisfaction survey." It is not clear the project has a way to assess how the impressive mass of lessons learned have contributed to the overarching goals.
- The project should break some of these tasks out into their own projects/speakers. There is much information that should be explored further.

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

Bill Buttner; National Renewable Energy Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- This project is of a very special nature; it specifically addresses one of the most critical hydrogen safety components in a holistic and integrated way. The project interfaces with all players (i.e., industry, permitting bodies, developers, and manufacturers) and with all other parts of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program). It is well aligned with the evolution of the overall Program area. In recent years, the project has developed from activities aiming to produce a fundamental assessment of sensor performance toward activities aiming to understand the complexity of sensor deployments in the various stationary and transport applications.
- The team did a very good job of keeping the approach "neutral." While the presenter is clearly very knowledgeable and committed to the work, he did not have bias in the presentation and gave the facts, positive or negative. The statement at the bottom of slide 6 is right on.
- The project features good background investigation and cooperation with the Joint Research Centre (JRC).
- The sensor laboratory work is very timely and a very much needed capability.
- The project and work on sensors is important for the industry—it is recognized that additional information is needed and welcomed. In that sense, the project is fulfilling DOE goals and objectives. However, a confusing part of this presentation (and the others from NREL) was how this activity addresses the three barrier statements (listed below), since the project is neither a code nor a standard activity.
    - C. Safety is not always treated as a continuous process
    - F. Enabling national and international markets requires consistent regulations, codes, and standards
    - G. Insufficient technical data to revise standards
- Overall, the approach to meeting the barriers to implementation of safety sensors is fine because this effort should support industry partnerships, safety working groups, and code development. However, it seems that the tailpipe emissions work might be straying somewhat from the intent of this project. Also, it is not clear how this project interacts with the H2FIRST (Hydrogen Fueling Infrastructure Research and Station Technology) sensor project that was implemented; there was no mention of supporting or interacting with that particular project, although they were both led by NREL.

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

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

- The project delivers important short-term support to meet DOE objectives, but it is also helpful in identifying and achieving long-term goals. Examples of this latter aspect are the book on sensors technologies and the gap analysis and recommendations at the service of standards and regulations. An example of the former aspect is the collaboration with sensor developers to meet the requirements of specific applications.
- The KPA Inc. work and the SAE International document work seem extremely relevant and important to the commercialization of hydrogen and all types of fuel cell electric vehicles. The technical report may be very valuable to station developers in their project submissions for funding.
- The team is making good progress in setting up the laboratory and developing sensor test methods.
- The research testing was on point. Technical areas of concern were identified and improved.
- The accomplishments were adequate and meet the needs of the Safety, Codes and Standards sub-program.
- The publication of information is good; however, the quality of production/manufacturing of sensors needs to improve.

Question 3: Collaboration and coordination with other institutions

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

- The project has developed excellent working relationships with industrial partners, (international) governmental bodies, and codes and standards developers. It is thus in the best position to play a reference role for this part of the safety galaxy.
- The collaboration with various agencies on different kinds of projects demonstrates the flexibility and knowledge base of the team.
- The project seems to work with codes and standards, testing, and commercial entities on a regular basis, and it should be part of any further H2FIRST sensor projects going forward.
- The project features excellent communication with other technical laboratories, especially JRC.
- The collaboration with outside partners is excellent.
- The project features good collaboration. Presenters should refrain from making comments that imply collaborating organizations do not have routine interactions and do not have good working relationships. This indicated that NREL was the reason the collaborators were able to interact/work together, which is not true.

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

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

- This research is very much in line with and advances progress toward Hydrogen and Fuel Cells Program goals and the objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The sensor technology is much needed for compliance testing.
- There is so much work needed for sensors, and this team is providing leadership and relevant research and development of test methods.
- This is an important aspect of facilitating the implementation of hydrogen fuel cell vehicles because maintaining a safe environment is key for success.
- A lot of good information is being developed. The next step is to have it applied in the field/real life.
- The impact of the project is mainly incremental and in many different directions: from the recommendations for Phase II of the Global Technical Regulation (GTR) to the SAE group addressing onboard sensors, and from the international collaborations within a European project and the International

Energy Agency/Hydrogen Implementing Agreement to the support to end users related to sensor field deployment.

- It was good to accentuate the point that this is about educating the community on the usefulness of sensors. The presenter did a good job of "validating" the relevance of this work. There could be more potential impact and relevance if the project worked with suppliers on refining guidance on sensor application, use, and installation.

Question 5: Proposed future work

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

- The proposed future work is in line with the previous project goals, but it is more focused on strategic, present priorities related to the practical installations (e.g., the use of sensors in tunnels and in confined spaces). It also further explores detection methods to meet additional detection aspects, such as those related to fuel quality. In this sense, the project is continuously adapting to the evolution of overarching safety goals.
- The proposed future work is very well focused on the key issues.
- The project needs to work more closely with the automotive industry to ensure the knowledge is shared, and to identify possible weaknesses (e.g., non-compliance) of sensors being used in compliance testing.
- The project basically proposes to continue its interactions very similarly to how it operates currently. It would be good to see some emphasis on identifying inexpensive sensors for hydrogen production, delivery, and onboard monitoring—following up on the report generated by the H2FIRST project.
- There seems to be uncertainty on the next steps and the impact on real-life acceptance of hydrogen, and on how this will improve the reliability of sensor technology. Addressing the reliability of sensors—when taken out of the box, or reducing the number of "failures" when new—would be a key initiative.

Project strengths:

- The overall approach of the laboratory and the types of projects it is involved with has evolved, demonstrating the team's flexibility and openness to various options/uses for sensors and to improvement of sensors and their uses. The work with GTR and KPA Inc. (i.e., private industry) is excellent. The investigation of Wide Area Monitoring (a potential future application for outdoor use at stations) is good.
- The project tackles all aspects of hydrogen sensors and constitutes an internationally recognized competence center for this technology. Considering the limited amount of funds, it shows a very high level of efficiency.
- The principal investigator has a good background in sensors and is involved in the sensor and safety community.
- Bill Buttner is the expert in the field of sensors, and he has done outstanding work on this project.
- Project strengths include identifying information and defining key terms/information for industry.
- The project features a very capable team that is focused on key issues.

Project weaknesses:

- There are no observed project weaknesses.
- There were not any apparent weaknesses.
- Based on the presentation, there is a need to communicate with industry, either through an SAE committee or directly. Sensors in this application are not well known, and this type of research should be shared widely.

Recommendations for additions/deletions to project scope:

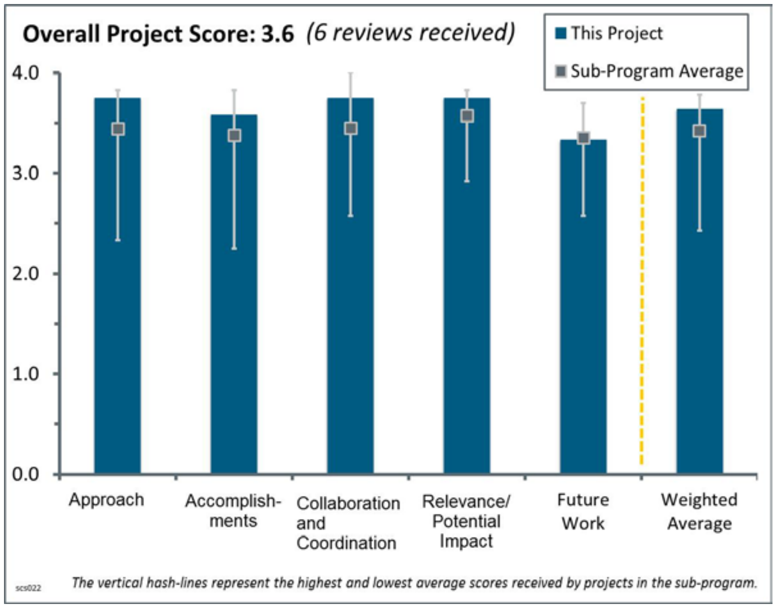
- While this work is good, there is a need for more guidance on the installation of sensors—where to place them, how many are needed, maintenance recommendations, etc. Current codes and standards say to follow manufacturer instructions, but those need improvement. Because this project already works with industry, it should be an "easy" next step. The team could take the KPA Inc. work further and do some case studies at actual facilities (which could also feed into codes and standards revisions on sensor use). This would require collaboration—for example, with other projects/laboratories that work closely with authorities having jurisdiction. The project team could use California as the testbed.

- Perhaps it is possible to couple sensor performance indicators with risk assessment tools to be able to answer the question of where to more effectively install safety sensors to ensure capture of all possible hazards related to hydrogen accidental releases.

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

Morry Markowitz; Fuel Cell & Hydrogen Energy Association

Brief Summary of Project:



This project supports and facilitates development and promulgation of essential codes and standards to enable widespread deployment and market entry of hydrogen and fuel cell technologies. The goals of the project are to (1) ensure that best safety practices underlie research, technology development, and market deployment activities supported through U.S. Department of Energy (DOE)-funded projects; (2) conduct research and development to provide critical data and information to define requirements in developing codes and standards; and (3) develop and enable widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Question 1: Approach to performing the work

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

- Code harmonization and information dissemination will play such a huge role in the overall market success within and beyond California. Exposure is one thing, but playing from similar playbooks is another. The more codes and standards can be harmonized, the easier it will be on everybody. Establishing a clear picture of discrepancies and establishing pathways to fix them is the right first step.
- Regarding the degree to which barriers are addressed, the project is well designed, feasible, and integrated with other efforts. The project provides good insights to addressing the stated barriers (on slide 2)—namely, F, H, and J.
- The approach is good; it involves facilitating and coordinating the participation of members in the working groups of the normative bodies. The team made a strong effort to identify critical items and prioritize work. The website is becoming a reference resource for stakeholders.
- The approach provides a forum for interested parties to participate, for education and outreach to occur, and for the identification of standards requirements, just to mention a few attributes of this effort.
- There certainly is no lack of entities and activities to coordinate. The structure and amount of working groups are appropriate.

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

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

- This work is critical and needs to continue. Relationship building is crucial, and the project is focusing on it. Ideally, the information developed by this effort will be integrated into existing systems/organizations.
- The accomplishments and progress indicate that the project is doing good work, and the national and international interfacing efforts are valuable.

- The degree to which progress has been made and measured against performance indicators is good, as is the degree to which the project has demonstrated progress toward DOE goals.
- The results over the years have included the development of international standards for hydrogen infrastructure and the promotion of U.S. interests in this area.
- The meetings and connectivity are clearly happening. There appears to be a lack of direct impact, apart from coordination, which is important but a soft goal. More emphasis should be put on other direct impacts.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- The project interacts well with other entities and projects, such as the Fuel Cell and Hydrogen Energy Association (FCHEA), code development organizations (CDOs), standards development organizations (SDOs), and the National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee.
- The project team is connected and collaborating with all of the appropriate groups.
- This is a truly international effort.
- The tent continues to grow, which is all for the better.
- Coordination with multiple SDOs/CDOs is a strength of the project, but interfacing with pre-normative activities could be improved.

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

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

- The project does a good job of supporting and advancing progress toward the Hydrogen and Fuel Cells Program (the Program) goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- The project is very relevant to Program goals and seems to work well with industry members to support trade interests. The website and coordination effort illustrate the strong, positive impact of the project.
- This effort is a necessary component for the development of a globalized industry.
- All of this work helps to establish this trust.
- The increase in coordinated efforts is apparent.

Question 5: Proposed future work

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

- The project will end by November 2015. The project has effectively planned its future in a logical manner by incorporating appropriate decision points; considering barriers to its goals; and, when sensible, mitigating risk by providing alternate pathways.
- Continuity in this effort is needed now more than ever, as the first “real” infrastructure and automobiles are put in service.
- The challenge is balancing the long-term timeframe of the codes and standards environment with the need for short-term results in some respects.
- The Special Task Force for Strategic Planning is a relevant proposition to anticipate critical items. The future work is mainly carrying on the present activities.
- The future work seems to be more of the same. It is not clear whether alternative approaches have been fully explored, and whether there is a way to better anticipate looming hurdles for the industry.

Project strengths:

- The project features excellent communication. The teleconferences provide an excellent opportunity for stakeholders to exchange information and discuss important milestones.
- This project provides a multiyear, continuous experience in promoting and coordinating normative efforts at the national and international levels.
- The project features well-coordinated efforts with other partners and provides meaningful support to FCHEA codes and standards.
- The strength is in the collective participation.

Project weaknesses:

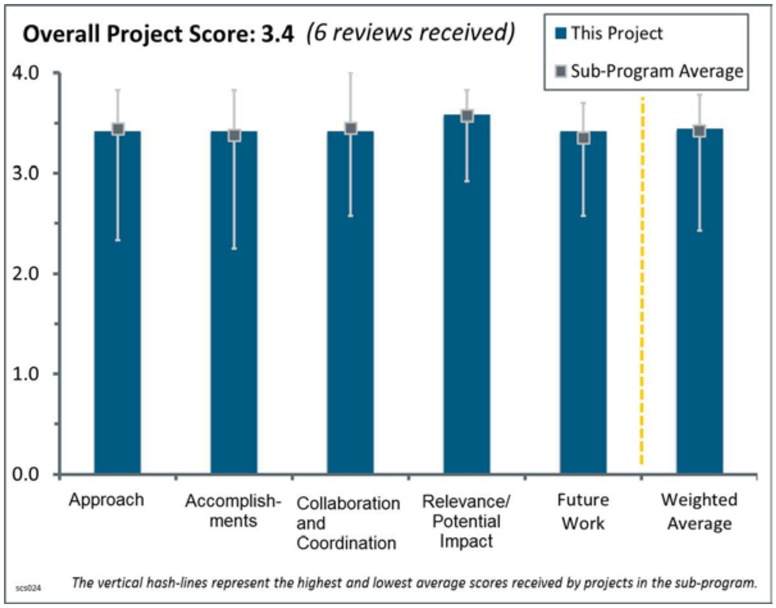
- The lack of interface with a research activity is a weakness.
- Progress may be delayed by standards bureaucracy.

Recommendations for additions/deletions to project scope:

- To the maximum extent possible, this effort should be integrated with the H2tools.org and Hydrogen Safety Panel efforts so that lessons learned are centralized and accessible to all.
- No change is needed, but FCHEA could play the role of interfacing normative activities with research or pre-normative activities (e.g., round-robin testing).
- This effort must continue to be supported.

Project # SCS-024: Hydrogen Contaminant Detector

Daniel Terlip; National Renewable Energy Laboratory



Brief Summary of Project:

The goals of this project are to (1) reduce the installation cost of a hydrogen fueling station to be competitive with conventional liquid fuel stations; (2) improve the availability, reliability, and cost while ensuring the safety of high-pressure components; (3) focus a flexible and responsive set of technical experts and facilities to help solve today's urgent challenges and unpredicted future needs; and (4) enable distributed generation of renewable hydrogen in a broader energy ecosystem.

Question 1: Approach to performing the work

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

- Protection against contaminants arising in hydrogen fuel is a complex problem. This effort has been systematic in identifying the important factors that must be accounted for and how that might be accomplished.
- This was a $30,000 study to understand the state of the art for hydrogen contaminant detection suitable for hydrogen fueling stations with an SAE J2601 fill. This work has been completed and is reported in a National Renewable Energy Laboratory (NREL) report.
- A market study as described is appropriate. The data needed were included in the earliest edition of SAE J2719. It is suggested that NREL speak with Mike Steele, the SAE International chair of the Fuel Cell Standards Committee (FCSC). He has the supporting documents and presentations for this activity. The generation of engineering requirements is appropriate. It is not clear whether the requirements were vetted by industry. Again, Mike Steele would be a sound resource.
- This approach seems much better aligned with and geared to the commercial application. Working more closely with Los Alamos National Laboratory (LANL) may speed up the process even further. It is good to see the collaboration with California Air Resources Board (CARB) on station configuration, SAE International on contaminants, and original equipment manufacturers (OEMs) on levels indicating process upset. In addition, please note it is helpful to include links to reports in the slides.
- Near-term solutions are not likely "one size fits all." It is not clear why it needs to be that way. Lower-cost alternatives may work better in some situations, while other station configurations may require higher-cost alternatives for hydrogen contamination detectors (HCDs). On slide 8, the statement was made that "not all contaminants are probable in stations," which appears to support this contention.
- The first barrier described in the presentation, "A. Safety Data and Information: Limited Access and Availability," has not been addressed well. However, the following barrier from the U.S. Department of Energy (DOE) Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) is being addressed well: "G. Insufficient Technical Data to Revise Standards – Research and operational data collection activities are underway to develop science-based codes and standards. New approaches for data generation, collection, and analysis will also be needed to close safety knowledge gaps." The results of this project will facilitate publication of revised SAE International and International Organization for Standardization (ISO) technical committee (TC) 197 standards relating to fuel quality and cleanliness, as well as the promulgation of these requirements.

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

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

- The project is 100% complete. The report was published (for this project), and the Phase II proposal was submitted. Funding Phase II is strongly suggested, as is working more closely with LANL in that phase.
- The researchers are finished. The report was published by NREL under the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project.
- The project accomplishments are comprehensive. The project has identified customer and functional requirements, integration of detection into a station system, contaminant levels of interest, measurement techniques and existing equipment through a survey, and technology gaps. The team has proposed the next steps that are needed.
- The data summary is very interesting. It should be noted that "OpCost" is usually presented in dollars per hour or dollars per year.
- This project has accomplished a good deal, considering it was started so recently (during the fourth quarter of fiscal year 2014) and is funded at the level indicated ($30,000 total with 50% expended). The presentation did not describe the following applicable DOE goal: "Develop and implement practices and procedures for the safe conduct of DOE-funded hydrogen and fuel cell projects. Provide the scientific and technical basis for requirements in critical [regulation, codes, and standards] to enable full deployment of hydrogen and fuel cell technologies in all market sectors." The project should consider more clearly articulating how this important work aligns with the overall DOE goals and objectives, as well as the technical challenges and barriers the project is addressing in outreach and communications to make it clearer to the audience how this project fits in to current research and development (R&D) needs.
- The cost impact of the inline hydrogen contaminant analyzer is not clear. It is also unclear whether there is a path toward cost reduction. "Manufacturers that submitted information about available sensors have not expressed strong interest to develop sensors that meet [the] list of requirements developed by H2FIRST HCD project team." The team needs to discuss what can be done to change this or how this can be addressed.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration appears excellent. It is not clear what collaborations are occurring with sensor manufacturers, aside from requesting input/information through survey. The project should consider international collaboration for this. It is not clear that international collaboration is currently part of the project.
- This was a survey of the state of the art in contaminant detection technologies. This team consulted with the appropriate experts in the code development world and in the technology space.
- Again, it is great to see collaboration with all of the key players (e.g., CARB, OEMs, and SAE International). The presenters should be sure to also indicate (in the slides) that there is communication with LANL, other laboratories, and internationally because this was not apparent. The use of the SAE J2719-1 table (and communication with the chair) should also be indicated. It would be wise to carry out the market survey.
- It appears the right project partners are involved. Further work collaborating with related efforts could improve uptake of the project results and reduce the potential for duplication of effort. This project is fairly new and is funded at a very low level. Closer integration of the activity with SAE International activities and enhanced outreach of the project goals and progress within H_2USA and SAE International would be useful; however, it is recognized that these take time and effort, which may not presently be accommodated in the project's level of effort.
- Collaboration was performed by both research organizations and parties responsible for initial infrastructure deployments.
- The collaboration list is somewhat limited. The engineers with the data may be found at SAE International FCSC (M. Steele), CSA HGV (S. Marxen), ISO 19880 (J. Schneider), and ASTM Committee D03 on

Gaseous Fuels (R. Dominguez). ASTM is especially important. It is where the instrument manufacturers are interfacing with this endeavor.

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

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

- This work is extremely important for stations currently rolling out and those that will be in the immediate and near future.
- This work is likely too difficult for industry to accomplish by itself. This effort will accelerate efforts to standardize quality control and maintenance issues for delivery of a quality product.
- The OEMs are currently insistent about inline sensing. Therefore, the project is highly relevant.
- HCD is critically important for fuel quality assurance. This survey report pulls this information into one place, which is very valuable.
- Although not noted in the presentation, this project seems to be relevant to the following DOE goal in the MYRDDP: “Develop and implement practices and procedures for the safe conduct of DOE-funded hydrogen and fuel cell projects. Provide the scientific and technical basis for requirements in critical [regulations, codes, and standards] to enable full deployment of hydrogen and fuel cell technologies in all market sectors.” Specifically, the project relates to the following objective: “Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards.” The presentation could be improved by clearly linking project goals back to appropriate published DOE goals and objectives.
- The overview of targets and available sensor equipment with resulting gaps (compared to targets) do not indicate how many gaps there are exactly because of the bandwidth of sensor capabilities.

Question 5: Proposed future work

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

- Phase II is essential/needed.
- The next step in the process, the development of deployable test systems, will be more difficult. The plan calls for engaging industry, which is a necessary first step.
- The proposed follow-on is interesting. It would be nice to evaluate sensor systems. It is not clear at which step the sensor systems are designed and fabricated.
- Some proposed next steps seem logical; however, it is not clear what impact technology gaps have on the team’s ability to develop a suitable system or conduct suitable testing. Describing go/no-go decisions and validation partners more fully could improve the proposed future work. There is some potential for this work to lead to a development project that addresses unacceptable gaps in technology, which might be useful.
- Future work for this particular effort is irrelevant—the work is done. However, it will be important to keep this information current as the technologies change and as the tolerance toward the contaminants changes.
- The project is missing efforts to analyze the cost of sensors (in dollars per kilogram dispensed)—especially because all sensors available are at least two times more expensive than the target installed cost of $5,000.

Project strengths:

- This project directly addresses a need defined by industry for effective use of hydrogen quality standards (i.e., SAE J2719 and ISO 14687-2), as well as develops requirements for cleanliness and testing. Integration into H_2USA’s Hydrogen Fueling Station Working Group allows for close collaboration with many of the key stakeholders and opportunities for real-time refinement.
- The project has demonstrated a comprehensive approach.
- The expertise of the laboratory at NREL and the desires of the OEMs are project strengths.
- The gaps are identified.

- The project did an okay job in understanding the current state of the art. The project is done, and the results are published.

Project weaknesses:

- The project weaknesses are not known at present, but they will become known with the effort to place equipment in the field.
- Articulation of alignment to DOE goals and objectives, as well as how the project addresses barriers and technical challenges, could use improvement. The project's level of effort may not be adequate to facilitate coordination with key stakeholders at a sufficient level. An increase in technical interchange meetings with SAE International and H_2USA, along with information dissemination through broader channels, could increase understanding about the project and increase stakeholder input to guide future efforts.
- A project weakness is the lack of relevant collaborations.
- It does not appear that the identified gaps will be filled any time soon because manufacturers that submitted information about available sensors have not expressed strong interest in developing sensors that meet the list of requirements developed by the H2FIRST HCD project team.

Recommendations for additions/deletions to project scope:

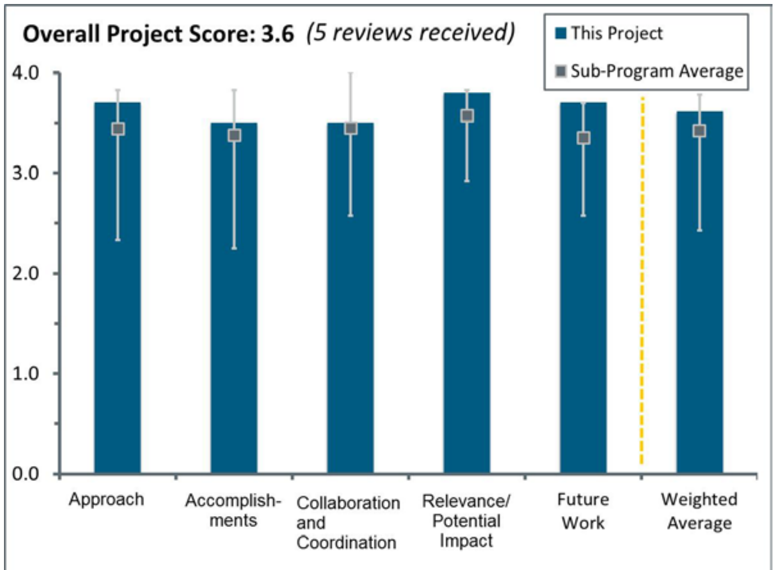
- In the cases of some station configurations, three HCD locations are possible, but it is not clear which location is most essential and challenging. The project should do the following: (1) consider variations and focus first on an HCD location that is related to a contaminant that does irreversible damage to fuel cells in fuel cell electric vehicles; (2) focus on the least damage-related contaminant HCD location last; and (3) consider what it would take to have the third HCD potential location removed from the list of potential HCD locations.
- The project should interface with SAE International, CSA, and ISO 19880 committees for data requirements, as well as with ASTM Committee D03 for instrument manufacturer outreach.
- The project should work with the ISO WG 24 Draft Technical Report 19880-1 document committee, CSA HGV TC, and SAE International. The technology should be implemented at "real" commercial stations for field testing.
- Interface with stakeholders should be increased. The ability for the results of the gap analysis and testing to lead to new work (whether a part of this project or not) would be useful in launching an effort that improves upon the available technologies.
- The state of the art for HCD devices really needs to remain current. This technology space will change in the coming years. This will be a result of improving technology, as well as changing requirements.

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

Chris LaFleur; Sandia National Laboratories

Brief Summary of Project:

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



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

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

- The approach of developing performance-based safety methodologies is sound and worthwhile. The project lead is a fire safety engineer. This adds significant credibility and increases confidence when working directly with authorities having jurisdiction (AHJs). However, it is critical to avoid potentially sending mixed messages to the AHJs. Collaboration with industry stakeholders on messaging is recommended. Use of developing modeling tools had the double benefit of validating the project results and contributing to the further development of the models. Direct involvement in the International Organization for Standardization (ISO) working group (WG) that is developing general requirements for gaseous hydrogen fueling stations is an effective way to coordinate with key national and international stakeholders and keep the project focused on the most significant concerns.
- The approach is very comprehensive and timely.
- The approach is multidisciplinary and multi-methodology. It integrates all aspects and all players to reach the objectives (obtaining industrial input for frequencies data, achieving excellent scientific competences required for a science-informed tool, and engaging with stakeholders, such as code developers and AHJs).
- The approach is two-pronged. The first approach is to allow alternative methods to show compliance with the model codes. The second approach is to generate the research to relax the existing prescriptive requirements.

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

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

- This project will certainly contribute, once finalized, to the overarching goals of the DOE Hydrogen and Fuel Cells Program (the Program). Thanks to the integrated approach, it even has the potential to accelerate the achievement of those goals. It appears that the project's degree of accomplishment is also aligned with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The only uncertainty is related to possibly failing to reach consensus among the stakeholders. As already mentioned by previous reviewers (in 2014), there is some suspicion about probabilistic methods among end users and AHJs.

- This project has been ongoing for many years and is always focused on the highest-priority needs. Significant progress has been achieved in the gaseous hydrogen risk analysis. The project's current focus on liquid hydrogen storage issues is timely.
- The accomplishments and progress to date are impressive.
- Working both domestically and internationally is consistent with the recent efforts across the board in codes and standards harmonization. While the rest of world may not use the National Fire Protection Agency (NFPA) work, the efforts with ISO are critical to getting other countries on board with the quantitative risk assessment (QRA).

Question 3: Collaboration and coordination with other institutions

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

- Collaboration and coordination levels are appropriate for this point in the project.
- The collaboration section shows collaboration with the key laboratory activities, but it is not clear whether this collaboration extends to messaging. A more clearly articulated and coordinated approach with related industry and laboratory efforts regarding messaging with AHJs would improve the project. To avoid perception issues, the presentation would benefit from a sentence or two relating to the openness and fairness in developing project partnerships.
- The project has developed strategic collaboration with key industry players, is well integrated in the national codes and standards frame, and reaches out to end users. Regarding the international dimension, the project also strives for worldwide consensus achievement in the frame of the ISO and makes use of the International Energy Agency's Hydrogen Implementing Agreement research and development collaboration for further tuning its science-informed tool.

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

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

- This is a high-value project with clear alignment to the Program's goals and objectives, as well as with the technical challenges and barriers the project addresses.
- This activity is highly relevant and has the potential to reduce capital costs.
- The impact of this project can be very big, but the impact depends on (1) the team's ability to develop an integrated tool that is well validated and accepted by the scientific community, and (2) the adoption and use of the tool to produce performance-based designs. While the first condition is more related to SCS-011, the second condition is specific to this project and, if fulfilled, could have positive consequences on other fields and trigger wider adoption of the performance-based design and probabilistic approach.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- The proposed future work is very good, but outreach needs to be addressed. Just because the NFPA book committee agrees does not mean that AHJs will accept the methods. Working with state authorities who have jurisdiction over their states (plus New York City) is suggested. States such as Massachusetts, Connecticut, New York, New Jersey, and Florida are recommended. If those officials get on board, getting the county or municipal official to accept the methods will be easier.
- The proposed future work is very relevant and important. Information on technology transfer, however, is limited. For this critical technical work to be useful in achieving the desired adoption of risk-informed alternative compliance methodologies, a well-thought-out plan for vetting, educating, resolving concerns, etc. should be included. To avoid potentially sending mixed messages to AHJs, this activity should be performed with other key groups that are involved in related efforts. These groups include the California Fuel Cell Partnership, the Fuel Cell and Hydrogen Energy Association's Hydrogen Codes Task Force,

H_2USA's Joint Regulations, Codes, and Standards (RCS) Task Team, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory and, at the appropriate time, the NFPA Hydrogen Technologies Technical Committee.

- It would be beneficial to include an educational portion in California permitting workshops. In addition, the project should work with NFPA staff (perhaps as an H_2USA project) to offer a NFPA course on the implementation of NFPA 2 across the country. The educational element could/should educate workshop attendees on the history of the setbacks and explain the rationale for the alternate methods/performance-based option (risk equivalency) so that the AHJs might be more apt to approve/accept it through the permitting process. (To clarify, this is not to show the AHJ how to use the QRA but to show how to apply Chapter 5 of NFPA 2 when a project proponent submits a plan using this method.)
- The project management has a clear vision of the pending milestones and critical deadlines. The time to achieve the important goal of inclusion in the updates of the NFPA 55 and NFPA 2 is limited, but the plan to achieve this is realistic.
- This is an excellent plan for future work; however, it does not appear to be realistically funded to meet the code revision needs in 2020. Separation distances and mitigations for liquid hydrogen are one of the key barriers for the large-scale success of the hydrogen fueling infrastructure. Coupled with Hydrogen Risk Assessment Models (HyRAM) and the liquid hydrogen release studies also being done at Sandia National Laboratories (SNL), this alternative compliance effort may make an impact on U.S. code and also have a worldwide impact through the collaborative work with ISO TC 197 WG 24. However, there should be a near-term funding mechanism within DOE to assist in accelerating this important gap. This is basic science and should be assisted as soon as possible.

Project strengths:

- The project relies on a very competent team and capable management. Strategic interfaces with stakeholders have also been put in place. Project goals are very ambitious because of the novelty of the methods adopted and the short time frame available for reaching them.
- This project responds directly to industry needs in developing RCS and is well aligned with DOE goals and objectives.
- The project strengths are the needs of the industry and the abilities of the laboratories.

Project weaknesses:

- The project weakness is the idea of public outreach to the local AHJ.
- An adoption strategy closely coordinated with key stakeholders is described in comments under "Proposed Future Work" but is currently lacking.
- The only apparent weakness is the high risk of the project due to the lack of acceptance of the approach among stakeholders and the very tight schedule for acceptance. The probabilistic approach is not widely accepted by AHJ or design engineers.

Recommendations for additions/deletions to project scope:

- This project has an excellent plan for future work; however, it does not appear to be realistically funded to meet the code revision needs in 2020. Separation distances and mitigations for liquid hydrogen are some of the key barriers to the large-scale success of the hydrogen fueling infrastructure. Coupled with HyRAM and the liquid hydrogen release studies also being done at SNL, this alternative compliance effort may make an impact on U.S. code and also have a worldwide impact through the collaborative work with ISO TC 197 WG 24. However, there should be a near-term funding mechanism within DOE to assist in accelerating the liquid hydrogen releases and the HyRAM tool. This is basic science and should be assisted as soon as possible.
- It is recommended that the outreach focus on the states (and New York City) that have central jurisdiction to accept the methodology. If they accept and endorse the methodology, then the states with distributed jurisdiction are most likely to accept and adopt the methodology. The first step might be state fire marshal and state building inspector trade organizations.

- The team should develop a coordinated plan for promoting acceptance of the resulting risk-informed methodologies into the codes and standards.
- Abandoning a traditional, deterministic methodology and prescriptive approach to design is difficult. Demonstrating the results and the advantage of using the new approach in real cases is critical for project success. In addition, hands-on sessions with a wide group of stakeholders would lower the “psychological” barrier represented by a new “unknown” system. The creation of an area on H2Tools dedicated to practical cases and the hosting of question and answer sessions would help. Finally, it is not clear if the project has a backup plan. The impact of the project results could still be important even if the adoption of its approach in the next code updates does not take place.

2015 — Market Transformation
Summary of Annual Merit Review of the Market Transformation Sub-Program

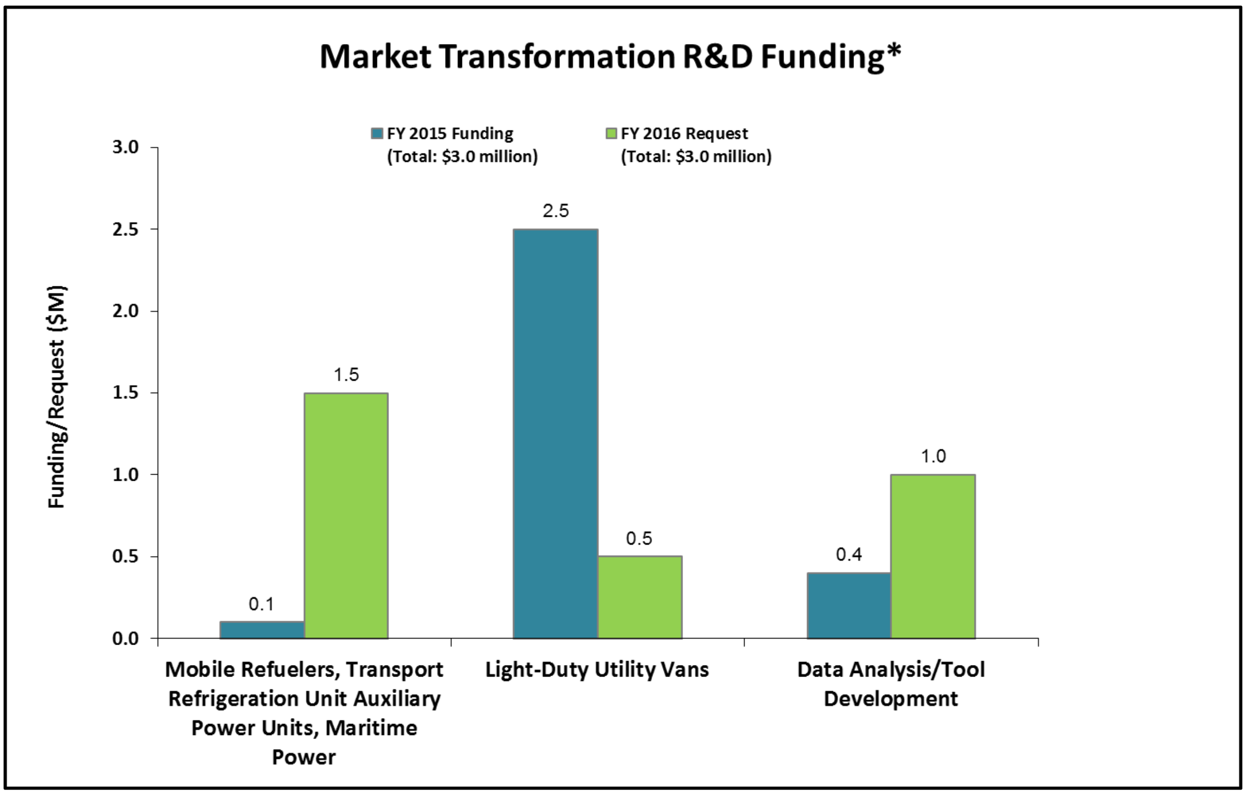
Summary of Reviewer Comments on the Market Transformation Sub-Program:

The purpose of the Market Transformation sub-program is to spur market introduction by testing technologies in pre-commercial applications. By supporting initial commercialization in key new technology applications, this sub-program helps to identify and overcome barriers to marketability and to reduce the life cycle costs of fuel cell power through various technical and non-technical solutions. The current focus of the Market Transformation sub-program is to build on past successes in lift truck and emergency backup power applications (part of the U.S. Department of Energy's [DOE's] American Recovery and Reinvestment Act of 2009 [Recovery Act] efforts) by exploring the market viability of other potential technology applications. Four projects were reviewed this year, and these projects are highly leveraged, with more than half of the funds provided by DOE's partners. This substantial commitment of external resources shows the high level of interest in exploring applications and markets where the hydrogen and fuel cell industry can expand and the technologies can play a valuable role.

Reviewers generally shared positive comments about the sub-program's projects, noting that the projects have been well planned. Reviewers stated that the sub-program's coordination with agencies is commendable and allows the sub-program and the other agencies to leverage funding to achieve mutual and individual goals; however, reviewers also suggested that increased collaboration with private companies could be beneficial.

Market Transformation Funding:

With the market successes achieved by fuel cells in lift trucks and backup power applications as a result of prior fiscal years' and Recovery Act funding, the focus of fiscal year (FY) 2015 funds was on a new application: battery/fuel cell light-duty hybrid service vans that will demostrate a value proposition for utlities and other types of operations and maintence fleets. The Market Transformation sub-program budget for FY 2015 was $3 million.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on progress in each area.

Majority of Reviewer Comments and Recommendations:

The Market Transformation sub-program's projects were rated average to high, as overall ratings ranged from 2.3 to 3.5, with an average score of 3.2. The projects were judged to be relevant to DOE activities and employ good or adequate technical approaches. Reviewers emphasized the need for data collection to develop business case reports that can be used to support further market expansion.

Airport Ground Support Vehicles: This project received an overall score of 3.4. Reviewers reported that the plan to complete this project is reasonable and progress to date is on schedule, scope, and budget. However, they mentioned that the cost of delivered hydrogen was not reported, making it impossible to understand the value proposition. In addition, reviewers were concerned that the data set for fleet operations—which is critical for identifying further technology improvements—was not reported.

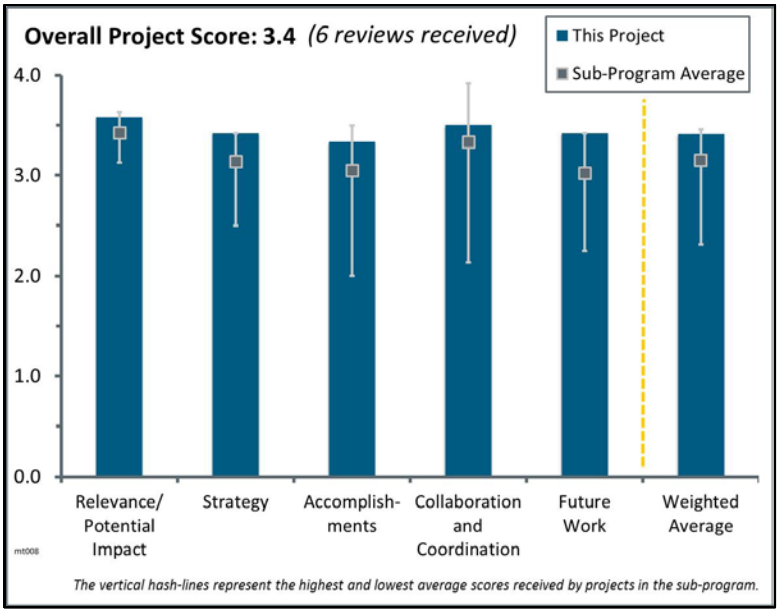
Hydrogen Energy Systems as a Grid Management Tool: This project received an overall score of 3.4 for its efforts in modeling, testing, and validating potential applications for hydrogen energy systems to address grid stability issues. Reviewers stated the project does a great job of recognizing barriers and issues and taking actions to address them. Reviewers also stated that the project is worth continuing, and that data collection and analysis will be a key factor in determining a business case. Reviewers pointed out the lack of installed operating equipment as a weakness, and that more economic analysis showing cost components was needed.

Maritime Fuel Cell Generator Project: This project received an overall score of 3.5 for its efforts in developing, designing, and testing a first-of-its-kind hydrogen fuel cell power generator for maritime applications. Reviewers stated that the project has done a great job in its outreach campaign. Reviewers asserted that cost and benefits analyses are needed, as well as potential markets.

Fuel Cell Hybrid Electric Delivery Van Project: This project received an overall score of 2.3. Reviewers praised the project's concept; however, they also noted the project has fallen behind schedule because of supplier and other issues. Reviewers commented that the project team spent nearly a year developing the project requirements, an inappropriate amount of time to allow for attaining the project goals within the project schedule and budget. Reviewers stated that the project had a good strategy and plan for implementation; however, they also commented that the recipient had failed to obtain the required cost-share resources. Reviewers stated that the project had the potential to impact Fuel Cell Technologies Office goals related to the implementation of fuel cells in commercial vehicles and initially had a considerable amount of non-federal funding; however, they reported that changes to the project team and funding has put this project in jeopardy of not meeting its objectives.

Project # MT-008: Hydrogen Energy Systems as a Grid Management Tool

Richard Rocheleau; Hawaii Natural Energy Institute



Brief Summary of Project:

The objectives of this project are to (1) demonstrate the performance, durability, and cost benefits of grid-integrated hydrogen systems; and (2) support development of regulatory structures for permitting and installation of hydrogen systems in Hawaii. Electrolyzers will operate under dynamic load conditions to mitigate impacts of intermittent renewable energy. Hydrogen will be supplied to shuttle buses operated by County of Hawaii Mass Transit Agency and Hawaii Volcanoes National Park.

Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- Electrolyzers can play a critical role in energy systems that have a substantial share of fluctuating renewable energies. This project addresses renewable hydrogen production and its use in vehicles and provides learnings in this context.
- This is a highly leveraged project across many different organizations and is highly focused to balance with natural, renewable energy systems. The reviewer is not aware of a more advanced grid support hydrogen project anywhere in the United States or the world.
- The location, partners, and objectives are well aligned with U.S. Department of Energy (DOE) goals from the perspective of hydrogen generation for transportation (leveraging grid services and available renewables). The project also aligns with market transformation objectives for the learning of one site to have a positive impact on future sites.
- The project addresses a real need to deal with grid perturbations due to heavy amounts of renewables.
- The project has had its ups and downs, but the data collected on the operation of the electrolyzer and refueling the hydrogen vehicles will be worthwhile and would add to the Hydrogen and Fuel Cells Program.
- The project appears to generally line up with research and development objectives.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- Barriers faced by Hawaii Natural Energy Institute (HNEI) have been unique and challenging, and the fact that HNEI has overcome them will serve as a potential response for later projects. HNEI’s project is a mix of great and unique challenges coupled with equally unique responses.
- Overcoming the barriers has consistently been a challenge for this project. This highlights the real-world challenges. It would be good to see how the lessons learned from this project are used for addressing Barriers A and H.

- The project does a great job of recognizing barriers and issues and then taking the necessary actions to address them.
- The project has a good plan to identify and evaluate all issues.
- This project does address many of the barriers required to implement hydrogen technology. Unfortunately, many of the problems encountered and overcome were regional and specific to this project. However, lessons learned from this project would still be worthwhile.
- It is unclear how far the project addresses the analysis of the benefits of the electrolyzer operation for the grid (the link between field testing and modeling). This may include not only frequency stabilization but also storage capacity and provision of hydrogen to other energy sectors.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project has done a great job on developing grid support as planned, on developing data for operating systems in harsh environments as planned, and on responding to unforeseen natural challenges (lava) and manmade challenges (parental protests).
- The project has had some delays but overall appears to be working well toward accomplishing its goals. Some of the delays due to environmental conditions were unavoidable.
- The project has had many delays, but the project team has agreed to continue the program and to collect data for two years past the project's end date, which is this September. The data collected are still important and should be gathered and disseminated.
- Moving the initial testing to Powertech was a good strategy, given the siting challenges that have continued to be a problem. It seems that testing is still delayed, and response time testing does not seem as relevant because that testing has been completed already. Even given the real-world challenges of siting, not having the equipment in place and operational is a negative.
- The project has identified analytically the value of an electrolyzer in stabilizing the grid.
- The complete system operation (hydrogen production, including service to the grid and bus operation) has not yet started.

Question 4: Collaboration and coordination with other institutions

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

- The project does well at collaborating and utilizing available resources to achieve its goals. The project's interaction and support of other DOE projects in Hawaii is noteworthy!
- There are many good state partners, and there is also involvement from National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory for safety. Involving NREL in data analysis is recommended for the extended portion of the project.
- There is great partnering with a number of partners.
- The collaborations are strong and represent many different stakeholders. Missing from this collaboration list are Powertech and the company providing the electrolyzer, which seem to be important collaborations for project success.
- The project needs more involvement with the electric utility, although admittedly, this is difficult.
- Including the local utility/grid operator is critical.

Question 5: Proposed future work

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

- The commitment to operate the system beyond the end of the DOE-funded project is critical. A detailed analysis will be needed to quantify the benefits of electrolyzer operation to the grid. Future work should focus on identifying opportunities in Hawaii to increase the share of renewables and the role hydrogen can play in this context.

- Though not a ding on the project, DOE should consider remaining a part of this activity (at no cost) for data gathering. The results could be beneficial for other parts of the Hydrogen and Fuel Cells Program .
- The team is strongly encouraged to go forward after the official project ends to collect as many data as possible.
- The future work makes sense for the tasks. The dates do not seem to match with the project status, as of the Annual Merit Review material due date. It would be good to see what the projected run time is outside of the DOE-funded project.
- A key indicator here is that DOE funding is ending, but the project has two more years of life.
- The need for cyclic testing of electrolysis modules is recognized.

Project strengths:

- The project has strong leadership. Project activities are bringing visibility and a positive attitude toward fuel cells in the state of Hawaii.
- The team was flexible in addressing siting issues. Complete system testing at Powertech should help to ensure a smooth start of operations in Hawaii.
- This is an invaluable project with a strong, well-run management team.
- This is a good team that had to overcome a considerable number of everyday and not-so-everyday issues. The goal of the team to go forward and collect data beyond the project's official end is commendable.
- The project is strong in the collaborations, project goal, and siting.
- There is great planning and contingency response.

Project weaknesses:

- The project has no noted weaknesses.
- In this project, the hydrogen produced will be used to fuel buses. Other potential hydrogen users and their impact on the business case should be identified.
- The fact that the electrolyzer is not now directly tied to a renewable energy source is a weakness. It would have been good to assess the cost of producing hydrogen from renewables in Hawaii's high electrical cost market.
- The project weakness is the lack of installed and operational equipment at the site. If the project does not find ways to decrease the time from start to implementation, future projects may not be able to sustain this level of effort.
- There are too many development issues in series, i.e., cycling electrolyzer and fuel cell-powered buses.

Recommendations for additions/deletions to project scope:

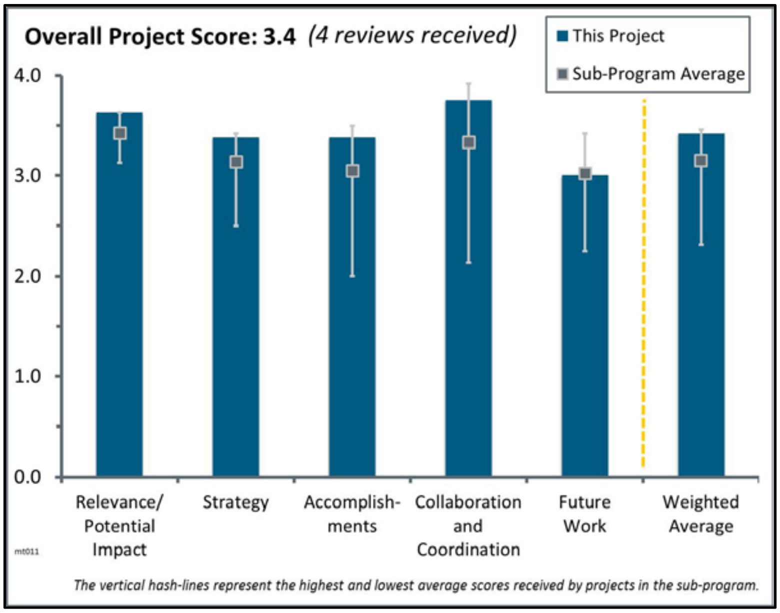
- It is to be hoped that the team can continue to collect data, and it would be good to involve NREL if NREL staff are available.
- DOE should remain a partner with HNEI (at no cost) to gather data through the life of this project.
- Identification of ways to decrease the time and effort for installation and operation is important. It would also be good to see how the electrolyzer will effectively be operated for grid services and hydrogen demand if the hydrogen demand is not high or consistent. It is not clear whether this will be handled by hydrogen storage or through operating the electrolyzer.
- The overall economics of the system need to be analyzed.
- The project should measure the life of the electrolysis stack in cycling conditions.

Project # MT-011: Ground Support Equipment Demonstration

Jim Petrecky; Plug Power

Brief Summary of Project:

The objectives of this project are to (1) develop an 80 V (~20 kW) fuel cell product for cargo tractors, (2) conduct testing with the Charlatte CT5E cargo tractor, (3) conduct a factory acceptance test to demonstrate performance parity with the battery, (4) build 15 cargo tractors for deployment, (5) build a hydrogen installation at Memphis–Shelby County Airport, (6) conduct permitting with the Memphis Fire Services Bureau, (7) conduct two years of demonstration in airport operations, and (8) use lessons learned to make improvements.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- This is an outstanding project. The project has designed and tested a fuel cell-based baggage tractor and will soon deploy it. The project will help pave the way for bringing fuel cell technology to areas that complement the fuel cell vehicles and help promote hydrogen infrastructure and dissemination of safety information. This is all very positive.
- The project addresses safety issues with hydrogen, value of low emissions, hydrogen refueling issues, and delta for fuel costs. The project also quantifies the market size.
- The project demonstrates the feasibility and practicality of fuel cell systems replacing diesel power airport equipment. Acceptance of this technology will reduce the CO_2 emissions. The objective of lower energy expenses will have to be demonstrated with low cost of delivered hydrogen.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.4** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project seems to be well organized and very feasible, and at the end, it will be very successful. Installing hydrogen technology (particularly liquid hydrogen technology) is no small achievement in any setting but is very noteworthy at an airport. The project team seems to have properly engaged the local fire/safety authorities at the deployment airport, which is critically important.
- It is a good strategy for a fuel cell company to explore a new market with fleet operations.
- The project addresses most issues; however, there is no mention of economics based on fuel cell capital cost. The project should highlight that $2500/kw is a break-even number. Any air quality measurements and the impact on the fuel cell should be shown.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- Progress is good in site preparations, refueling infrastructure building, and hardware demonstration. Cost benefits have been presented. However, the (assumed) cost of delivered hydrogen is not reported, which makes it difficult to estimate the value of the fuel savings projections.
- In reviewing the 2014 presentation, the project was originally listed as ending in 2015. This 2015 presentation lists the project end as 2017, so there seems to have been an extension. This reviewer is unsure about this, as he also reviewed this project in 2014. If the extension is due to project delay, then there could have been improved project progress, so the rating for this category is only a 3.5. On the whole, however, a good deal has been accomplished, even if it was not on the original schedule. This is still excellent progress.
- This is a great project—well organized and well planned.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.8** for its collaboration and coordination.

- Deploying technology like this, along with creating a refueling infrastructure, involves many moving parts and requires being highly collaborative, not only within the project team but also with the local aviation and fire/safety authorities. Based on the project presentation, this all seems to have gone well and will continue to go well. The project team should be commended on this front.
- Collaboration and coordination could not be any better.
- This project needed much coordination with several organizations.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Demonstration data and assessments remain for the next two years. There were no specifics on what sort of data will be provided to the National Renewable Energy Laboratory; the data should include capital and operating costs, durability, and records of maintenance to identify high-maintenance components and research and development needs.
- There was not much focus on this because of where the project is, with two years to go. In a general way, the project presented some ideas for where this technology could go with other pieces of non-vehicular fuel cell ground equipment.
- The project needs to get units at the site as soon as possible. Field data are the most critical.

Project strengths:

- Strengths include the following: (1) replacement of diesel-operated equipment with high-efficiency, clean-emissions fuel cell power, (2) successful installation and demonstration, and (3) good coordination with several organizations.
- This is a well-conceived project that addresses fuel cell market transformation in the high-priority aviation ground service equipment market. The deployment site looks ideal because it starts in an aviation application that does not involve the public (but the public is right next door).
- The project is well organized and has good partnerships.

Project weaknesses:

- Economic analysis will be the key to others' recognizing the potential of this technology. More information is needed about the cost breakdown in the public domain.

- The deployment site does not test the technology against cold weather. The project has, however, tested the technology down to -20°C in an environmental chamber. However, it would be good to do some real cold weather testing on these units. This is not a recommendation that the project be modified in response to this comment, only an identification of a weakness in the location with regard to the local climate.
- It is taking too long to get to airport testing. The impact on fuel cells of air impurities at the airport should not be minimized.

Recommendations for additions/deletions to project scope:

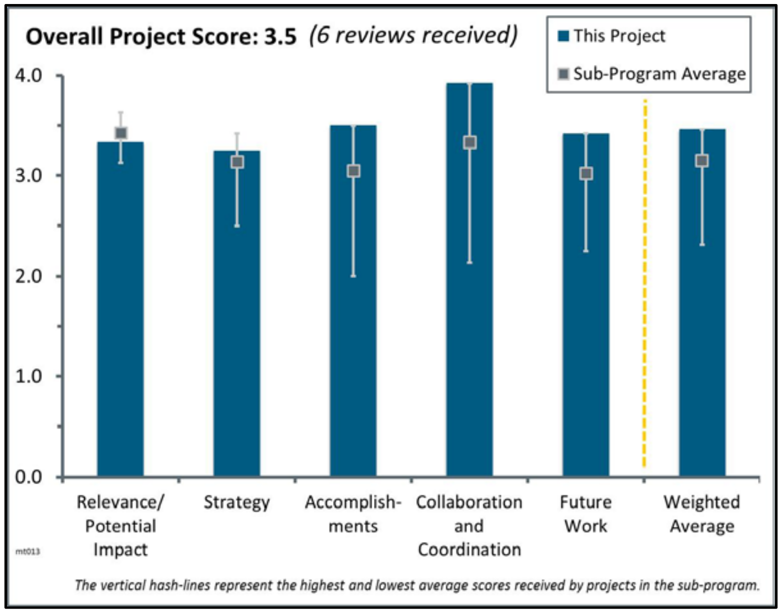
- There are no recommendations for additions/deletions. The project should keep doing what it is doing and carefully keep track of how the units fail in the field. It will be very important to get feedback from the end users on how the units can be improved. A note on the presentation: the authors should be careful about the technical details in the presentation. On slide 15, there was a plot showing the use of the battery in surge mode, but there were no identifying numbers on the y-axis, so one could not tell what power was being provided by the battery. Also, no mention was made of the assumed hydrogen price in the cost savings slide, which is required to understand the plots. These are important details that need to be provided in such presentations.
- The project should show economics, including fuel cell cost assumptions; gas analysis results; and impact on stack life.
- The project should consider an independent assessment of the economics of this demonstration.

Project # MT-013: Maritime Fuel Cell Generator Project

Joe Pratt; Sandia National Laboratories

Brief Summary of Project:

The overall objectives of this project are to (1) lower the technology risk of future port fuel cell deployments by providing performance data of hydrogen proton exchange membrane fuel cell technology in this environment; (2) lower the investment risk by providing a validated business case assessment for this and future potential projects; (3) enable easier permitting and acceptance of hydrogen fuel cell technology in maritime application by assisting the U.S. Coast Guard and American Bureau of Shipping in developing hydrogen and fuel cell codes and standards; (4) act as a stepping stone for more widespread shipboard fuel cell auxiliary power unit deployments; and (5) reduce port emissions with this and future deployments.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

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

- This is potentially a high-visibility project that clearly advances hydrogen applications for transportation and refrigeration—the team deserves credit for both points. While storage limits the amount of refrigeration in this early first adaption, the deployment nonetheless demonstrates the wide-open scope of hydrogen possibilities. Equally significant is that this project provides important data on the operation of fuel cells in a harsh maritime environment with multi-axis movement.
- The project will help the Hydrogen and Fuel Cells Program (the Program) and the fuel cell industry better understand the challenges and benefits of semi-portable auxiliary power units. The use in a difficult environment (salty air) provides an opportunity to evaluate dependability and areas for improvement.
- With changing emission standards (on board as well as in the port), fuel cells are an important innovation for maritime applications. The project introduces this technology to this industry.
- This is an outstanding project to introduce fuel cells into the maritime industry. However, the project team needs to show a quantitative benefits analysis that includes environmental and other factors—and especially cost.
- To be sure that this is not testing an application with a limited market, it would be good to see more discussion of the potential market that could evolve if this demonstration is successful. It would also be useful to see whether the hydrogen infrastructure deployed could be utilized for other applications to expand the project's scope.

Question 2: Strategy for technology validation and/or deployment

This project was rated **3.3** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The investigator provided a key indicator that he is sharply focused on critical barriers: issues from two weeks ago have been resolved, and he indicated that today's issues will not be issues tomorrow. Another

indicator was that in response to a variety of questions from reviewers, the investigator provided answers that indicated the issues had been previously considered. The downside is that the barges do not have enough hydrogen storage to run all the refrigerated container (reefer) units during a run to Maui (somewhat similar to a 19th century steamship relying on sails). That said, it is hard to decide between a grade of 3.5 and 4.0, because 0.5 points seems like too strong of a hit for less than perfection, so the score could easily be switched.
- The use of other Program resources (e.g., Sandia National Laboratories' [SNL's] risk analysis group) to address problems is beneficial to the project and the Program.
- The project seems well designed, with the right array of stakeholders involved. The delays with the fuel cell unit are probably the biggest concern in terms of execution, although it appears these are being addressed. The hydrogen solution also seems to be somewhat of a temporary patch on a bigger problem with how to supply and store hydrogen in this environment, so it should be made clear how much this affects the business case for this application.
- The overall timing seems to be critical. Once the system is installed, sufficient time is needed to field test the complete system in both applications (in the dock and on the barge).
- All the stakeholders have bought into the project. However, the effects of an ocean environment on fuel cells need to be addressed more seriously. Salt spray could be a problem.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

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

- The project did an excellent job of identifying key regulatory issues that will need to be further addressed to support maritime fuel cell applications. This effort helped identify early regulatory gaps that the Program should help address.
- The project fully meets/met DOE goals. It is unique, valuable, and far-reaching.
- Overall, the project seems to have progressed well. The fuel cell delays were an issue, but they seem to have been addressed.
- The team has managed well, overcoming difficulties as they occurred.
- It is great that the project identifies all the stakeholders and gets their input.

Question 4: Collaboration and coordination with other institutions

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

- This is an apparently complete and real team—it is very comprehensive. The best part, something that DOE can probably use elsewhere, is the U.S. Coast Guard letter advising that this hydrogen project is breaking new ground.
- The project has integrated well with other Hawaii activities. Collaborations are appropriate for the successful implementation of the project.
- The partnerships and collaboration on this project appear to be very good, with the right entities included and plenty of outreach and engagement.
- It is hard to think of better cooperation among the stakeholders.
- The team includes all relevant competencies.

Question 5: Proposed future work

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

- The efforts to remain committed to the project through the entire demonstration activity are positive and should provide valuable information for the Program.
- There is room to grow and expand this project—something that will grow the U.S. knowledge base for hydrogen but also something that will reduce the state of Hawaii's dependence on imported petroleum.

- Outlining the business case will be critical to understanding whether this project is simply an interesting demonstration or has real-world potential. In particular, it will be useful to see how a project like this could scale up to a large fleet of reefers for which a significant volume of hydrogen would be needed.
- Market transformation requires the right technology/product but also the market/customer. It is not clear how the project includes or addresses potential system operators in the maritime industry.
- This is good, but a fuel cell needs to be tested close to the ocean on a boat.

Project strengths:

- The project has strong collaborations with many partners, which is great. Using the Hickam station supports the beneficial use of another hydrogen resource in Hawaii. The project's outreach campaign is noteworthy.
- The project lays the groundwork to introduce fuel cells to the maritime industry. The project offers an immediate hydrogen demand for installed hydrogen infrastructure in Hawaii.
- The project has strong program management—it is very professional.
- The partnerships developed for this project appear to be very solid and are helping stakeholders better understand hydrogen and fuel cells. The project also appears to be working particularly well with the end user.
- The project involved all major and minor stakeholders.

Project weaknesses:

- No weaknesses were noted.
- The project would benefit from more analysis or evidence of the overall strength of this application; for example, (1) that this application is a major market or will drive fuel cell deployment in multiple applications, and (2) that it has the ability to scale up to more than 5–10 reefers. It would also benefit from some indication that fuel cells compare well to other alternatives for this application.
- The project needs to pay attention not only to being a valuable one-off showcase, but to opening the door for wider deployment of fuel cells in the maritime sector.
- Some air quality measurements are needed as soon as possible.

Recommendations for additions/deletions to project scope:

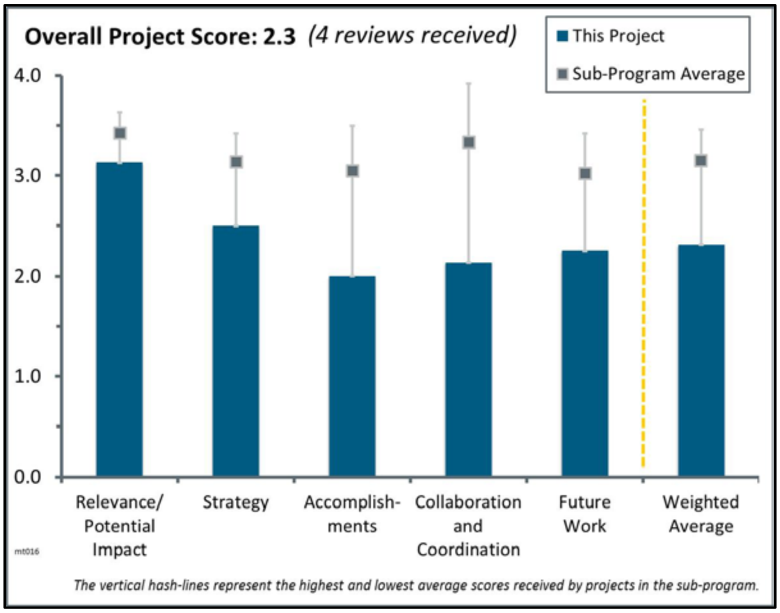
- The benefits (e.g., economics, emissions, and noise) to the site operator need to be made more obvious. Hydrogen supply is probably the most critical factor in terms of the economics. A sound concept is needed, including synergies with other possible applications at the same location. Questions around using hydrogen on board ships/vessels in the context of international standards need to be examined in more detail.
- After the demonstration is completed, the project team is encouraged to broadly share information about what is learned through the operational activities (e.g., performance, salt corrosion issues, safety data, and stakeholder feedback on issues and safety) with the Hydrogen Safety Panel and the National Renewable Energy Laboratory's codes and standards group.
- These results should be disseminated among the right companies or regulatory agencies for this marine application to keep it from being just a "one-off" demonstration.

Project # MT-016: Fuel Cell Hybrid Electric Delivery Van Project

Jason Hanlin; Center for Transportation and the Environment

Brief Summary of Project:

The overall objective of this project is to substantially increase zero emission vehicle driving range and increase the viability of electric drive medium-duty trucks. In Phase I, the project team will carefully develop and fully validate a demonstration vehicle to prove its viability to project stakeholders; funders; and the project's commercial fleet partner, United Parcel Service, Inc. (UPS). In Phase II, the project team will build and demonstrate a pre-commercial volume (up to 16) of the same vehicles for at least 5,000 hours of in-service operation.



Question 1: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- The project would help determine the potential for fleet operations of range extenders. If feasible, this could provide a valuable user for early refueling station deployments.
- This is a great project and could result in an early adopter of fuel cells, which would get good publicity. Everyone sees the UPS truck.
- This project had the potential to advance progress toward Fuel Cell Technologies Office goals on the implementation of fuel cells in commercial vehicles and initially had considerable non-federal cost share. However, it appears that changes to the project team and funding have put this project in serious jeopardy of not meeting its objectives and goals.

Question 2: Strategy for technology validation and/or deployment

This project was rated **2.5** for its project design, approach to addressing barriers, feasibility, and integration with other efforts.

- The project has a good strategy and plan for implementation.
- The project has the potential to address the stated Hydrogen and Fuel Cells Program barriers.
- The project had the potential to address many of the barriers in adapting fuel cells to commercial vehicles, but the ability of the current team to fulfill all of the project objectives is an issue.

Question 3: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.0** for its accomplishments and progress.

- Nearly a year after its start, the project has failed to achieve any tangible results. The awardee has failed to achieve its milestone deliverable for one prototype vehicle. The awardee indicates that achievement of that milestone is at least one year away. The project's primary vehicle development partner has withdrawn from

the project, which has gone to a new vehicle development partner. The awardee indicated that the cost estimates for the vehicles have increased and that the new design will not meet the project performance objectives. The awardee indicated that the project does not have resources to meet its cost-share commitment. This project is failing with respect to schedule, budget, and technical objectives. The project progress to date is unsatisfactory, and the project performance to date is testimony to the high likelihood that the project will fail.
- Because of partner and funding problems, this project has not been able to show much progress, and it appears to be almost a full year behind schedule.
- The project has gross overruns and lacks financial controls; it is $2 million in the hole, and there are no deliverables yet.
- The project has fallen behind schedule because of supplier issues. Reduced funding from one of the partners may have significant implications for final deliverables.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.1** for its collaboration and coordination.

- The project appears to be working hard at developing good collaborations. The issues with one supplier (who withdrew from the project) have hampered progress.
- The team has a prime partner in UPS but had serious problems due to the replacement of a suitable electric vehicle manufacturer. The replacement supplier, USL, is listed in the presentation as both Unique Electric Solutions and Unique Electric Services. It is unclear whether this supplier has the experience and capability to support this project, especially after having been brought on board so late.
- The awardee has failed to deliver its commitments to obtain the required cost-share resources. The coordination with the project's cost share partners appears to be both slow and non-compliant with the terms of the award.
- A major supplier backed out of the project before it even started, which set the project back months.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- Most of the future work is now aimed at designing and building a single vehicle that is a technology-validation-type project rather than the proposed market transformation project, which was aimed at building and testing a fleet of vehicles. It is not clear at this time whether funds are available for the Market Transformation sub-program portion of this project.
- Delays and potential funding impacts (due to reduced funding from one partner) need to be fully considered and addressed.
- There is a recognized need for additional funding and potential funding sources.
- The proposed future work is unrealistic in the context of available project resources.

Project strengths:

- The impacts of vehicle routing on the power requirements appear to be well analyzed and thought through.
- The project has good partners in UPS and the state of California.
- This is a good project, in concept.

Project weaknesses:

- The SAE J2601 fueling limitations need to be resolved. The project team recognizes this and is working with the SAE committee. Some of the anticipated routes appeared to require 15 kg, yet only 10 kg of onboard hydrogen will be provided. It will not be possible to facilitate some early routes (e.g., hills). There are significant early project delays.

- Having to add an electric vehicle manufacturer so late in the project is a weakness. Having to reduce the amount of onboard hydrogen from 15 kg to 10 kg may affect range for some UPS routes. The project has not secured funding at this time to complete the Market Transformation sub-program portion of the project.
- The awardee reported that the project has spent almost a year developing the project requirements. The time that has been spent establishing requirements is inappropriate for attainment of project goals within the project schedule and budget.
- There are gross cost overruns.

Recommendations for additions/deletions to project scope:

- It is not clear that any consideration has been given to who will provide approval of the van configuration (e.g., the National Highway Traffic Safety Administration or the Pipeline and Hazardous Materials Safety Administration). It may be beneficial for this project to work with other DOE projects (e.g., refrigeration trucks and the maritime project) to determine what DOE requirements should apply. It is not clear how the vehicle will be identified to assist first responders. This should be considered/addressed for the final van configuration.
- This project should be changed to a Technology Validation sub-program project if funding is available, and the Market Transformation sub-program or fleet portion can be restructured as a separate project.
- The project team needs to identify additional funding sources as soon as possible.
- Based on the current project status and expected outcome, all project activities should be terminated at the earliest opportunity.

2015 — Systems Analysis
Summary of Annual Merit Review of the Systems Analysis Sub-Program

Summary of Reviewer Comments on the Systems Analysis Sub-Program:

The reviewers considered the Systems Analysis sub-program to be an essential component of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's (the Program's) mission. They found the projects to be appropriately diverse and focused on addressing technical barriers and meeting targets. In general, the reviewers noted that the Systems Analysis sub-program is balanced between near- and long-term research and development (R&D) and well managed. They stated that the sub-program has extensive collaboration with industry, national laboratories, and academia, and that it exhibits the ability to address immediate analytical needs, meet overall objectives, and focus on supporting hydrogen infrastructure development.

Some reviewers commented that the sub-program is effective in providing analytical support and key insights for the Program's R&D efforts and guidance for R&D efforts to address key barriers. Reviewers also noted that the analysis and model portfolio is balanced and has made good progress toward understanding the issues, challenges, and opportunities related to achieving the Program's technical targets. In addition, reviewers commented that the models, tools, and financial analyses are helpful in understanding the current status of the technologies and near-term challenges; in particular, reviewers highlighted the development of the Hydrogen Financial Analysis Scenario Tool (H2FAST) and its benefit to states that are developing and evaluating infrastructure deployment.

Key reviewer recommendations for this sub-program include the following: (1) more emphasis is warranted on near-term market barriers and the transition to and early deployment of hydrogen fuel cell electric vehicles (FCEVs) and infrastructure; (2) international technological progress, policies, and implementation should be closely tracked, and the global learnings should be incorporated into the Program; (3) analysis of consumer behavior should continue and be explored with stakeholders; (4) low-volume production and market penetration should be incorporated into the cost analysis; (5) the FCEV fuel economy range should be updated and compared to current FCEVs; and (6) funding for the sub-program should be increased so that it can continue to address a wide range of analytical topics.

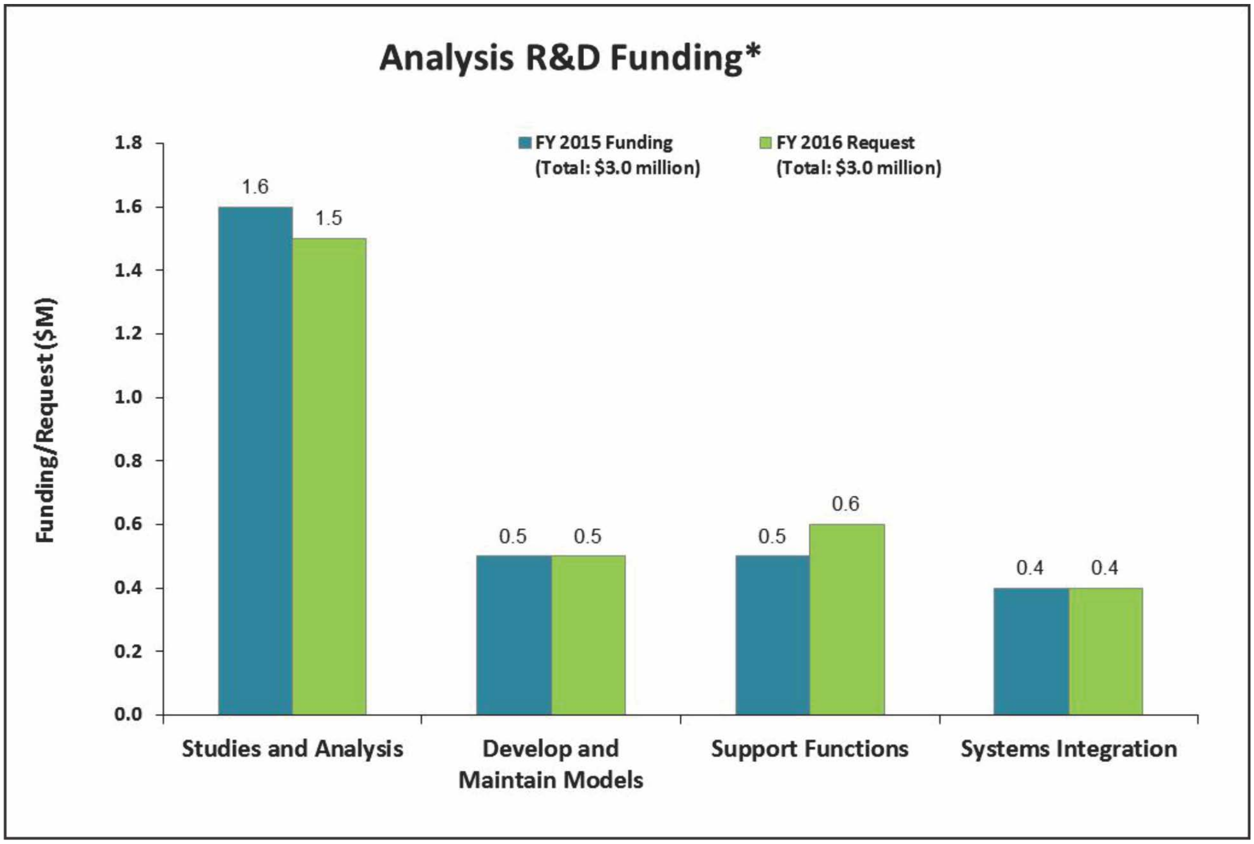
Systems Analysis Funding:

The fiscal year (FY) 2015 appropriation for the Systems Analysis sub-program was $3 million, as shown in the chart on the following page. Funding continues to focus on conducting analysis using the models developed by the sub-program. In particular, analysis projects are concentrated on analysis of hydrogen for energy storage and transmission, early market adoption of fuel cells, continued life cycle analysis of water use for advanced hydrogen production technology pathways, the levelized cost of hydrogen from emerging hydrogen production pathways, the impacts of consumer behavior, the cost of onboard hydrogen storage options and associated greenhouse gas (GHG) emissions and petroleum use, and hydrogen fueling station business assessments. The FY 2016 request level of $3 million, subject to congressional appropriation, provides greater emphasis on analysis of the employment impacts of hydrogen and fuel cell technologies; sustainability; early market adoption of fuel cells; life cycle analysis of GHG emissions and petroleum use for future hydrogen production technology pathways such as solar thermochemical and photoelectrochemical; the levelized cost of hydrogen from emerging hydrogen production pathways; and the impacts of consumer behavior.

Majority of Reviewer Comments and Recommendations:

The maximum, minimum, and average scores for the 14 Systems Analysis projects reviewed in the 2015 Annual Merit Review were 3.6, 3.0, and 3.4, respectively.

Infrastructure: The four analysis projects reviewed in this topic area received a favorable average score of 3.3 for assessing the costs of hydrogen infrastructure development and understanding the hydrogen infrastructure costs compared to other alternative vehicle infrastructure. Reviewers acknowledged that the projects enable a better understanding of the station configuration, hydrogen station components, the trade-off between consumer refueling time and vehicle range, and the cost of dispensed hydrogen at various dispensing pressures. In terms of next steps,



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area.

they suggested the projects examine and apply learning-by-doing curves based on actual data for future stations, conduct more in-depth collaboration and consultation with original equipment manufacturers to calibrate costs, explore trade-offs between refueling rates, and investigate the cost for different pre-cooling designs and the price elasticity of refill time.

Model Development and Systems Integration: Four projects involving model development were reviewed, receiving an average score of 3.5. These projects received favorable reviews and were regarded as well aligned with the current sub-program goals and objectives.

Reviewers commented that the JOBS H2 (JOBS and economic impacts of Hydrogen) model provides a useful understanding of the range of potential employment impacts due to hydrogen infrastructure deployment and identifies focus areas for R&D funding. Reviewers recommended expanding the project to include an analysis of the infrastructure rollout in California, employment benefits of federal versus state or regional infrastructure investment, and an analysis option for the “net impact” of potential job displacement.

Reviewers acknowledged that expanding the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model platform to include water-use life cycle assessment addresses critical and relevant Program issues associated with hydrogen production, and that the comparative evaluation to conventional fuels is significant. They noted that the model enables industry stakeholders and energy producers to understand the water consumption sensitivity associated with electricity, biofuels, and process cooling methods. Reviewers also found the future work for the GREET project to be robust, but they noted the need for more collaboration with stakeholders, such as utilities. They also stated that future analysis should include uncertainty ranges for the reported results and regional impacts of fuel production on water consumption.

Reviewers commented that the *Infrastructure Investment and Finance Scenario Analysis* project with H2FAST is well thought-out and addresses a critical barrier in engaging the investment community. The reviewers noted that the Internet-based and Excel models represent a significant accomplishment and enable potential investors to make quick financial investment evaluations of hydrogen fueling infrastructure. They also stated that the project exhibits excellent collaboration and validation of the model. The reviewers recommended making the H2FAST model details and code available to the public.

Programmatic Benefits Analysis: Two projects were reviewed in this topic area, receiving an average score of 3.4 for assessing the costs and GHG emissions for multiple hydrogen production pathways. The reviewers commented that these analysis projects, which assess the Program's benefits (in terms of cost and reducing GHG emissions and petroleum use) and the emerging hydrogen pathways with renewable resources, are relevant to the Program's objectives and illustrate the merits of hydrogen as an alternative transportation fuel for light-duty vehicles. Reviewers commented that the projects have strong collaboration with industry and academic stakeholders and enable the benefits and impacts of emerging technologies to be assessed for a wide range of variables and scenarios. The reviewers recommended assessing near-term, lower-market penetration, and low-volume production in the scenario evaluations.

Studies and Analysis: Four analysis projects were reviewed, receiving an average score of 3.4. The projects covered a range of topics, including the status of non-automotive fuel cells, fuel cell cost analysis, and the application of tri-generation fuel cells for infrastructure development.

Reviewers commented that the *Status and Prospects of the Non-Automotive Fuel Cell Industry* project provides an understanding of how market incentives can excite disruptive technologies such as fuel cells in new markets. They found the analysis to be valuable for the assessment of current and future policy in support of fuel cell technology and product commercialization. The reviewers recommended expanding the work scope to explore the effect of state and market incentives, such as the California Self-Generation Incentive Program and Renewable Identification Numbers (RINs) for material handling equipment and hydrogen infrastructure development.

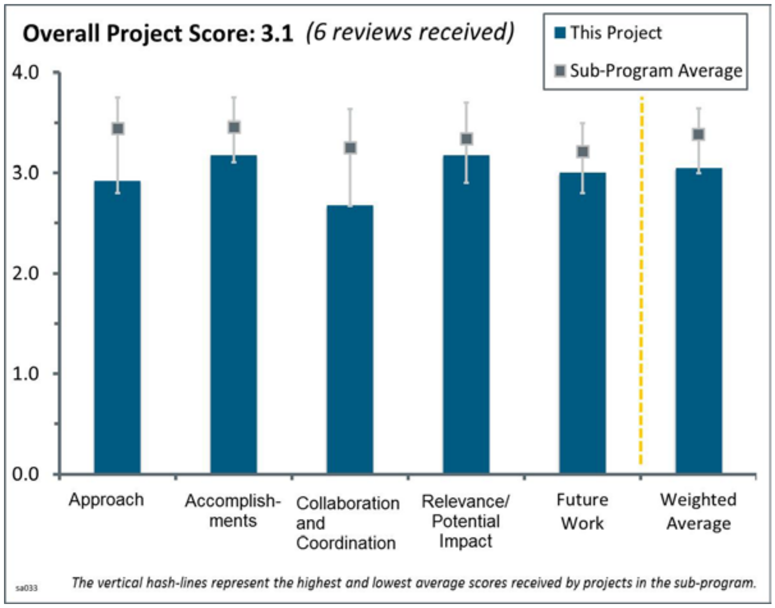
Reviewers noted that the *Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost* project has used a very good strategy and has applied the well-respected Argonne National Laboratory Autonomie model to configure FCEV subsystems and assess vehicle cost changes resulting from improved fuel cell peak efficiency. The reviewers acknowledged the project's strengths in assessing the impacts of meeting targets on the vehicle cost and providing key insights for setting R&D priorities. The reviewers recommended the results include a sensitivity analysis of key input variables to assess the main drivers for reducing the vehicle cost.

Reviewers stated that the *Tri-Generation Fuel Cell Technologies for Location-Specific Applications* project provides insight about the potential number and location of tri-generation fuel cell systems in an early FCEV market as an infrastructure build-out supplement. The reviewers observed that the project provides scenarios that will help developers consider the business case for tri-generation and help drive policies toward favorable incentives to assist technology implementation. Reviewers suggested sharing the project with key stakeholders in the Northeast for the development of a market transformation strategy.

Reviewers commented that the *Performance and Cost Analysis for a 300 kW Tri-Generation Molten Carbonate Fuel Cell System* project provides a comprehensive approach to validating modeled capital and operating costs against actual costs at the Fountain Valley tri-generation fuel cell unit to compare efficiency, economics, and system integration. Reviewers noted that the project's collaboration and strategy provide a useful assessment of the tri-generation system and will be beneficial in assessing other tri-generation applications, such as buildings and hospitals, to help provide hydrogen fuel at reasonable cost, particularly during the transition phase. Reviewers recommended improving the presentation of the project results to convey the inherent trade-offs between electricity, hydrogen, and heat.

Project # SA-033: Analysis of Optimal Onboard Storage Pressure for Hydrogen Fuel Cell Vehicles

Zhenhong Lin; Oak Ridge National Laboratory



Brief Summary of Project:

The overall objectives of this project are to (1) develop a method to optimize onboard hydrogen pressure in fuel cell electric vehicles (FCEVs) by integrating a wide range of factors, (2) conduct case studies and provide useful insights for the industry and research and development planning, and (3) identify the optimal pressure that reduces system cost and increases market acceptance of hydrogen FCEVs..

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project researcher employed an effective approach to this work by integrating all of the necessary parameters required to develop this optimization analysis, including hydrogen station costs, vehicle onboard storage cost, and the costs associated with refueling inconvenience. The external models and tools look like they are the adequate ones for this type of analysis.
- This project seeks to understand the optimal hydrogen pressure for onboard storage in a hydrogen-powered fuel cell vehicle based on tank and fueling station costs and driver inconvenience. As such, it does a good job of modeling a complex problem using a simple model, but the system is probably more complex than can be represented by the few parameters used here.
- The approach is very good, but it is not clear how it addresses the barriers of system life cycle assessments and codes and standards. Understanding optimal pressure given an array of dependent variables can help station owners determine the best configuration in the early market. The results could have been better presented—they were confusing and difficult to understand.
- The researchers have taken a reasonable approach to the difficult problem of addressing consumer behavior. For the work to be credible, it must somehow be validated with observations of actual consumer behavior.
- Pressures should be considered in a continuum, not just at the three pressure levels. The optimum level sought by the project might not be one of the individual pressure levels considered. Maybe there is a benefit of going to 15,000 psi—analysis should not be truncated at the round number of 10 ksi because it is the standard today. The volume of storage should be considered as a parameter as well. For example, hydrogen could be stored in the roof of the car if this would make the car twice as desirable; perhaps this is not the case, but it should be considered. Or perhaps vehicles could be 1 foot longer to increase range by "x."
- It was not entirely clear what barriers were being addressed or what approach was used to address those barriers.

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

This project was rated **3.2** for its accomplishments and progress.

- The team made very good progress in terms of the upgrades to the Hydrogen Optimal Pressure model by including both range value and zero-emission vehicle (ZEV) credit values. This makes the analysis more complete. It will be good to see how the implementation of mixed pressures within the same station will affect the overall results of this analysis.
- The researchers have made very good progress in creating a tool that all users can use to gauge optimum hydrogen pressure. The ZEV aspects are intriguing, but the researchers need to closely follow any congressional action.
- The model development work has progressed well.
- Although the work was interesting and it was good to see that it is providing a publicly available model, there are some weaknesses in the modeling approach. First, it did not appear that the model was considering vehicles that were designed for high pressure but were being refueled at lower pressures. This would seem to be the most likely adoption of lower-pressure refueling. It also appears that policy and consumer impacts are being handled in a very simplistic manner. Because ZEV credits and consumer choice play so significantly into the results, it is important to spend time making sure these are a robust and detailed part of the model.
- The results are good, but it is difficult to understand them in the way they are presented. For instance, on slide 12, the principal investigator (PI) presented potential cost components in dollars/kilogram using variables that are not additive; ZEV loss is an original equipment manufacturer (OEM) cost, while hydrogen cost and refueling hassle are costs only from the driver’s perspective. It would have been interesting for the presentation to have had at least one slide summarizing results from previous years, particularly those from the model, which are interesting and show the extent of the work that has been done.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- There is good collaboration with Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory in terms of generating the proper input and parameters from the hydrogen station side. The researchers will get great benefits if they also try to establish some collaboration with the automobile industry, especially now that hydrogen fuel cell vehicles are being introduced to the market.
- The project features a good set of national laboratories working together. This project desperately needs direct input from OEMs. The OEMs have already decided on the pressure of hydrogen to be used in the next-generation rollout of cars; if this model is to be of any use, it needs to be part of the engineering design of the generation of vehicles after this one.
- Not having OEMs directly collaborating on this analysis seems like a major gap because pressure would have a direct impact on their products. Perhaps OEMs are not interested in collaborating. It may even be worthwhile to get a set of consultants with backgrounds in the OEM world to provide inside information (of course, no proprietary information should be shared).
- It would be good to see more collaboration with stakeholders. Although Air Products is a collaborator, it appears to be the only stakeholder, and the connection is through the U.S. DRIVE Partnership, which is a weak linkage. It would be good to see input from OEMs and suppliers.
- The PIs need to extend collaboration to organizations with access to consumer behavior data. Kalibrate has a project to site hydrogen stations and long-standing expertise in understanding consumer fueling behavior. Collaboration with Kalibrate would be a good place to start.
- A quick check with automotive manufacturers would have uncovered a number of potential improvements for the work. Otherwise, the collaborations are adequate.

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

This project was rated **3.2** for its relevance/potential impact.

- This project is relevant and provides essential analysis for the system cost of storage, codes and standards for storage, and market transformation to enable hydrogen-fueled vehicles. The synergistic relationship is very good between the cost of the tank and station with consumer needs and ZEV tax credits.
- This project aligns with some of the other pressure optimization work being done by ANL and the Fuel Pathways Integration Tech Team, which has been of interest to U.S. DRIVE partners. It is particularly interesting to understand the effects of ZEVs on market penetration.
- Even though 700 bar delivery pressure has been established as the delivery pressure for the fuel cell electric vehicles entering the market in the initial rollout, it is clear this type of analysis will be extremely valuable to station operators and consumers regarding what may be the most optimal delivery pressure once the market has been established.
- If the results can be validated, the model could yield important information.
- It seems that industry momentum for 70 MPa is so significant that it is unclear whether analysis could make a difference. However, this analysis provides an understanding of the trade-offs.
- Because the barriers this work is addressing are unclear, it is not apparent how the project is adding value. For example, it is not clear how this project is adding value above and beyond the very similar work in pressure analysis done at ANL, which seemed to have a more defined objective and approach to address barriers.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Adding daily distance variability and uncertainty analysis will strengthen this project.
- It would be good to bring voices of OEMs into the “discussion.” It may be necessary to aggregate OEM contributions to avoid proprietary issues and competitive conflicts. Maybe questionnaires/reviewer feedback would be a good way to get OEM input.
- In addition to the proposed future work, the team should include collaboration with OEMs to obtain feedback on the model; perhaps the software tool should be shared with automotive manufacturers to conduct “deep-dives” and case studies and to get their input.
- The proposed work seems appropriate, but the end date stated at the beginning of the presentation will definitely need to be extended for the team to complete the proposed future work.

Project strengths:

- The project features strong modeling capabilities and expertise, as well as a good understanding of the issue.
- Having a publicly available model as an output is a project strength.
- The synergistic interdependence of all relevant factors is a strength.

Project weaknesses:

- This project suffers from being poorly defined. A better definition of the objective and the barriers would help a lot. The team should make sure the future work addresses these issues. Additionally, the way policy and consumer aspects are being addressed is overly simplistic. For example, it is probably not realistic to use a rental car cost as the cost of consumer inconvenience. This may be a realistic approach for someone who can plan well ahead and then make a rational choice. Consumers often do not have the luxury of planning well ahead, and they are well known not to make rational decisions. Inconvenience even one time during a year will often means a consumer will never go back to that brand.

- Early adopters have already decided on the tank pressure, and there is no real attempt in the model to accept that tank and station costs are very variable. Just looking at the Toyota Mirai and Toyota’s ability to rapidly reduce tank costs shows that this is a dynamic market. The project needs to collaborate with several vehicle OEMs and potentially station developers for real-world experience.
- Weaknesses include the lack of OEM input and validation of consumer behavior, as well as the difficulty of using the tool.

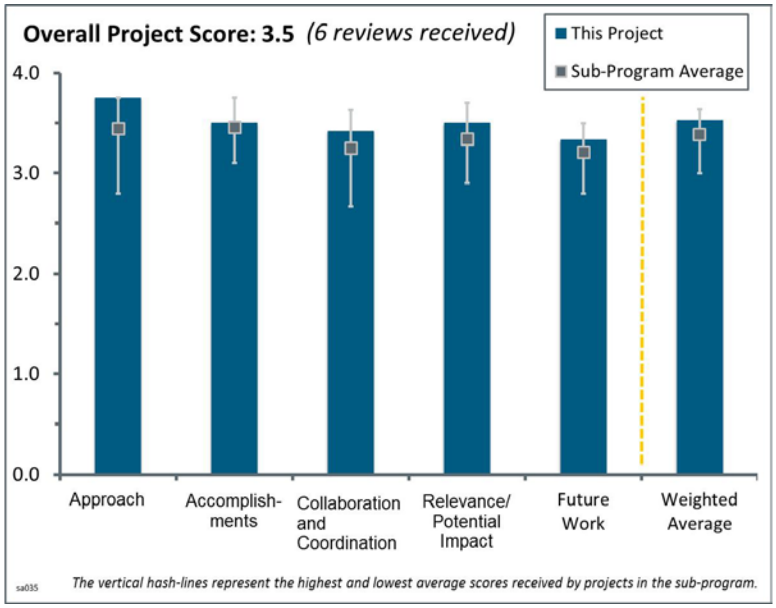
Recommendations for additions/deletions to project scope:

- The researchers need to seek a way to validate their model assumptions. A diary study might be useful. They could consider a survey, for example, to assess consumer preference for vehicles with various ranges. They should also work with companies whose business it is to understand how consumers behave.
- The team should consider collaborating with automotive manufacturers. The team should also include other potential incentives, such as low-carbon fuel standard credits and ZEVs post-2018. The team should also produce charts that reflect the points of view of different stakeholders—consumers, OEMs, and station owners—instead of lumping together all of the costs.
- The value this adds beyond the work at ANL (i.e., SA-045) needs to be more clearly defined.
- More interaction with OEMs is needed.

Project # SA-035: Employment Impacts of Infrastructure Development for Hydrogen and Fuel Cell Technologies

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

The objectives of this project are to (1) develop a consistent framework to estimate the impact of hydrogen infrastructure investments by the Fuel Cell Technologies Office (FCTO) and others; (2) develop a tool to address barriers/gaps in the FCTO analysis/modeling portfolio; (3) evaluate the impacts of alternative hydrogen and fuel cell infrastructure deployment scenarios; (4) provide input for evaluating FCTO research, development, and deployment targets; (5) work with stakeholders to develop robust, user-friendly tools with appropriate functionality; and (6) report analytical results to demonstrate the benefits of the FCTO activities.

Question 1: Approach to performing the work

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

- This project uses a well-developed modeling platform for consistent analyses of job creation associated with the development of hydrogen fueling infrastructure. The analytic framework makes excellent use of existing models and analyses as the basis for its modeling.
- The project uses an input–output approach that captures supply chain input, which is very important. It distinguishes development versus operation. The project covers the full life cycle labor supply chain—planning, construction, equipment, and operation. The researchers looked at gaseous delivered hydrogen; it is unclear how the jobs landscape changes with the use of distributed generation, for which the system has to be monitored/maintained as well (and may add supply chain jobs).
- The team makes good use of preexisting models by incorporating them into the work. It would be good to know, at least conceptually, the sensitivity of the model to detecting losses from other sectors. This may be out of this project's scope. As it stands, this model calculates how many total jobs can be related to hydrogen, but not the net number of extra jobs created. Perhaps there could be a conceptual effort put toward identifying how many jobs are created versus shifted. Determining the net jobs seems more important. In the early years, it is understandable that this work on hydrogen stations is mostly creating additional jobs, but it is unclear when and how hydrogen station job activities subtract from other sectors to the degree that it would make a difference. For example, the team should imagine a 50% penetration scenario.
- The approach appears to be very sound and rooted in standard approaches for the subject. However, it might be good by way of explanation to review other activities or sector studies that have been evaluated using the same set of tools and general approach. Also, it is not certain that the model would not also be able to predict the impact of less gasoline consumption to generate a net impact. These types of models should be able to evaluate any level of marginal change.
- The approach is excellent, but some of the assumptions from California and other U.S. areas might require refinement with new incoming data.

- The analysis should consider even larger hydrogen stations. In the "longer" term, one expects to see stations as large as ~9,000 kg/day. The analysis seems to be artificially truncated at 1,000 kg/day and may not benefit from economies of scale.

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

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

- This project is progressing well. The initial analysis of the California hydrogen roadmap using both California multipliers and U.S. multipliers provides an understanding of the range of employment impacts that might accrue as a result of infrastructure deployment. The stochastic simulation capabilities that have been added to the modeling will be very useful in further understanding the range of employment impacts that might occur as a result of the rollout of hydrogen infrastructure.
- The ability to tie jobs to industry development on a project and/or system basis is of high value and very useful for industry, developers, and public officials.
- The project is important to improving understanding of regional differences and providing objective information.
- The results seem reasonable and show the impact of infrastructure rollout; it makes sense that development starts right away with start-up, then drops off, then grows, while station operations activities add jobs each year with new stations/larger stations. Economic activity peaks in 2022—the last year of new station development in the current plan, in the California case only. It is unclear what would need to happen beyond 2022, from an infrastructure perspective, to meet the needs of the hydrogen vehicle market, and whether there is currently a plan in place. The level of station development jobs is much higher for the United States case than the California case, as the development jobs are mainly imported from outside of the state of California. It would be useful to understand the job impacts if other station components are imported from overseas. It might be nice to see a proposed breakdown of total jobs versus location-specific information.
- The progress looks good. Inclusion of the California Fuel Cell Partnership rollout in the analysis is good. This is an important metric to track accurately and compare with other regions. A potential criticism of the project could be that it does not advance hydrogen directly into implementation; instead, the project tracks its progress. It is unclear how tracking progress fits DOE's goals.

Question 3: Collaboration and coordination with other institutions

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

- The collaboration on this project is very good. The JOBS Advisory Group, in particular, provides an excellent mechanism for feedback from stakeholders. The project team should better acknowledge and recognize the role played by other DOE researchers and industry collaborators in providing necessary data and modeling (e.g., Hydrogen Analysis [H2A] model, Hydrogen Delivery Scenario Analysis Model [HDSAM], and Regional Input–Output Modeling System [RIMS] modeling; National Renewable Energy Laboratory composite data products [CDPs]; and original equipment manufacturer [OEM] costs) for this project, although they are not direct collaborators.
- The collaboration with industry, academics, associations, and others is all appropriate and well received.
- The collaboration is good, and the project is integrated with many institutions.
- Collaboration and coordination were not specified that much on the slides, but a very good description of how the team is working with others and feedback loops is shown on slide 4. Quick response cards can direct users to access the jobs models and are an interesting idea for spreading usage/information sharing. An advisory board is an important point of a project such as this one; perhaps H2USA could be a member.

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

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

- Job creation has often been overlooked, but it is a key element for public support. This project fills a needed area to identify jobs and associated economic output development, and to build support for policy that will encourage project development that creates jobs in the supply chain.
- The main role of this work will be to prove to policymakers the value of hydrogen. In this way, it broadly helps DOE reach its goals of proving the effectiveness of FCTO funding.
- The project seems valuable and supportive of the Hydrogen and Fuel Cells Program.
- It is good to see the overall context of models, including the commerce model. This project is fairly different from other models in that it is not technology-focused. Maybe it is not as high of a priority in some ways, but as a unique and small project, it belongs in the portfolio and fills a gap.
- It will be useful for policymakers to understand the economic benefits of fuel cell vehicles and hydrogen fueling infrastructure, especially as public investment in infrastructure is considered. This project helps inform policymakers of those benefits. Because the number of jobs created may be low compared to the overall investment in hydrogen and fuel cells, it would be useful for the project to note that hydrogen fuel cell vehicles accrue other benefits that might be considered by policymakers, particularly environmental and greenhouse gas emission reduction benefits (although it is understood that analyzing those benefits is outside the scope of this study). In addition, because policy decisions regarding public infrastructure investment may be made at both the federal and state levels, it would be useful for this project to analyze the effects of federal investment in stations in California and California investments in hydrogen infrastructure (some of the hydrogen stations that will be part of the overall station rollout in California have received federal funding, but many have or will not).

Question 5: Proposed future work

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

- The future work for stationary fuel cell deployment and liquid hydrogen is important and timely to meeting future infrastructure needs for zero-emission vehicle rollouts and fuel cell deployment associated with end users and grid applications, and the work could potentially be used to justify public support and incentives.
- The project team is adding liquid hydrogen stations and larger stations. The team is also adding uncertainty analysis for fuel cells and rollout options. The presentation includes good examples of what could be funded if money were available—this information is not present in that many talks.
- The future work looks good.
- The future work is headed in a good direction. It is unclear whether uncertainties can be identified sufficiently.
- The project should be reviewed by high-caliber economists. Also, adding reviewers from the oil and gas and automotive OEM industries (with economic backgrounds) should be considered. These have to be the “right” people—folks who set policies and do macroanalysis for companies/governments. Also, downstream benefits and job contributions should be considered. Each car on the road contributes to the economy in terms of productivity and jobs. There should be a way to attribute economic benefit for the number of cars supported by the infrastructure. Even though fuel cell electric vehicles are a small percentage of the total fleet on the road, they have a proportional benefit—just the same as how hydrogen stations are a small percentage of the total fueling infrastructure. It is a significant omission to stop the analysis at the nozzle. Job and productivity benefits should extend to services rendered by the end result (miles traveled by vehicles).
- To the extent possible, it would be better for the project to focus on analyzing employment benefits and not on further model expansion/refinement (although it is recognized that some expansion of modeling capabilities may be needed). For future work, the project should consider alternative infrastructure rollouts, particularly potential infrastructure rollouts in regions outside California. It would also be useful if the analysis considered the impacts of actual/planned/projected infrastructure investments by states and the

federal government separately, particularly to understand the employment impacts of federal investments in infrastructure.

Project strengths:

- Good baselines have been set up; the team can replace current data with better data as they become available. Range versus uncertainty versus sensitivity analysis—these tools are linked now.
- The project proves the value of hydrogen. The project has good collaboration. It specifically compares California to the United States. It could help identify areas to focus funding more effectively.
- This project provides a useful understanding of the range of employment impacts that might accrue as a result of hydrogen infrastructure deployment.
- Strengths include (1) the objective analysis to identify job creation and economic development and (2) the easy-to-operate-and-use calculator tool.
- The project is relevant at the project level and flexible.

Project weaknesses:

- In terms of gross versus net, the project does not take into account jobs displaced in gasoline dispensing, etc. This is challenging at this stage, as discussed by the presenter. It is not clear what a “good” or “acceptable” number of jobs created would be—there is a good deal of hype around battery plants creating lots of jobs, which has not materialized. It is also unclear what a good measure of a technology is in terms of how many jobs are created up the supply chain. These numbers seem more reasonable and realistic, but it is unclear whether they are “attractive” from a U.S. investment perspective.
- It is understood that a full macroeconomic analysis of job creation and job transfers is outside the scope of this analysis. However, from a policy decision-making perspective, it is difficult to propose public funding of hydrogen and fuel cell vehicles without knowing whether such funding will actually lead to greater employment or just a shift to producing/staffing hydrogen fueling stations instead of gasoline stations, and to producing fuel cell vehicles rather than gasoline vehicles.
- Weaknesses include the following needs:
    - Clarify direct, indirect, and induced jobs.
    - Confirm and refine, as needed, the difference in variables for application to California and other U.S. areas.
    - Consider a marketing plan, potentially for use with the U.S. Department of Commerce and/or the Small Business Administration, to encourage job-creating projects.
    - Consider whether/how many existing jobs are displaced.
- Simply tracking metrics could be considered noncritical because the model is not actually creating the jobs that it is tracking in a direct way, but rather it is creating them indirectly.
- The project is not able to determine net impacts.

Recommendations for additions/deletions to project scope:

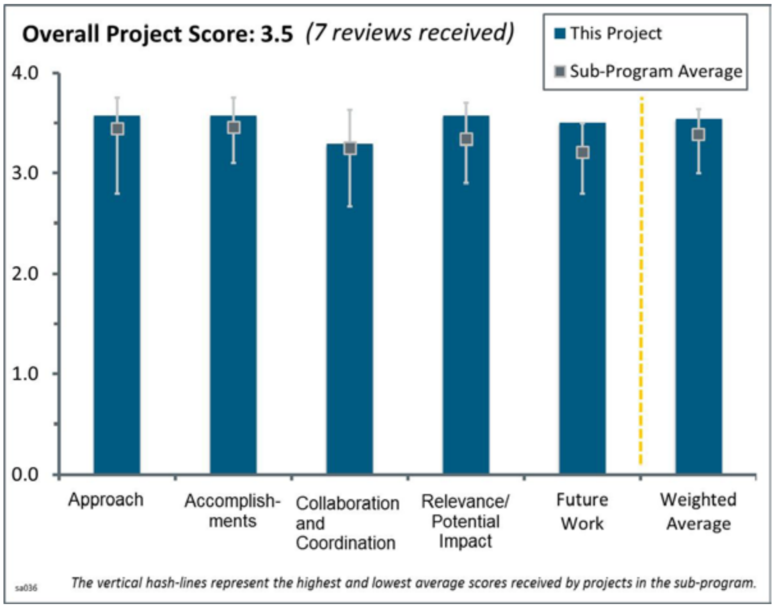
- The project should consider infrastructure rollouts outside of California. Understanding the employment benefits of federal infrastructure investment versus state or regional infrastructure investment would be useful.
- The project team needs to consider a marketing plan and marketing partners to encourage use of the model and development of the appropriate public policies to encourage job-creating projects.
- The project’s scope should be expanded to include the method of hydrogen generation, if it is not existing natural gas reforming plants.
- At some point, the project will have to look at net jobs. When there is high penetration, it is unclear when hydrogen station deployment becomes a zero-sum game.
- The project should include gasoline and calculate net impacts.

Project # SA-036: Pathway Analysis: Projected Cost, Life Cycle Energy Use, and Emissions of Emerging Hydrogen Technologies

Todd Ramsden; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to (1) determine cost, energy use, and greenhouse gas (GHG) emissions of hydrogen fuel pathways deployed in a mature market; (2) provide detailed reporting of hydrogen cost and capital costs of complete hydrogen fuel pathways to support fuel cell electric vehicles; and (3) report the life cycle of energy and feedstock usage and GHG emissions.



Question 1: Approach to performing the work

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

- The objective of the project is to determine the cost, energy use, and GHG emissions of different hydrogen pathways, assuming they are deployed in a mature market. The project uses existing models, tools, and studies by others to analyze different pathways. Seven prior pathways were reported out in last year's U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review meeting. The current activities added four new pathways not previously analyzed, involving pipeline delivery and dispensing at 700 bar. The use of preexisting analyses and studies is a very efficient use of data and avoids needless duplication of effort.
- This is a great example of the kind of analysis the Systems Analysis sub-program should be doing to help inform DOE's research and development (R&D) agenda. It points directly to reducing the costs of producing low-carbon hydrogen (production, compression, storage, and delivery) as a critical research objective. It shows the relative importance of each step to the total cost of vehicle ownership for different pathways, but it also clearly shows that compression, storage, and dispensing are critical for all pathways.
- This project takes a very sound approach by utilizing very robust tools (e.g., the Hydrogen Delivery Scenario Analysis Model [HDSAM]; the Hydrogen Analysis [H2A] model; and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET] model) that are essential for estimating hydrogen production and delivery costs as well as for estimating GHG emissions. The analysis demonstrates good consistency by following the same approach used in previous analyses on eight previous technology pathways. The four new emerging pathways being analyzed will provide DOE with valuable information in order for research work to continue on these advanced production pathways.
- This is a critically important task that needs to be performed so that DOE can make informed decisions about funding, demonstration, and implementation of hydrogen production pathways. The task is fully integrated into the existing modeling framework.
- Analysis tools supporting the project are well developed and vetted through previous analysis work. The analysis of emerging hydrogen production pathways leverages DOE's investment in past work and provides a common basis for evaluating existing and future production technologies and hydrogen supply pathways.
- The work is pretty good, although there has not been enough time for a thorough review of the new pathways by members of the U.S. DRIVE Partnership Fuel Pathways Integration Technical Team (FPITT), as was done previously. These reviews have uncovered a number of issues in the past. The work is important because it has to be done and stakeholders need to know the cost, GHG emissions, and energy inputs of these pathways, but these results are less meaningful when all the components are assumed to be produced "at volume" and market penetration is assumed to be high.

- The approach is generally good. However, one concern is that the inputs from a multitude of models are being taken without much concern for vetting those models. As a result, there is a risk that assumptions that may be unrealistic are being used to develop the technoeconomic and emissions results.

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

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

- The project provides a clear and transparent understanding of the relative costs of current and future hydrogen supply pathways, including infrastructure. The analysis results are well documented in the future technologies report that is already complete and under review. The analysis provided a thorough and consistent understanding of new emerging hydrogen production technologies not previously available.
- Four additional pathways for hydrogen production were considered, providing excellent comparative data to the pathways considered in the previous year. The up-to-date results of the analysis will be publicly available in DOE-reviewed reports.
- The researcher presented on the project's significant progress, including the completion of the report on future technologies, which will complement the report published last year on current technologies. Very detailed preliminary cost information was presented for the new pathways being analyzed.
- There has been quite a lot of progress toward understanding emerging pathways.
- The accomplishments and progress are good.
- This project would have merited an "outstanding" rating for this question, but it features a curious choice of time frame and vehicle penetration levels. It is highly unlikely that by 2025, 15% of the vehicles on the road will be hydrogen fuel cell vehicles. That may seem to be a minor issue, but in a time frame after 2025, such as in 2040, when 15% (or more) of the vehicles on the road could be hydrogen fuel cell vehicles, there will be a different electricity grid (which affects the GHG emissions of different pathways, especially electrolysis using the grid). There will also be a different fleet average miles per gallon, which will affect the importance of fuel cost in the total cost of ownership. Road loads might be reduced, favoring battery electric and fuel cell powertrains over internal combustion engines (ICEs) and ICE hybrids. Finally, the choice of time period affects technological readiness, which affects costs, as noted in the presentation. Getting the scenario right matters and affects the answers.
- Given the lack of publicly available data, it is quite an accomplishment to develop these cases, but there is much work to be done to refine them.

Question 3: Collaboration and coordination with other institutions

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

- The Macro-System Model required ongoing collaboration and alignment with other national laboratories and was vetted by the U.S. DRIVE FPITT and Hydrogen Production Technical Teams and others. There is ongoing work that will incorporate the learnings from this project into the various models/tools that interface with the Macro-System Model.
- The collaboration with other national laboratories and the experts on the models and tools being employed in this work seems to be very appropriate.
- The collaborations are excellent.
- The budget was not big enough to support a lot of collaboration, so it is not surprising that there are only a couple of active collaborators listed (probably not funded). However, equivalent credit is deserved for appropriately choosing and using the models developed by others.
- There is good collaboration with industry representatives and the other national laboratories involved in the analysis tasks. The team should consider input from the industries that would actually develop some of these technologies, especially the technologies further out, such as photoelectrochemical (PEC) and photobiological production.
- A thorough review of the pathways by FPITT would be useful to make sure the inputs are technically sound. The principal investigator (PI) mentioned additional vetting by other U.S. DRIVE technical teams.

This will be very valuable to ensure the technologies selected for the pathways are reasonable, given the many possible configurations.
- It would be good to include inputs from experts in the technologies that were involved in the pathways analysis. Currently, it appears the only involvement by experts in coming up with the pathways is in the models for the individual components, but these experts should also help vet the systems analysis.

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

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

- This project is essential to DOE-funded R&D on the future hydrogen production pathways because it will provide much additional information on these technologies, which in the end will contribute to the direction and efforts of these R&D programs. The project will also enable DOE to fund additional work on carbon capture and sequestration.
- The analysis provides good direction for DOE’s R&D activities related to photobiological hydrogen, PEC, and solar thermochemical hydrogen (STCH) production methods. This work establishes a foundation of hydrogen cost related to these emerging technologies, along with an understanding on GHG emissions.
- The impact of these models cannot be overstated. As long as the inputs can be updated as the technology matures, the work will allow DOE to make informed decisions.
- The entire life cycle cost and GHG impacts are the most important metrics to understand in evaluating any technology. This is clearly one of the most important activities in the hydrogen space.
- By improving the scenario assumptions and carrying out the planned additional pathway analyses, this should become an outstanding project.
- The emerging technology pathways are known to be uneconomic at this time, but it is unclear how far they are from meeting DOE targets. This analysis attempts to answer that question, and to some extent it provides an answer. Because the assumptions are based on a potential future scenario, the results do not reflect current costs, but they do provide a way to assess the delta between near-term technologies and emerging technologies.

Question 5: Proposed future work

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

- Completing this work with the new GREET cases on emerging renewable production pathways, in addition to looking at emerging delivery and storage technologies, will make this analysis work very complete.
- The PIs have identified additional pathways to consider in the future, including high-pressure truck delivery, dispensing at 500 bar, and cold and cryo-compressed onboard storage.
- A reassessment of the time frame and other scenario(s) assumptions should be an important part of the future work. Expanding the portfolio of pathways analyzed is the right direction.
- The team will meet to discuss gaps that should be filled and commit to continuously updating the model. This latter task should be funded until the hydrogen economy becomes a mature reality.
- This project analyzed only pathways published in H2A. There are many potential component combinations in the PEC, STCH, and photobiological pathways. The work could benefit from sensitivity analyses looking at different technology combinations that are more likely to succeed in the marketplace. The team needs to discuss potential technology configurations with the Hydrogen Production Technical Team—the PI mentioned this is in the plans. None of the emerging technology cases demonstrated economic feasibility. Given that, the value of additional work is questionable, unless there is a substantial reduction of GHG emissions or another kind of societal benefit. The team should consider including the impact of renewable identification numbers and low-carbon fuel standard credits on hydrogen production cost through different pathways, including biomethane.
- The future work is somewhat limited to refining results with the U.S. DRIVE FPITT and Hydrogen Production Technical Team. Additional analysis from this work has been identified but is pending future funding.

Project strengths:

- Linking together the appropriate models from the Systems Analysis sub-program library is exactly the way projects like this should be done. There are state-of-the-art models in the library, and the researcher has appropriately chosen which ones to use. The subject of this analysis (understanding which parts of the production, delivery, compression, storage, dispensing, and vehicle system are responsible for the most life cycle cost) is precisely the kind of systems analysis that contributes to formulating an intelligent research agenda.
- This analysis fills a DOE gap related to understanding hydrogen production cost and GHG emissions associated with emerging technologies.
- The ability to study the impact of emerging technologies on the overall hydrogen economy is valuable and is needed to integrate the wide range of options available.
- Strengths include the collaboration with the U.S. DRIVE teams and the use of a set of models that are reputable and constantly reviewed.
- The project features a thorough understanding of hydrogen production and delivery from all sources under consideration.
- Strengths include the robust Macro-System Model and the leveraging of U.S. DRIVE and technical teams.

Project weaknesses:

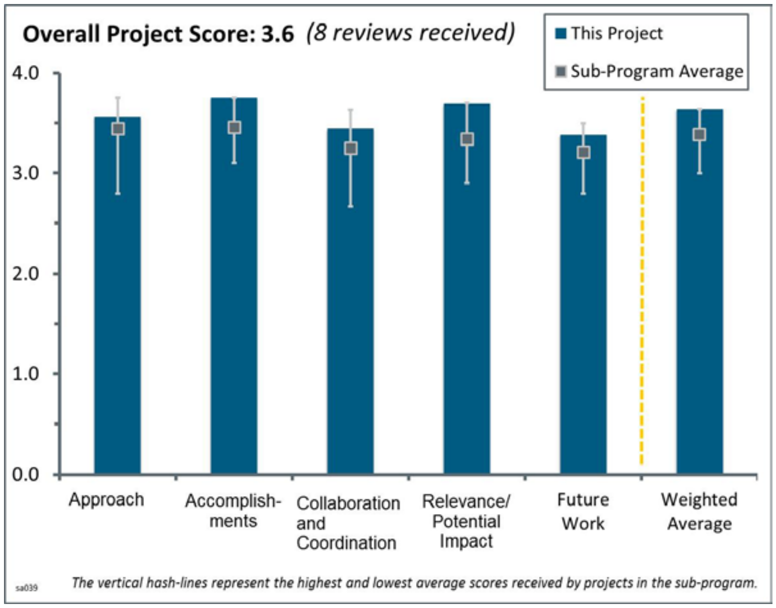
- The project objective was to determine the cost, energy use, and GHG emissions of emerging hydrogen production pathways. In the area of energy use, only direct energy use from non-renewable energy sources is included. It may be good to understand the total energy requirements (non-renewable and renewable) for the emerging hydrogen pathways. It is somewhat unclear whether the total cost of energy is included in the production cost estimates.
- Assuming a 15% vehicle penetration is unrealistic. Some of the efficiencies/yields of the advanced technologies are location-specific. The results are generic, and it is difficult to assess where the technologies would result in the costs/GHG emissions presented. The results present only single-number results without considering variations. It would be more useful to have some sort of uncertainty charts.
- The only concern is the value of conducting such analyses for future scenarios (many years in the future) based on current data and knowledge. As the hydrogen market approaches maturity, these analyses will need to be performed once again, and one thus questions the value of the current studies. It is unclear how sensitive the results are to the input.
- The time period chosen does not match the market penetration assumption. This needs to be corrected, even if it costs more to do it.
- The project needs better inputs for the less mature technologies, such as PEC and solar thermal.

Recommendations for additions/deletions to project scope:

- The team should do the following:
    - Conduct “deep-dives” into project assumptions.
    - Develop a GHG life-cycle analysis before additional cost modeling is performed.
    - Consider near-term cases with lower market penetration, low-volume production, etc.
    - Produce variability ranges or mention what the potential cost variations could be.
- The team should reprioritize the future work so the assessment of biomethane steam methane reforming can be set as a higher-priority analysis that should be performed.
- The team should keep up the good work; these studies provide a consistent framework to judge the different pathways available to bring about a hydrogen economy.
- There should be more industrial input.

Project # SA-039: Life Cycle Analysis of Water Consumption for Hydrogen Production

Amgad Elgowainy; Argonne National Laboratory



Brief Summary of Project:

Argonne National Laboratory (ANL) has expanded the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to include water consumption. ANL has (1) identified major contributors to water consumption in the upstream supply chain, and (2) evaluated water consumption for the fuel production stage.

Question 1: Approach to performing the work

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

- Adding water consumption data to hydrogen production pathways is absolutely essential for the development of sustainable, environmentally sound practices. This is an outstanding addition to the modeling suite's capabilities.
- The approach is excellent, with a comprehensive analysis of multiple fuel products that lends itself to comparative assessment.
- This work establishes a good fundamental understanding of the water consumption associated with hydrogen and energy production. The information and knowledge gathered through this project has been transferred into an updated GREET model.
- The principal investigator (PI) employs a logical, methodical approach to investigate each aspect of water impact. The evaluation of parameters and subsequent exportation into the GREET model is reasonable and appropriate. The focus on current production pathways is logical. The PI's approach is to holistically look at issues surrounding water consumption in each hydrogen production pathway. The PI is thorough and well organized, but this approach could lead to some critical aspect of water usage being missed. Peer review is recommended.
- The project team has a very good understanding of the issues around water consumption. The definition of "consumption" can be fuzzy, particularly in systems that are difficult to measure, such as evotranspiration of biomass; the researchers are doing a very good job delineating boundaries and defining conditions for the analysis. This is a very challenging topic, but it is very important.
- It would be better to take the approach of a consequential life-cycle analysis (LCA) rather than an attributional LCA for understanding water consumption.

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

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

- It is very nice to see the water consumption model improve each year; the researchers' commitment to making the water model as good as possible is outstanding. It was particularly nice to see the dry versus wet cooling trade-off for water consumption and its impact on the energy balance.
- The accomplishments were clearly discussed for each production pathway and indicate a logical consideration of water usage for each. The total impact is a thoughtful examination of water usage that provides considerable confidence that the analysis captures all relevant factors.

- This project has developed information on water use that was not previously available, including information on water use for different types of fuel, technology, and geographic areas for fuel production.
- The latest work refined previous water consumption factors for hydrogen production and established new water consumption factors for new renewable hydrogen production pathways. The team integrated the latest information into the GREET model.
- The presenter did not show the results of evaluating different water treatment options, which is part of the approach. Otherwise, the presenter covered the points outlined in the approach.

Question 3: Collaboration and coordination with other institutions

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

- The model is clearly improving, as the researchers are seeking input from the best industrial and governmental sources.
- The team collaborated with the previous researchers studying water consumption within DOE and solicited input and feedback from industry players.
- The collaboration and partnerships appear to be broad, well based, and appropriate.
- The researchers have reached out to industry, DOE, and DOE laboratories to obtain information. This reviewer's company was also approached to provide feedback. The researchers have done a tremendous job of reaching out to pertinent stakeholders. It is understood that the overall water consumption of the water flooding pathway is small, but the researchers should find a more up-to-date source of data for water injection in water flooding. The reference cited is from 1964.
- There appears to be a lack of peer review, leading to the fear that some (unknown) aspects of water usage were potentially overlooked.

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

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

- Water is a critical resource and will become even more critical in the future. It is important that industry stakeholders and energy producers understand water consumption within their industries and markets because it is often overlooked today. This work provided new knowledge of water consumption associated with hydrogen and energy production. Also, the work developed and updated water consumption for major power and energy production processes.
- The water cycle for energy generation is relevant and tremendously important. Researchers have mostly focused on greenhouse gases (GHGs) and energy LCA, but very little importance has been given to water, which is becoming a more restricted and expensive commodity in certain regions, such as California.
- Water consumption is just as important to consider for energy production as energy inputs, and it is an extremely relevant issue for DOE to consider. Making this into a real LCA is impressive.
- This project will meet research needs to develop information on water use to help decision making for fuel production, including type of fuel, technology, and geographic area for production.
- The project analysis revealed some surprising aspects and adds to the Hydrogen and Fuel Cells Program's understanding.
- Water is a very important topic, especially if one is considering fuel production at the local level and starting in California.
- Water use is a critical issue that DOE needs to address for all pathways.

Question 5: Proposed future work

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

- It is nice to see this project expanded into all factors and industries that consume water. It is very good to see that purification will become part of the project.

- The team plans to refine existing work and explore new areas, including hydrogen pathways involving low and no water consumption. It will be valuable to understand regional and seasonality differences in water consumption, water life cycle, and availability.
- The future work proposed is adequate. It would be good to see the integration of different LCA results for fuels production, including GHG, energy, and water, on the same slide to have a clearer picture of how the fuels fare against one another. Also, it would be good to see the variability of the results represented by uncertainty bars, or the research team should pick a region or a set of regions and do a "deep dive" into how the numbers vary; water stresses (e.g., the need for irrigation, and water constraints in California versus Florida) and feedstock availability (e.g., biomass and wind) will be different in different parts of the country.
- The future work for tri-generation technology is appropriate to expand the scope to meet the needs of the hydrogen fuel cell industry and automotive original equipment manufacturers seeking fuel supply for fuel cell electric vehicles. Additional information on heat and power may provide additional value to end users and help reduce energy costs.
- The team should include some more mid- to high-technology-readiness-level (TRL) technologies, for example, algae biomass systems.
- It would be good if the project leader could include work toward an index for water stress.

Project strengths:

- The PI's logical, thoughtful, and comprehensive analysis approach is the project's main strength. The numerical assessment of water usage and incorporating that information into the GREET model are strengths.
- The project team takes a nice, pragmatic approach in closing the DOE gap related to water consumption and energy and hydrogen production.
- The comprehensive approach and comparative analysis of multiple fuel products are strengths of this project.
- The project fills a critical need that is not currently addressed by existing models.
- Integrating water consumption into the whole LCA is a strength of this project.
- The project includes a good definition of project boundaries.
- The project features good stakeholder involvement.

Project weaknesses:

- The team needs to find mechanisms to get information to decision makers in energy sectors, drought/water constrained areas, and transportation markets. These weaknesses may be beyond the scope of this research project, but such consideration of a pathway to decision makers at this time might be helpful to the research design.
- The project needs more involvement from industry and peer reviewers at a very technical level.
- Collaboration and peer review with outside groups does not appear to have occurred.
- There are still some unknowns about total water usage.
- The lack of current data is a weakness.

Recommendations for additions/deletions to project scope:

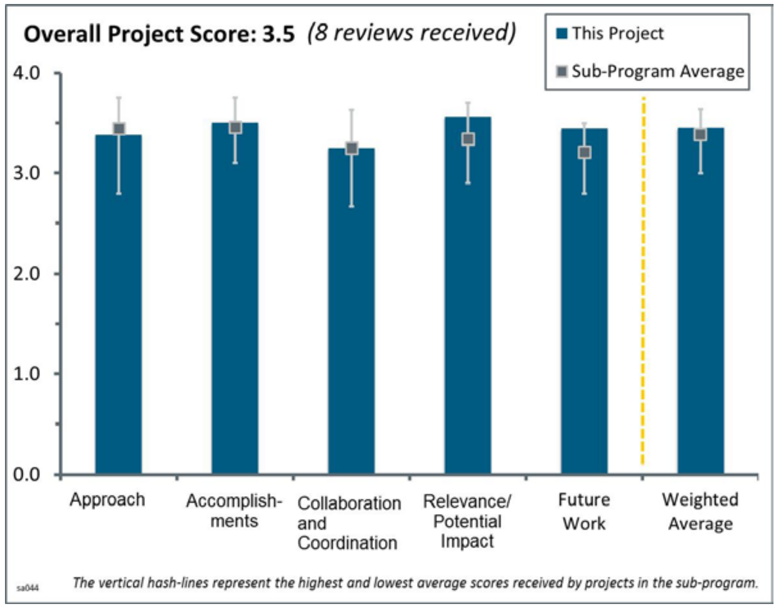
- There are no obvious recommendations.
- It would be good to see the integration of different LCA results for fuels production, including GHG, energy, and water, on the same slide to have a clearer picture of how fuels fare against one another. Also, it would be good to see the variability of the results represented by uncertainty bars, or the team should pick a region or a set of regions and do a "deep-dive" on how the numbers vary; water stresses and feedstock availability (e.g., biomass and wind) will be different in different parts of the country. The presenter did acknowledge that other analyses at ANL are already looking into local water stresses and that the project may integrate this work. The team should definitely integrate other ANL work into this analysis.

- The team should consider internalizing the full regional value and cost of water in the comparative fuel cost analysis. This will be difficult and potentially beyond the current scope of the research, but it may help with assessments for regional production of hydrogen and other fuels.
- These water consumption results should be added to a mapping utility so the information can become geographic; it would be great if this could be done to at least the county resolution level.
- Peer review with industry practitioners of each hydrogen production pathway would strengthen confidence in the project's analysis.

Project # SA-044: Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost

Aymeric Rousseau; Argonne National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) evaluate the benefits of advanced fuel cell systems and hydrogen storage from an energy consumption and cost point of view, and (2) provide guidance on future research priorities by evaluating the potential of technologies to accelerate petroleum displacement. Argonne National Laboratory (ANL) will gather component and vehicle assumptions, size the vehicles to meet similar vehicle technical specifications, model several light duty vehicle classes, evaluate the impact of advanced fuel cell systems on component sizing and weight, and perform the simulations on the U.S. standard driving cycles.

Question 1: Approach to performing the work

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

- The study's approach used the existing Autonomie model, which is well developed. The principal focus areas were fuel cell and vehicle hydrogen storage, which represent the greatest areas for performance improvement and cost reductions. The work scope evaluated the design of fuel cell hybrid vehicles across a broad class of consumer vehicle platforms.
- The project is taking data from all sources (i.e., Vehicle Technologies Office [VTO] and Fuel Cell Technologies Office [FCTO]), including information for fuel cell, drivetrain, storage, and other programs. It includes aspects such as the fuel cell size trade-off with battery size, cost, and efficiency and the contribution of each. The goal is to use modeling to provide feedback to programs on research needed to meet targets versus what research targets can be relaxed. The project includes the U.S. DRIVE Partnership and industry/academia, acknowledgment of fast-moving technology and the need to adapt, and state of the art versus predictions. The project team's process involves putting data together and synthesizing them, feeding them into modeling tools, and releasing results reports to stakeholders. The project team clearly defined "low" as business as usual and "high" as U.S. Department of Energy (DOE) targets.
- It is a very good strategy to include future improvements and their impact on fuel cell electric vehicles (FCEVs). Vehicle performance parameters and contributing factors are included nicely.
- The project uses the well-respected Autonomie model to configure FCEV subsystems and assess vehicle cost changes resulting from improved fuel cell peak efficiency. The project assesses the impact on FCEV configuration and cost resulting from an assumed increase in fuel cell peak performance to 70% efficiency. This helps one understand how increased fuel cell efficiencies can affect FCEV design and cost. The project would have benefited from assessing whether a 70% peak efficiency assumption was reasonable, and from further analyzing FCEV configurations and cost resulting from the project team's best assessment of a reasonable upper-end fuel cell system efficiency.
- The technical work is very solid; the models are carried out well, and the evaluations are very comprehensive. It is difficult to evaluate a project that is based on the assumption that everything is produced at volume only. Generating results for the early markets, too, would help one better assess the gaps for the transition. Some of the input numbers do not seem reasonable, and the Autonomie team should have questioned that aspect of the project.

- As conventional cars have incorporated better technologies, they have not become more fuel-efficient; instead, they have become faster (better acceleration) and larger. Original equipment manufacturers (OEMs) target sales, not fuel efficiency. This analysis should consider the adoptability factor of cars and the cars' sales appeal, not just their improved efficiency/fuel economy.

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

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

- The work provided validation that fuel cell hybrid vehicles will maintain their fuel cell efficiency advantage over conventional vehicles in the long term, and that performance improvements in conventional vehicles can cost effectively be applied to fuel cell vehicles. The scope of work encompassed a broad population of vehicles, which is valuable in understanding total petroleum and greenhouse gas emission reductions countrywide.
- The project team has done an excellent job evaluating how FCEV component configurations and the resulting vehicle costs, fuel economy, and weight will change as a result of improvements in fuel cell system efficiency.
- The impact of improvements by FCTO and private work is included. There is good consideration of uncertainty. The technology improvement monitoring is quite comprehensive. There is a good basis for project improvements. The simulation efforts and model development efforts are well focused. The tools are capable of future use and enhancements in technology.
- The team identified relative fuel economy improvements compared to other platforms, consistently, across targets.
- The team has made good progress since the last review; it accomplished an assessment of the impact of lightweighting and higher-efficiency components on overall system energy consumption and cost. However, the main slides do not show petroleum displacement results, which is one of the goals of the analysis. Slide 29 (one of the reviewer-only slides) shows there was an analysis of fuel consumption, but there is no mention of petroleum displacement results.
- The team generated assumptions through inputs based on experts' opinions on feasibility and status. The team walked through high-impact variables and the ability to drop fuel mass and engine power (e.g., lighter storage and more efficient balance of plant). This leads to a >50% decrease in the cost of storage and a >70% drop in fuel cell cost. The gap between fuel cell hybrid electric vehicles and conventional vehicles drops to ~10% in 2025; the weight is approximately equal. There is a good tie to the big picture from a modeling perspective; it is hard to say how the work overcomes the barriers because it depends on what the other groups do with this information.

Question 3: Collaboration and coordination with other institutions

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

- The project included two-way collaboration and coordination with other organizations. Inbound collaboration to the study included cost and technical performance data from automotive components to the entire vehicle. The project learnings and results are being shared with DOE and other government organizations in a number of ways.
- Realistic projections of improvements can make this analysis quite valuable to OEMs and FCTO. The project features good collaborative efforts.
- The collaboration is good, but researchers should question some of the inputs from DOE/national laboratories. For example, slide 8 shows specific power for the fuel cell system (watts/kilogram) in the 2025 medium case as lower than in 2020. Also, it would be good to see a review by the U.S. DRIVE Fuel Pathways Integration Technical Team before the results are published.
- The project team appears to have very good collaboration with U.S. DRIVE partners. The project does not seem to have strong collaboration with other national laboratories or academic researchers. It is unclear how some of the listed collaborators assisted in the project analysis (e.g., the MA^3T and Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation [GREET] modeling).

- Collaboration and coordination were mentioned, but actual specifics were not provided in much detail. The presenter stated several times that there are many partners, etc., involved; it might help to have a slide that lists the contributors, similar to the slide Karren More (ORNL) and others sometimes include.
- The team should list the direct OEM contributors/reviewers for the analysis.
- It was not apparent how industry is involved. The team should make this clearer.

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

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

- The project's assessment of fuel cell vehicle configuration and costs resulting from fuel cell system efficiency improvements and performance targets for power density, storage, etc. provides a useful understanding of the impacts technology advancements will have. This analysis will aid DOE in setting its research priorities.
- The project's simulation results support the long-term viability of fuel cell hybrid vehicles compared to conventional internal combustion engines (ICEs).
- This is a great way to connect DOE investment with its impact on commercialization.
- Generally, understanding how the forecasts for components will play out in the entire system is valuable.
- The potential impact is high if the work is used to set strategy, which is not under the principal investigator's control. A plan to make the model publicly available would increase the significance of the project. The team has a good perspective on the difference between maintaining competitive balance versus the necessary end targets (e.g., 70% efficiency is not needed by 2020; 62%–64% may be fine).
- The work is good, and it is relevant; however, the assumptions are skewing the results. Autonomie considers components to be produced at volume, which is a problem, and some of the input data on power of the fuel cell system and power density are questionable.
- This is very relevant analysis. It would be good to have explicit concurrence from automotive OEMs.

Question 5: Proposed future work

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

- The future work will address the fuel cell hybrid vehicle in comparison to other vehicle power train platforms and vehicle classes that one assumes will include hybrid vehicles, plug-in hybrid vehicles, and battery electric vehicles. The plan to conduct sensitivity analysis on market penetration is valuable in advancing understanding of short- and mid-term cost effectiveness of fuel cell hybrid vehicles.
- It is a good strategy to get feedback from stakeholders. Checking assumptions and their adequacy is important. The impact of the trade-off between battery pack size and fuel cell size is expected to play a major role.
- Sensitivity analysis would be very helpful; it is good to see it on the list. The fiscal year 2016 tasks appear to be reasonable and directed.
- The proposed future activities appear to be useful and appropriate. One missing area is an investigation into whether 70% efficiency represents a reasonable upper-end efficiency and, if not, what the resulting cost and FCEV configuration at the upper-end efficiency would be.
- It would be useful to provide a parametric model of this analysis. It could help drive research goals and targets. The team should consider incorporating market adoption analysis into the modeling effort—models such as the Automotive Deployment Options Projection Tool (ADOPT) can shed light on the likelihood of OEM products being larger/sportier versus more fuel-efficient with the introduction of better technology options.
- It will be particularly interesting to see the results of the sensitivity analysis and the detailed analysis by component. It is understood that the results of this analysis will be given to Oak Ridge National Laboratory to further its market penetration analysis. The value of that analysis is questionable, given the assumption of production "at volume."

Project strengths:

- There are good collaborations with others. The project is iterative in that Autonomie's results provide feedback to DOE to assess whether targets are too aggressive, just right, or not aggressive enough. This can help DOE direct research and development funds and change targets when needed. The analysis looks at the system as a whole, integrating the performance of different components.
- The work involved input from industry. The simulation analysis further validated the long-term cost-effectiveness of fuel cell hybrid vehicles and provided an understanding of the impact of projected development in fuel cell efficiency and hydrogen storage. The work included a broad range of vehicle classes.
- Information goes in both directions—provides consistency across DOE offices and vehicles. The project defines pathways through scenario modeling to determine the impact. The modelers get inputs and targets, but also try to reset realistic expectations.
- The project's assessment of fuel cell vehicle configuration and costs resulting from fuel cell system efficiency improvements will aid DOE in setting its research priorities. The analysis is based on the well-regarded Autonomie model.
- The project is based on good tools and input from stakeholders. It features good collaboration efforts.

Project weaknesses:

- The model is set up to meet DOE targets instead of assessing technology changes and analyzing how fuel cell system components can improve in the out years and, based on that, calculating energy consumption, cost, fuel economy, and other parameters of interest. The model always assumes that components are manufactured at volume, which is not a realistic assumption in the early years.
- The weakness of the project is the inputs. Simply using DOE targets does not inform reality. It would be better to use more realistic projections of how technology, pricing, etc., will come into the market. Also, a sensitivity analysis would add value.
- The hydrogen storage cost analysis—particularly the 80% reduction assumption—needs to be checked. It is very significant. For comparison, ICE engine efficiency improvements are modest—this also needs to be double-checked.
- Considering the number of assumptions that underpinned the scenario analysis, it would have been valuable to provide sensitivity analysis of the results presented.
- The project findings are somewhat limited because the team did not complete a companion investigation into whether peak fuel cell system efficiencies of 70% are reasonable.

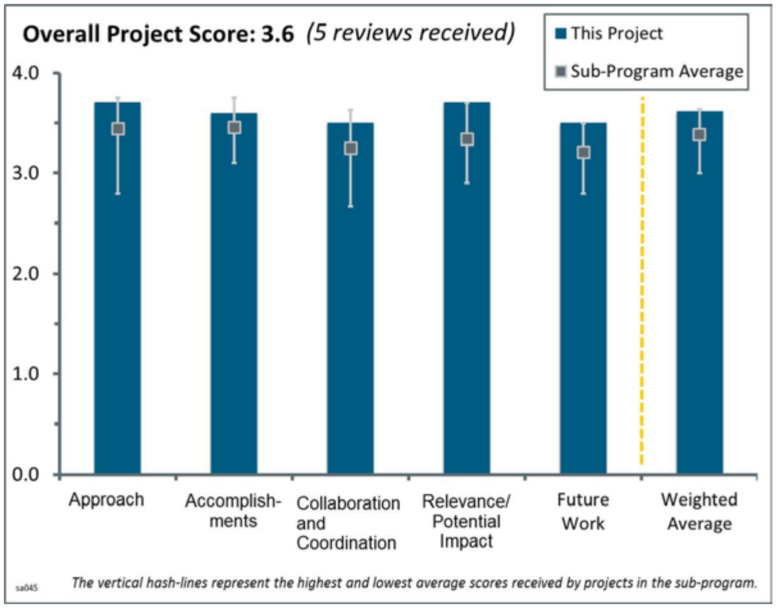
Recommendations for additions/deletions to project scope:

- On slide 7, costs should also be evaluated at low volumes. On slide 9, the team should compare hydrogen storage cost forecasts against historical compressed natural gas tank cost changes. The charts would be easier to understand if the key assumptions were stated on the slide. The researchers should review DOE input on slide 8—if power density did not change between 2010 and 2015, it is unclear why a jump from 640 watts/liter to 720 watts/liter is expected between 2015 and 2020. It is also unclear why the medium case specific power (watts/kilogram) system is lower in 2025 than in 2020.
- Battery advancements and their impact on FCEV progress present a great opportunity to increase the value of the project.

Project # SA-045: Analysis of Incremental Fueling Pressure Cost

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:



The objectives of this project are to (1) provide a platform for comparing the impact of alternative refueling methods and fueling pressures on the cost of dispensed hydrogen, (2) assist in the Fuel Cell Technologies Office's planning efforts, and (3) support existing U.S. Department of Energy (DOE)-sponsored tools. Argonne National Laboratory (ANL) will evaluate the impact of fueling pressure on fill rate and refueling cost, incorporate implications of SAE J2601 and MC Default Fill refueling protocols in the modeling of hydrogen refueling stations, identify cost drivers of various fueling technologies and configurations, and evaluate the potential of new concepts to reduce refueling cost.

Question 1: Approach to performing the work

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

- The researcher took a very sound approach in this analysis by using the proper modeling tools while at the same time using already established refueling protocols and identifying main cost drivers, such as precooling requirements for the different pressures analyzed.
- The approach is good and straightforward. Energy goes in, and hydrogen comes out. The team calculates cost, evaluates sensitivities, and makes recommendations.
- The approach is good. Clearly the investigators have given thought to building a model based on fundamentals and bringing in expert input. However, vetting the analysis through the U.S. DRIVE Partnership may not be sufficient. Important stakeholders, such as industrial gas suppliers, station owners, and key original equipment manufacturers (OEMs), are not members of U.S. DRIVE.
- The work is technically solid, and the strategy is well developed. This reviewer had not seen an analysis comparing both refueling protocols. It will be good to validate the results of the model in real-life conditions. The principal investigators did an excellent job addressing the barriers/challenges listed in the presentation.
- It would be helpful to have dynamic finite element analysis of a fill process to show the thermal dynamics of the gas and the layers of a tank. Hot spots in the tank are a concern to watch for, and the presentation is unclear in showing that the dynamics of the tank would not allow for the thermal diffusivity of the system to alleviate any hot spots. Dynamic analysis can also help drive design choices to make tanks more resistant to temperature escalations during fill processes.

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

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

- It is good this work is being performed; it is exactly what DOE should be doing. Looking at the issue of precooling may shed light on where research dollars need to be spent or on the cost benefit of providing or requiring precooling. The analysis of SAE J2601 is also very relevant to improving fill standards.
- The presenter discussed the project's significant accomplishments, including how the project team (1) determined the impact of precooling temperature on fill times at several ambient conditions and compared these two fill protocols, (2) achieved the preliminary results shown on the impact of refueling pressure on fill times at different precooling temperatures, and (3) identified the effect of partial vehicle fills on reducing refueling costs.
- This project is conducting excellent work, as usual.
- The cases analyzed in the preliminary results are adequate, given that they reflect a comprehensive range of ambient and precooling temperature conditions.
- A good deal of detailed modeling has been done. It would be good to see more attention paid to communicating the results and the meaning of the results. There were a large number of similar tables; it is unclear what these mean.

Question 3: Collaboration and coordination with other institutions

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

- This project utilized outside experts to verify calculations to give some assurance the calculations are relatively correct and relevant for industry.
- There is very good collaboration on this project, and it is good to see that a vehicle OEM provided input on the refueling protocols. For future work, collaborating with a hydrogen station supplier and operator could provide additional value to this work.
- The collaboration and coordination are good, but the investigators should consider additional collaboration with stakeholders not in the U.S. DRIVE Partnership or with existing connections to ANL.
- It will be good to validate the results with companies that already operate under the conditions analyzed in the model. Additional collaboration with companies such as Linde, Air Products, and Air Liquide would be favorable to test fill duration and potential system cost using different refueling protocols. Alternatively, this could be done at a testing facility that can recreate different ambient temperatures.

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

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

- This project will enable further development, optimization, and flexibility of upcoming hydrogen stations and their operations. It will also provide options to hydrogen station operators for reducing operating costs, and it will improve customers' experiences when fueling at hydrogen retail stations.
- Besides characterization, such research should generate ideas for making tanks more resistant to hot spots and for possibly reducing/removing the need for precooling. Also, the research could be applied in materials development for more thermally stable components or higher thermal diffusivity material sets.
- It is to be hoped that this work can be used to better direct funds toward optimizing precooling and help station owners know what to expect based on utilization. This project also furthers understanding of how to conceptualize the value of different pressures.
- This type of analysis is important to further understanding of how a free market will develop and would be affected by different pressures.
- This work has the potential to influence SAE J2601 and how dispensers are instrumented and operated.

Question 5: Proposed future work

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

- The proposed future work on the trade-off between refueling speed and cost for different precooling designs will be a great addition to this work. Incorporating the MC fill protocol in the Hydrogen Delivery Scenario Analysis Model (HDSAM) and the Hydrogen Refueling Station Analysis Model (HRSAM) will also be a great addition.
- It is great to see that the results will be integrated into HDSAM and HRSAM. It is to be hoped that the results will also be shared with SAE to help fill knowledge gaps and contribute to the creation of a 500 bar refueling protocol.
- The future work is logical. It makes a lot of sense to vet the results, update impacted models, and publish the findings. It is unclear whether there are any parties involved with codes and standards or policy that should be engaged with these results early on.
- The future work looks appropriate. This work must be benchmarked to measured data.
- The researchers should consider the price elasticity of refill time. The worth to the station and end customer of waiting an additional 30 seconds is unclear. For example, slower fill may require less refrigeration but induce fewer turnovers per dispensing position. On the other hand, the hydrogen could be cheaper to the end consumer.

Project strengths:

- The analysis is robust and features a great amount of detail and a good process to get feedback from outside parties.
- The project helps define costs and direct research and money toward high-impact projects. It advances standards.
- Strengths include the technical knowledge and experience of the researchers.

Project weaknesses:

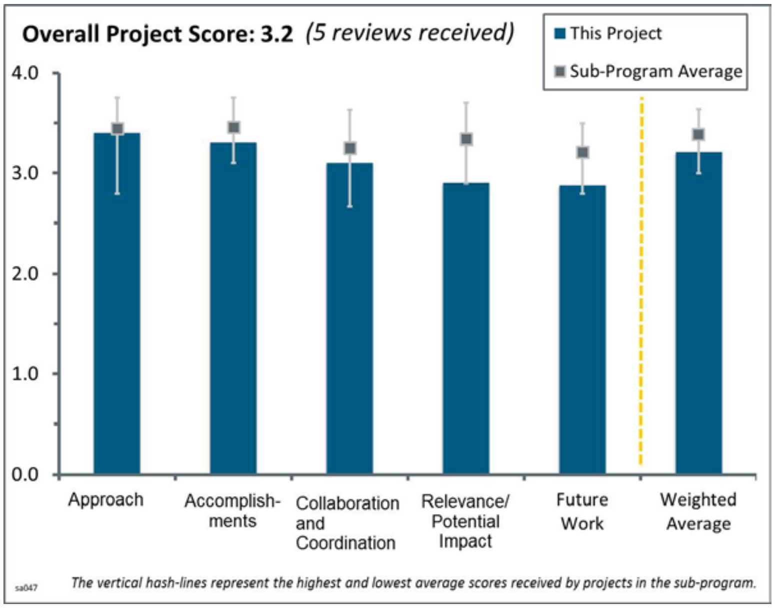
- One weakness is that the results are not communicated in a clear way. There are many similar plots, and this project would benefit from clear conclusions and useful takeaways. The team should spend time thinking about what the key conclusions and takeaways from the work are.
- The researchers could incorporate more refueling options/better ways of precooling.
- The project needs to include interaction with SAE.

Recommendations for additions/deletions to project scope:

- The team should research the benefit of going directly from liquid to precooled hydrogen to recast the value of liquid hydrogen delivery. This is out of scope for this project, but the work that really needs to be done is to look at how much the consumer values a three-minute fill. If given a choice, this reviewer would choose a slower, lower-pressure fill at a lower price. The three-minute goal seems arbitrary. Assuming five-minute fills on 350 bar were acceptable, it is not clear how many more dispensers would be needed. It is unclear how this affects station costs, especially at low utilization rates. The cost for refrigeration in early markets was quoted at $5–$7 per kg. It is not clear how common this situation will be and how it can be mitigated. It is not clear what would happen if refrigeration equipment were bought (incurring capital expenditure) but not operated (incurring an operating expenditure) unless utilization reached a certain threshold.
- The team should validate the results with companies with stations on the ground or in the laboratory. Autonomie predicts that with component improvements, the hydrogen mass needed for a 300-mile range can be reduced by up to ~3 kg by approximately 2045. This model can feed some of the results into Autonomie for assessment of the potential impact of precooling options on future vehicle cost.

Project # SA-047: Tri-Generation Fuel Cell Technologies for Location-Specific Applications

Brendan Shaffer; University of California, Irvine



Brief Summary of Project:

The objective of this project is to assess the potential number and location of tri-generation fuel cells, producing electricity, heat, and hydrogen, in an early fuel cell electric vehicle (FCEV) market scenario (circa 2015) in New York, New Jersey, Connecticut, and Massachusetts. The project will consider the use of natural gas and anaerobic digester gas as feedstock, as well as the viability of tri-generation units serving as a local hub for hydrogen production.

Question 1: Approach to performing the work

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

- Tri-generation is an attractive technology, but its implementation will be challenging because it must be sited correctly. This project makes a good start at siting such a system, by defining its size and markets. It seems to be well integrated with the other modeling efforts.
- It was a good strategy to include all relevant parameters and stakeholders for siting tri-generation systems. It will be valuable to include local collaborative partners. The market needs for the co-products are addressed well. The environmental benefits of the combined heat, hydrogen, and power (CHHP) system are estimated—this is good input for the subsequent analysis.
- The project's goal is to site a tri-generation system in the Northeast for fueling. The project team went after real data—sales of alternative fuel vehicles, demographics, etc. The project recognizes that siting is a major issue/question/concern with multiple products—location of the system at a fueling station site (distributed) versus at a wastewater plant site (central).
- The project assesses the potential number and location of tri-generation fuel cell systems (that produce electricity, heat, and hydrogen) in an early FCEV market scenario (circa 2015) in northeastern states. The project compares the results of hydrogen derived from natural gas with hydrogen derived from anaerobic digester gas.
- The approach to this work was good. However, it appeared the researchers ran out of time and did not complete all they set out to do. The budget may have been limited, but they should have done much more with the heat and electricity aspects of the technology. Also, the co-location strategy should have been more developed. This project depends on a very diverse set of siting criteria, and it required a little more coordination between uses. The hydrogen delivery did not seem optimized. The long distances the hydrogen is required to travel to some stations seemed unrealistic; it seemed that these distances would drive costs to be so high that delivery might not be an option.

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

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

- Excellent progress was made in identifying opportunities for deployment of a tri-generation system.
    - The >8 MW potential is a good start for top-25 sites. The parameter of driving distance for vehicles to stations is a quick check of commercial viability.
    - The cluster strategy is a good way to introduce FCEVs.
    - The scenario analysis results are relevant.
    - Anaerobic digester gas site characteristics are important—the use of biogas, or sludge to biogas, will provide additional hydrogen.
- The project team did a very nice job of considering all the possible sites in the Northeast. The team also did a very good job with the various trade-offs and provided a number of different scenarios that will help developers consider the business case for tri-generation and hopefully drive policy toward favorable conditions for implementation.
- The researchers made excellent progress on their stated deliverables and achieved a 98% completion rate. The final report will be issued shortly.
- The project features reasonable analysis of available locations of >8 MW. The cost is lower at a longer driving distance—it is unclear whether this is a capacity factor issue. The hub model seems much less cost dependent on the vehicles sold—it is unclear why that is the case. Distributed generation sites needed 80 MW installations; this results in some very expensive (e.g., $50/kg) stations. The hub model needs 10 hubs because of the low delivery cost. The project generally features good coverage of the trade space.
- This project proved that co-locating wastewater recovery facilities (WWRFs) and tri-generation hydrogen stations is a bad idea, but it is unclear whether the researchers quantified the extent of the problem in a very concrete way for anything but hydrogen delivery. Perhaps the concept was mentioned, but there are questions about competing uses for energy at a WWRF. Many make methane and electricity from that biogas energy. Questions remain about how this alternate use of biogas energy compares, and how this analysis helps DOE decide whether hydrogen is an added value on top of simple electricity generation.

Question 3: Collaboration and coordination with other institutions

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

- The researchers reached out to many entities—including the Massachusetts Clean Energy Center and the New York State Department of Environmental Conservation—for site data, etc. They also discussed the impact of the National Renewable Energy Laboratory (NREL) work (e.g., the Hydrogen Analysis [H2A] model).
- The study engages key stakeholders very well.
    - Northeast hydrogen groups should be included to increase the value of the work.
    - The team should include liquid hydrogen versus gaseous hydrogen trucks and suppliers.
- There was some collaboration with other institutions, such as NREL.
- The project only involved NREL; it should have had a broader set of inputs from all national laboratories in the analysis portfolio. Only one automotive original equipment manufacturer was involved. The project really needs input from the relevant industrial supplier of the technology.

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

This project was rated **2.9** for its relevance/potential impact.

- Renewable hydrogen co-production is very important for DOE goals. The project addresses this concept very well.
    - Green hydrogen from biogas is important.
    - Connecting biogas resources with tri-generation is a key to meeting DOE goals.
    - The hub production concept is useful during the transition to the ramp-up in deployment units.
- The project developed a consistent approach to assess the number and siting of systems in several northeastern population corridors. The approach is needed for judging different locations once the market is mature.
- There are some good cost numbers on hydrogen production at WWRFs and some good comparisons with other hydrogen production options. There would be more impact if the other aspects of tri-generation were incorporated in a more comprehensive way.
- Showing the business case for tri-generation should create more interest in this idea. Its place alongside other hydrogen production technologies should be more thoroughly investigated.
- It is good to show different scenarios in the project and how they impact dollars/kilogram—independent studies are useful. The team also needs to consider customer impact.

Question 5: Proposed future work

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

- The project was ending, but the team could still have provided better indications of what would need to happen next or what follow-on funds would accomplish; it is not clear that everything is really understood.
- The project is ending, so no future work was proposed.
- No future activity was proposed.
- No future work was proposed.

Project strengths:

- The project team has a good perspective on renewable hydrogen and the need/scarcity. The researchers made a good observation that feedstock matters—there is a need to use the biogas where it most makes sense, because it is not abundantly available.
- Hydrogen production and delivery costs for light-duty vehicles were covered, and the team made some good comparisons to other production technology.
- The study builds on existing tri-generation projects at the University of California, Irvine, and its collaborative partners. Leveraging the experience from Fountain Valley helps the effectiveness of the study.
- The team takes a consistent approach to locate tri-generation facilities.
- The research team considers all the factors that would play into a tri-generation scenario.

Project weaknesses:

- Identifying anaerobic versus aerobic facilities separately is critical. In addition, the current remaining life of the facility for new equipment is important. New equipment may provide an opportunity for a tri-generation system. Also, having information on whether the site flares the biogas or has engines to burn the biogas for energy will provide additional screening factors to determine the site suitability.
- The approach and results are susceptible to large uncertainties in technologies whose economics are unproven.
- The project team needs to focus more on the tri-generation aspect and value co-products appropriately.
- There is no input from a molten-carbonate fuel cell manufacturer.

Recommendations for additions/deletions to project scope:

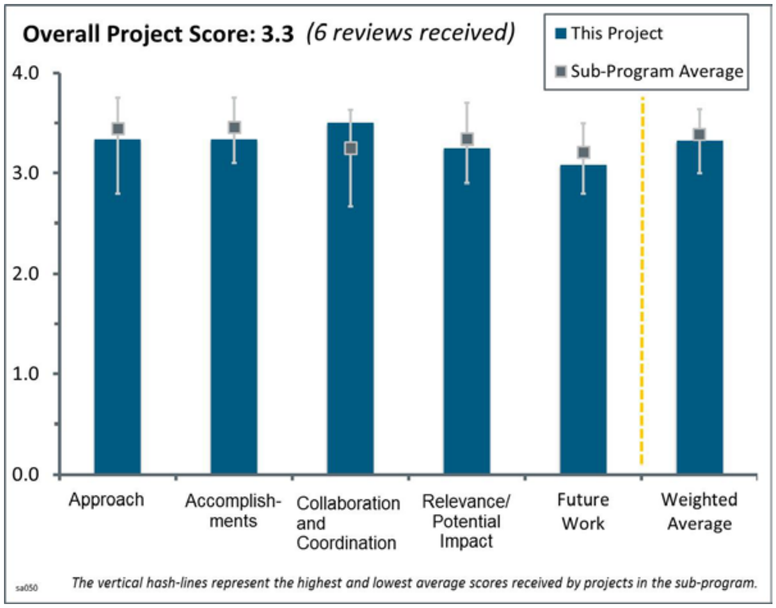
- It would be good for the project team to show an overall schematic with pricing, etc.; specifically, this could show the cost of hydrogen, the cost of electricity, and the capacity of both, as well as the use of heat (it works with the digester, but it may not be as viable in residential applications).
- The results should be shared with key stakeholders in the Northeast and used to develop a market transformation strategy. A compressed natural gas and hydrogen station together with electric vehicle charging for higher-value sites will be great to facilitate early market deployment.
- The project should expand to other regions of the United States.
- No additions need to be considered because the project is done.

Project # SA-050: Government Performance and Results Act Analysis: Impact of Program Targets on Vehicle Penetration and Benefits

Zhenhong Lin; Oak Ridge National Laboratory

Brief Summary of Project:

The objective of this project is to quantify the impacts of the Fuel Cell Technologies Office (FCTO) program targets on market penetrations and societal benefits of fuel cell vehicles. The goals are to (1) estimate fuel cell vehicle market share and the resulting reduction in petroleum use and greenhouse gas (GHG) emissions, (2) consider competition from all relevant powertrain technologies, and (3) collaborate on vehicle and infrastructure data.



Question 1: Approach to performing the work

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

- The work included an exhaustive comparison of fuel cell vehicles to all relevant powertrain technologies.
- The project uses the well-respected Market Acceptance of Advanced Automotive Technologies (MA^3T) consumer choice model to estimate the market share of fuel cell electric vehicles (FCEVs) and competing vehicle platforms. The approach of using a wide variety of alternative scenarios based on several choices each for key price, cost, and rollout parameters allows for a full understanding of the resulting range of potential FCEV vehicle market penetrations. Because estimates of petroleum use and GHG emission reductions are key outputs of this study, the project team should look at full fuel-cycle impacts using the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) energy and emission model. This model is considered the standard model for understanding fuel- and vehicle-cycle energy and emissions, and it has been well vetted by industry and stakeholders.
- How the model is actually being vetted is of concern. The projections are useful but seem very ambitious, and from the perspective of the barrier "understanding future market behavior," the results should be more in line with reality. This is a fundamental issue with using targets, and the team needs to work with industry to use realistic projections for the future in order to understand the future market behavior.

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

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

- The project team has made excellent progress at assessing a wide variety of scenarios, as well as estimating FCEV vehicle purchases under these scenarios and the resulting reductions in petroleum use and GHG emissions.
- Particularly useful are the waterfall charts showing the petroleum reduction and GHG emission reduction impacts as targets for hydrogen cost, fuel cell system cost, and storage cost are met.
- The analysis provides projections in the areas of fuel cell vehicle market penetration, petroleum use, and GHG reductions, which is the objective of the project.
- The number of vehicles and pathways integrated into the model is quite impressive, particularly for a new project. However, it is difficult to see how the project addresses the overall objective of quantifying the impacts of FCTO program targets on market penetration and societal benefits. This assessment could be

done by equating DOE's research and development (R&D) investments with the results from those R&D efforts and their contribution to meeting the targets.
- It appears there has been a good amount of progress regarding building a model to determine future states. However, the inputs need more work—particularly inputs of a scenario where DOE targets are not completely met.

Question 3: Collaboration and coordination with other institutions

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

- This project benefits from excellent collaboration and coordination from stakeholders across national laboratories, academia, and industry. Additionally, the project makes excellent use of DOE-funded modeling and capabilities such as the National Renewable Energy Laboratory's (NREL's) Scenario Evaluation, Regionalization, and Analysis (SERA) model and Argonne National Laboratory's (ANL's) Autonomie model.
- The project features a good amount of collaboration with industry, academia, and national laboratories.
- The project involved widespread collaboration and coordination with academia and other government organizations. More widespread collaboration from automotive original equipment manufacturers (OEMs) is needed.
- The project could benefit from input from energy companies. Also, work from ANL for early markets (Elgowainy, Reddi, and Brown, project PD-014) shows early market hydrogen costs of $9.50–$14.60/kg of hydrogen. This analysis only goes as high as $8/kg of hydrogen. The principal investigators from ANL's project should provide input to Oak Ridge National Laboratory.

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

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

- This project provides a very good understanding of consumer acceptance of fuel cell vehicles in relation to achieving critical DOE targets for fuel cells and hydrogen.
- Outside of the notion that the results, in their current state, are not representative of reality, this project is conceptually impactful and important. Basically, an integrated model to understand how consumers will choose vehicles, and how that will result in market penetration, is needed for investors to understand when it makes sense to fund investments. This will help to overcome uncertainty in the hydrogen space.
- The results are interesting, but the analysis does not address the objective of quantifying the impact of FCTO targets on market penetration and societal benefits. It is not possible to demonstrate a direct correlation between FCTO targets and market penetration. It is possible, however, to quantify how technology advances due to government-funded R&D are getting closer to the targets established by DOE. The objective of this analysis does not have anything to do with DOE targets. The question that the analysis answers is how potential cost reductions can impact future FCEV sales. Also, it is unclear how "societal benefits" are measured. It is unclear whether societal benefits include petroleum use and/or lower FCEV cost.
- The project has obvious overlap with other FCTO system analysis activities.

Question 5: Proposed future work

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

- The proposed future work of completing the analysis of the full set of scenarios and completing Government Performance and Results Act (GPRA) reporting is both reasonable and expected. The proposed fiscal year (FY) 2016 project work appears to be a useful addition to this project, but it may be overly ambitious. Scaling down the proposed FY 2016 work may be necessary.

- The team should run FCEV cases with higher dollars/kilogram values based on ANL work. Regarding slide 8—it would help to understand how market penetration level results compare with rollout announcements from OEMs and other forecasts from organizations such as the California Fuel Cell Partnership. Also, the project could compare its vehicle penetration with numbers from the National Highway Traffic Safety Administration (NHTSA) and the U.S. Energy Information Administration (EIA).
- There is a considerable amount of proposed work for FY 2015 and FY 2016 that may impact the results presented to date.
- The team should add a line item to run scenarios with input from industry in place of DOE targets.

Project strengths:

- The project's strengths include the following: (1) the use of the well-respected MA^3T consumer choice model to estimate the market share of FCEVs and the approach of using a wide variety of alternative scenarios based on several key parameters; (2) the excellent collaboration with industry/academia/national laboratories; and (3) the reliance on key DOE modeling capabilities, such as Autonomie and NREL's SERA model.
- This project is a good attempt to address the future market behavior of consumers in their adoption of alternative fuel vehicles, which is complex.
- The project features a very comprehensive set of vehicle technologies, as well as strong modeling capabilities.
- The integrated modeling approach and long list of collaborators add strength to this project.

Project weaknesses:

- The project team uses its own estimates of petroleum and GHG emission reductions, rather than using the fuel-cycle energy and emission estimates from the GREET model, which is considered the standard for analyzing transportation-related energy use and emissions.
- The project's weakness is that it is unclear how the model inputs are being vetted. DOE targets should not be used simply because they are targets. This results in a circular argument or self-fulfilling prophecy. To understand future markets, realistic projections are needed, not targets.
- Consumer acceptance is not factored in. There are other projects looking at potential market penetration. The project should integrate/compare results.
- The work includes 44 scenarios; the analysis would be more effective and meaningful if there were a down-selection to a few.

Recommendations for additions/deletions to project scope:

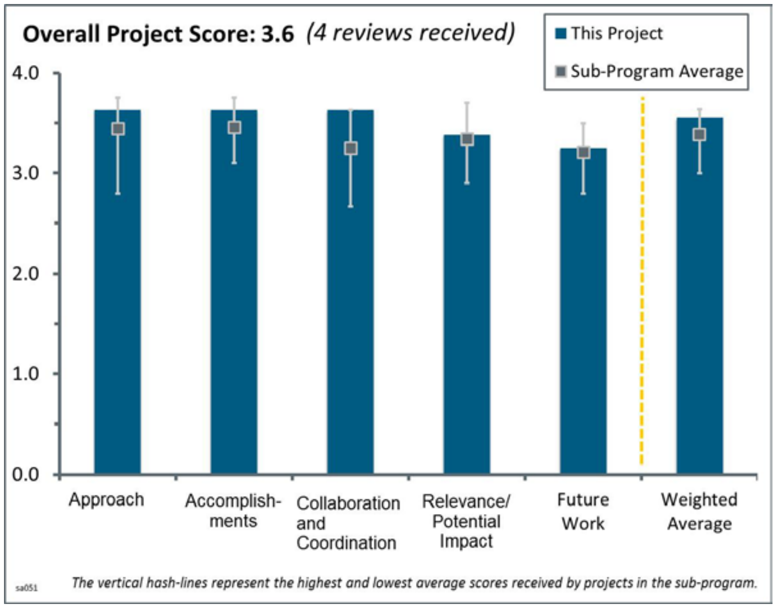
- The team should run FCEV cases with higher dollars/kilogram values based on ANL work. Regarding slide 8—it would help to understand how market penetration level results compare with rollout announcements from OEMs and other forecasts from organizations such as the California Fuel Cell Partnership. Also, the project could compare vehicle penetration with numbers from NHTSA and EIA.
- It would be interesting to benchmark the model's predictions against historical data on vehicle purchases by technology. It is unclear from the material in this presentation whether the model can have good predictive power.
- In presenting results, it would be helpful to provide the relative percent reduction in petroleum use and GHG emissions.

Project # SA-051: Infrastructure Investment and Finance Scenario Analysis

Marc Melaina; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to provide a quick and convenient in-depth financial analysis (the Hydrogen Financial Analysis Scenario Tool, or H2FAST) for hydrogen station projects and investments. H2FAST builds on the Hydrogen Analysis (H2A) model's discounted cash flow framework and can be applied across the entire hydrogen supply chain system and a broad range of scenario parameters. The National Renewable Energy Laboratory (NREL) has fully integrated the hydrogen infrastructure cost model results from the Scenario Evaluation, Regionalization, and Analysis model with the finance framework. H2A cost details, infrastructure timing, and logistics information are integrated across all finance calculations.



Question 1: Approach to performing the work

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

- This project is well thought out, and the approach of making a user-friendly model to fill a gap in the area of communicating infrastructure costs and risks is good. The project definitely addresses a critical barrier in engaging the investment community.
- The approach is solid and helps provide a quick response to potential investors. The different versions of the tool are useful for different types of users. Further, adding a visualization tool to locate potential stations will add a lot of value if the market grows and there are many more players involved.
- An Internet-based spreadsheet model is an excellent addition to the Fuel Cell Technologies Office's (FCTO's) stable of analysis tools. The team has done a good job of leveraging existing models.
- The project team has a good grasp of a complex technical subject.

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

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

- The Internet- and Excel-based models represent significant accomplishments to date. This project has delivered something broadly useful to those seeking to understand implications of work in the hydrogen arena. In this way, it has addressed critical DOE needs.
- Data outputs seem to be providing just the right information the financial community needs for decision-making. The fact that the tool has the flexibility to accept inputs and change assumptions on the spot adds to the value of the tool for informing financial institutions in real time.
- The Internet-based model is easy to use and gives quick answers to basic investor questions.
- H2FAST is a good tool to do first-cut analysis for U.S.-based deployments.

Question 3: Collaboration and coordination with other institutions

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

- The number and types of collaborations are good; the collaboration appears to need no improvement. It is particularly valuable that an independent financial analyst reviewed the model.
- There are connections through H_2USA and the U.S. DRIVE Partnership, and subject expert reviewers are involved.
- The principal investigators have assembled a talented team to produce and vet the model.
- The project appears to have collaborated very closely with the appropriate institutions.

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

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

- The project is definitely relevant to the DOE goals, in particular for getting the venture capital community engaged. It would be useful to consider (when designing the tool) the policy and regulatory community as well, because that community includes stakeholders involved in understanding costs and risks of infrastructure deployment.
- A tool such as this is essential for potential investors and planners.
- The immediate impact of the H2FAST tool is clear from an investor's perspective.
- Companies like to use their own models for financing, partly because most companies already have models with which they feel comfortable. This model can help as an instrument to double-check and validate assumptions.

Question 5: Proposed future work

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

- It would be interesting to fully develop the Business Case Scenario–Visualization (BCS-Vis) tool, but it would probably be more of an academic exercise than a useful tool, given that most station owners would either have an idea of where they want to locate their stations or hire a company such as Kalibrate to do the analysis. The rest of the proposed future work is good.
- The expansion of the model to include regional factors is a good addition. The team should consider incorporating outside firms such as Kalibrate to examine consumer acceptance issues.
- There is no apparent future involvement for federal regulators. There is clearly a lot of future work with state regulatory agencies (mainly California) but not much for federal agencies.
- It would be useful to look at interfacing with international databases (i.e., in Germany and Japan) to have a common tool for investors.

Project strengths:

- The product of this work is a user-friendly Excel model, as well as an Internet interface, which makes the product completely transportable and accessible by all. This is very appealing in terms of a product.
- The project is highly structured and has a strong focus on ease of use by the financial community.
- The team has created a comprehensive, easy-to-use tool for understanding station financing.
- Collaborations and validation of the model are good.

Project weaknesses:

- The fact that the model is being released in a protected manner is disappointing. Aside from transparency issues, there should be an option for an advanced user to unprotect the model and adapt it for his or her own use. After all, this is a publicly funded effort, so the product should be a public-domain tool. The project should consider opening up the H2FAST cells and code so that advanced users may modify the model for their purposes. To address concerns over making this too easy, the project could code a pop-up disclaimer stating that further modification may render the results invalid and requiring the user to acknowledge this fact.

- Potential stakeholders are not likely to use the tool for their primary financial analysis, given that companies tend to develop their own tools.
- The project is very U.S.-centric.

Recommendations for additions/deletions to project scope:

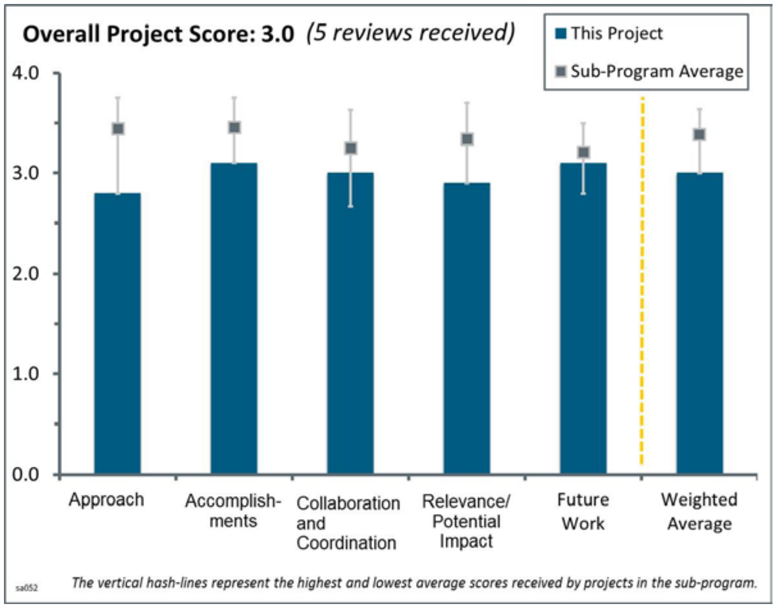
- The project should add international scope and add a module that follows the deployment of the Toyota Mirai in Europe, Japan, and the United States.
- A button could be added on the Internet model for user suggestions. The team may want to add a few “standard” cases to the model as a starting point for new users.
- FCTO has sponsored a number of very valuable tools, but these tools are not advertised appropriately, partly because the DOE website is so cumbersome to navigate. There should be a website on which all these tools are found, with easy explanations of their uses. In the next report-out, it would be good to read about the reaction of a financial institution to the outputs of the tool and find out whether the financial institution would find the information sufficient to make a decision.

Project # SA-052: The Business Case for Hydrogen-Powered Passenger Cars: Competition and Solving the Infrastructure Puzzle

Robert Rosner; University of Chicago

Brief Summary of Project:

The goal of this project is to support the development of a plausible business case for marketing hydrogen-powered fuel cell passenger vehicles and eventually including behavioral economic issues. Analysis will examine the competitive posture of hydrogen-powered fuel cell passenger vehicles in the marketplace and study the business case for a plausible hydrogen fuel distribution scheme.



Question 1: Approach to performing the work

This project was rated **2.8** for its approach.

- The incorporation of uncertainty is an important and valuable piece of this work. It gives the project a rigor that many overlook. The plan to gather and vet data from stakeholders will also give the project credibility. The project should not rely on U.S. Department of Energy (DOE) targets for this modeling effort, as so many others have. The idea behind projects like this is to test whether targets are realistic. In the approach, it is important to consider that many of the potential collaborators will have vested interests in a result (one way or the other), and a variety of different perspectives needs to be used for any set of inputs.
- The project attempts to make the business case for investing in hydrogen production and takes the perspective of a potential venture capitalist. This thinking outside the rigidity of the existing models will provide valuable insight into how outside investment can be obtained. The team has a sound approach to this problem; after identifying the appropriate data, a first-cut model will be built and vetted.
- This project is just starting up and is still forming its framework.
- The concept of generating statements for venture capital (VC) investment is interesting, but it seems that all the data generated are repetitive. Other projects are already assessing costs and producing business cases. It is hard to understand what is new about this project, other than getting a third party to collect data and estimate uncertainties. This should be stated in future presentations. Also, it seems that there is a mismatch of vehicles being compared. The vehicles compared in the vehicle price table (slide 19 in the reviewer-only materials) have different attributes, so the side-by-side comparison does not present a fair representation of how vehicles would fare against one another.
- It is not clear what value this project adds, compared to the existing literature (e.g., the McKinsey 2012 study).

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

This project was rated **3.1** for its accomplishments and progress.

- Much appears to have been accomplished in the first two months; this looks like a great start.
- The project has only been around for a couple of months, but it has already collected a fair amount of data. However, it is difficult to assess what exactly the final product will look like and how it will be different from other efforts/projects in existence. Regarding the results presented, total cost of ownership is not new. The U.S. DRIVE Partnership's Cradle-to-Grave (C2G) working group has produced much more

comprehensive results with as much uncertainty data as possible. DOE will produce a program record with the results.
- It is quite early in the project, but it is nonetheless hard to tell whether much work has been completed. It will be interesting to see the full results of this project at the next merit review. The plan for completion by the end of the year may be ambitious, given the current state of the project accomplishments.
- The provided accomplishments are in line with the phase of the project.
- It is hard to evaluate accomplishments and progress after only two months of work.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The project appears to have started working with some original equipment manufacturers (OEMs); otherwise, coordination and collaboration are hard to evaluate after only two months of work.
- The project has good university and national laboratory collaboration, but it clearly needs much more industrial input. The project should involve more OEMs.
- It may be beneficial to cross-pollinate with other similar models—e.g., the Scenario Evaluation, Regionalization, Analysis (SERA) model. However, it would also be advantageous to have an independent thought process for evaluating business scenarios.
- The stakeholders involved seem adequate, but the VC community should be involved earlier to ensure that the outputs and deliverables meet their expectations.
- There appears to be a heavy reliance on national laboratories and DOE. Future work needs to include detailed review and analysis by key stakeholders in OEMs and industrial gas companies, as well as station owners.

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

This project was rated **2.9** for its relevance/potential impact.

- It is very valuable to inform the investment and policy communities about hydrogen's potential. Because modeling is involved, it is helpful to have multiple and independent efforts to provide a spread of predictions of possible future trends.
- The project clearly considers how the private sector will be investing in the technology—it is a much-needed study.
- This has the potential to be a very impactful project, but it needs to have critical input from industry stakeholders. It is critical that OEMs from different regions (the United States, Japan, and Europe) are involved to vet the data.
- It will be good to get cost data that do not assume "at-volume" levels for system components and high market penetration. However, this project feels repetitive. It is hard to assess how this information can be useful. Further, the vehicles compared have different attributes, and the side-by-side comparison is not done on a level playing field.
- The potential impact appears to be poor unless significantly new data, compared to what currently exists in the literature, will be produced.

Question 5: Proposed future work

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

- Examining whether learning-by-doing curves are appropriate based on actual data is a next step that will contribute to an understanding of the future states. Challenging and testing today's assumptions are the most valuable aspects of this project.
- The future work looks to complete this important project on a reasonable timeline.

- The project needs to show impact—for example, by predicting future Mirai sales based on one year's worth of data.
- The proposed future work does not present anything new. The project should add as objectives the development of learning curves and deep-dives on the impact of subsidies on the newest advanced vehicles and alternative fuels.

Project strengths:

- This is a strong team with good technical and business backgrounds. Collaboration with the National Renewable Energy Laboratory and OEMs is great.
- The strength of this project is the commitment to data validation. DOE learning curves and other targets have always appeared quite optimistic, and it would be good to see whether these can be backed up with both industry input and actual data.
- The project is highly structured, and the principal investigator is very competent.
- The project looks at funding hydrogen production from a VC perspective.

Project weaknesses:

- The project needs much more industrial input.
- Feedback from the VC community and industry is needed about the overall usefulness of the project.
- It is not clear what the value added is compared to existing literature.
- The main weakness of the project at this point is how early it is, and the fact that not much progress has been made on which to base a review.

Recommendations for additions/deletions to project scope:

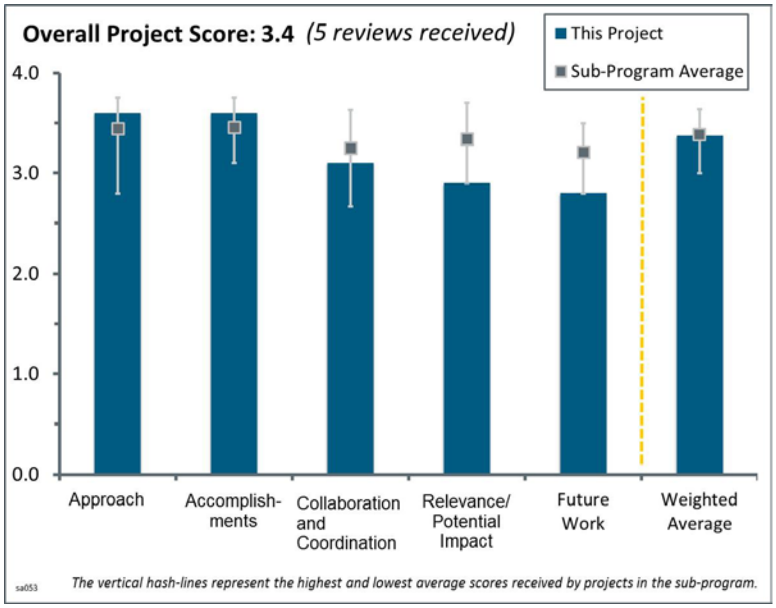
- Additional feedback from industry is needed about the overall usefulness of the project. The project team should discuss the project with the analysis Team Leaders in the DOE Fuel Cells and Vehicles Technologies Offices to ensure the work is not repetitive, considering what has already been done in these programs and by the C2G working group. The project should develop learning curves and deep-dives on the impact of subsidies on the newest advanced vehicles and alternative fuels.
- The project should consider emerging hydrogen production pathways.
- The project should make sure that detailed follow-up of the deployment of the Mirai in the United States is an integral part of this project.

Project # SA-053: Retail Marketing Analysis: Hydrogen Refueling Stations

Kent Schlesselman; Kalibrate

Brief Summary of Project:

The objective of this project is to develop an analytical approach to prioritizing and identifying the best locations for hydrogen refueling stations. Kalibrate will apply this framework to California to prioritize station network expansion beyond existing and planned locations.



Question 1: Approach to performing the work

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

- The approach reflects the many years of experience that Kalibrate has in siting refueling stations. The approach was appropriate, and the results pass the "laugh test," meaning that they make sense when they are looked at closely. However, it is difficult to understand why the distance to the hydrogen pipeline and other hydrogen delivery considerations were not in the list of independent variables considered. Perhaps these variables are embedded in some of the other independent variables.
- Kalibrate is clearly a leader in the field and approached the problem with standard methodologies adapted for hydrogen specifics.
- The project was conducted under an already proven approach based on the team's expertise in fuel retail network planning.
- The project is highly structured and focused.
- Kalibrate certainly understands what it is doing. The only suggestion would be to test whether the independent and dependent variables being used are the correct ones for hydrogen. Because the goal of most service stations is mainly to sell other items and not fuel, it is not clear that this would have any influence on station placement.

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

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

- Given the budget and timeline associated with this project, the results presented are of great value to the hydrogen industry in understanding the future market behavior in California.
- The project was completed, so the progress is good. The goals appear to have been completely met.
- The project has been completed with identification of the best potential locations for hydrogen stations.
- The project met expectations.
- The results were delivered on time and on budget, although it is difficult to see how this project can be further used without the accompanying software. Also, it would have been good to see hydrogen station developers commenting on the results and the general usefulness of the project, but perhaps that was outside of the scope.

Question 3: Collaboration and coordination with other institutions

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

- The project appears to have worked well with other institutions.
- There has been good work with relevant California entities.
- Collaborating with the team at the National Renewable Energy Laboratory (NREL) has been very valuable for this work. The project will also benefit if there are additional interactions with vehicle original equipment manufacturers (OEMs) that are already deploying fuel cell electric vehicles (FCEVs) to the California market.
- It seems odd that OEMs (e.g., Toyota, Honda, and Hyundai) are not listed as collaborators, because they would have a very good understanding of the market for hydrogen vehicles and therefore the target consumer for hydrogen. This seems to be a big gap in the approach of defining variables that one should examine.
- The team could have benefited from additional input from hydrogen station owners such as Air Products and Air Liquide, as well as gasoline station owners. It would be particularly interesting to find out whether these organizations would use the tool for planning purposes.

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

This project was rated **2.9** for its relevance/potential impact.

- The study provides a great starting point for siting future hydrogen stations.
- To some extent, this seems a bit outside the DOE goals in this area. It is nonetheless very interesting, and from a purely academic stance, it would be good to see the work continue. To make this more relevant, it would be nice to turn this into a publicly available model.
- The impact needs to be evaluated; the project needs to look at how potential investors would react to using this tool to determine where to place a hydrogen refilling station. It would be good to know the result in terms of traffic volume for a station once an investor follows Kalibrate's recommendations.
- This project seems more of an academic exercise than something that is likely to be used by companies to site their next hydrogen stations. Companies use their own models and contractors. Further, because there is no user-friendly tool accompanying this project, it is even less likely that companies will adopt the results of the project.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- As proposed, one great addition to this work will be to analyze other regions in the United States where there are plans to introduce FCEVs.
- The project has been completed on time and on budget!
- Because this project is over, no future work was proposed; it would be interesting to show this in Germany and Japan.
- There is no proposed future work.
- While it is true that the project is finished, with no clear plan to continue, the proposed future work is nonetheless not well thought out.

Project strengths:

- Strong analysis and a long history of doing this sort of work gives confidence that it is being done well.
- The project is highly structured.
- Industry experience is a strength.

Project weaknesses:

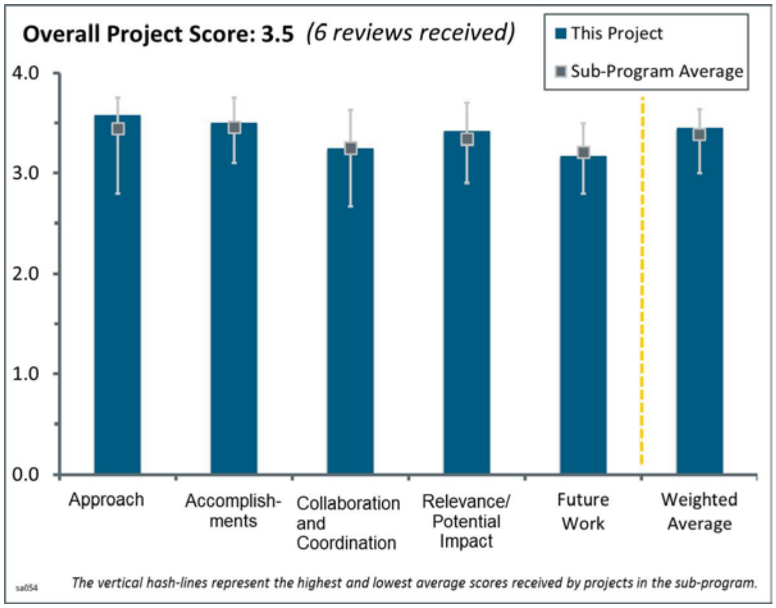
- The results are not likely to be used by industry, and there is no user-friendly software tool.
- The model is not publicly available.
- The project is very California-centric.

Recommendations for additions/deletions to project scope:

- This should be applied to the U.S. Northeast, Europe, and Japan.
- It is OK to stop the project and use the results to advance Marc Melaina's (NREL) visualization tool for future hydrogen stations.

Project # SA-054: Performance and Cost Analysis for a 300 kW Tri-Generation Molten Carbonate Fuel Cell System

Shabbir Ahmed; Argonne National Laboratory



Brief Summary of Project:

The objectives of this project are to (1) determine the performance and cost benefits of a molten carbonate fuel cell (MCFC) plant that can co-produce electric power, hydrogen, and heat; (2) develop meaningful definitions for cell, stack, electrical, and hydrogen production efficiencies in tri-generation modes; (3) explore scenarios in which the MCFC tri-generation system has particular cost benefits, including the scenario for charging electric vehicles (EVs); and (4) examine strategies for improving the performance and reducing the cost relative to the one-off Orange County Sanitation District tri-generation system.

Question 1: Approach to performing the work

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

- The project has a perfect approach to combine real costs of capital with real costs of electricity and hydrogen production. This project will produce real-world data for use going forward with tri-generation.
- The approach for this project is well thought-out and reasonable. The project develops an MCFC tri-generation performance model and uses the findings of that model as inputs to an MCFC cost model, which was also developed by the project team. The cost modeling appears reasonable, but comparisons to other stationary fuel cell cost modeling tools would have been beneficial, particularly the National Renewable Energy Laboratory's (NREL's) Fuel Cell Power Model, which was developed to model tri-generation systems.
- The bottom-up approach is quite effective. There has been a comprehensive evaluation of all parameters, including efficiency, economics, and components. Use of the Hydrogen Analysis (H2A) model provides data on a comparable basis. System model assumptions are relevant. The charging station add-on is a very good idea. It helps EV infrastructure and provides grid support.
- The approach is comprehensive and breaks the modeling effort appropriately into individual, transparent, and verifiable assumptions.
- This is a complex and important problem in terms of how to balance both outputs (power and electricity) and what the markets are. The researchers are looking at metrics and economics and developing meaningful efficiency definitions with multiple outputs. The project considers diurnal cycles. The model includes thermal integration, purification, compression/storage/dispensing (to 10 bar), and a five-stage ionic compressor.
- The system piping and instrumentation diagram shows pressure swing adsorption (PSA), yet feedback from FuelCell Energy is for electrochemical hydrogen purification.
    - Cost modeling should be done in a consistent manner with all other U.S. Department of Energy (DOE) production projects by using the H2A platform. One possibility would also be using the Fuel Cell Power Model or the Hydrogen Financial Analysis Scenario Tool (H2FAST).
    - Waste heat utilization is optimistic. Installation of combined heat and power (CHP) systems have shown ~12% to 20% utilization because of real-world impacts of hydronic system operation; for

example, heating is only necessary during a few months of the year, or the quality of heat is not adequate for steam generation (heat quality decreases when hydrogen production increases).
    - It is not clear whether this project is running a thermodynamic simulation of a tri-generation system. It is not absolutely necessary, but if the project team is doing so, the results would be interesting to publish.
    - In future reporting, the team should provide costs in a normalized fashion. For example, storage cost should be reported in dollars per kilogram, stack should be reported in dollars per kilowatt, etc. Stakeholders in this technology area use such normalized values and are calibrated to them.
    - The team should report performance in a normalized way. For example, hydrogen purification should be reported in kilowatt-hours per kilogram of hydrogen.
    - Normalizing numbers to the maximum alternating current (AC) output rating of the system (when it is not producing hydrogen) is suggested.

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

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

- The project has made excellent progress. Analysis results are consistent. Total combined heat, hydrogen, and power (CHHP) and hydrogen + power (H+P) efficiency should be included. Fuel cell performance improves because of lower utilization and improved reactant compositions. This needs to be added. The parametric analysis is done well.
- Clearly, a large amount of work has been performed, and some really nice insights into the costs of such a system are emerging.
- The project team has made very good progress, namely on the development of MCFC tri-generation system performance and cost models and the estimation of the cost of produced hydrogen for a system designed with and without EV charging.
- Progress to date represents the synthesis of substantial amounts of data into a single-system analysis. However, overall results could be summarized more clearly by providing a top-level summary of energy flows and costs. A steam-to-carbon ratio of two is assumed. This should be further justified. While assumptions are difficult to present for a project of this scope and in the limited DOE Hydrogen and Fuel Cells Program Annual Merit Review format, the presentation did not discuss assumptions on the cost analysis in enough detail for reviewers to fully assess their validity. A system thermodynamic and electrochemical model was done in GCTools, providing a ready-build platform for fuel cell analysis.
- The constant fuel assumption used in this analysis implies the system can adapt its output with some variation (hydrogen production can be increased with the same fuel amount inputs). The analysis shows 46% efficiency at 100% electrical output (no hydrogen production) to efficiencies in the 20s with hydrogen production—as stated in the review, this can be misleading to the general population. The project needs to come up with a total “effective” efficiency shown as a separate metric. Looking at sizing and the inflection point at 300 kW and the need to be greater than this to be competitive is very interesting. Hydrogen costs seem high relative to claims of other technologies; it is unclear how $6.50/kg–$9.20/kg is going to benefit the overall picture. Again, this may be a misleading picture because the project is also producing electricity, and it was not clear how these traded off.

Question 3: Collaboration and coordination with other institutions

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

- There is very good collaboration with national laboratories. The use of real data from appropriate industrial organizations was outstanding.
- The project has a good strategy to engage all stakeholders. Involving the University of California, Irvine (UCI), and Air Products and Chemicals International would be beneficial.
- The project suggests good coordination, but it could be improved by fuller vetting of modeling results rather than just collaboration on input parameters.

- This project appears to have been conducted mainly by the project team itself. There has been some interaction with industry stakeholders and fuel cell researchers, particularly in the area of component cost, but the project does not seem to have strong collaboration with a wider range of national laboratory, academic, and industry researchers.
- A body of past work was not referenced. For example, work by UCI would be relevant. FuelCell Energy is an excellent source, but it is also good to look at actual systems.
- The presenter did not really describe the collaborations in detail; it was just on a slide. Hence, it is unclear how iterative/interactive these discussions were.

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

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

- Tri-generation technology offers a great transition opportunity for multiuse infrastructure. It is timely to help fuel cell electric vehicle (FCEV) original equipment manufacturers. The grid, EVs, and FCEVs benefit from this study.
- The project provides a good assessment of MCFC tri-generation systems, which provides useful information on additional avenues for producing hydrogen for FCEVs. Such production leverages other needs (e.g., building heat and electricity) to help provide hydrogen fuel availability at reasonable cost, particularly during the hydrogen transition.
- Making the case for large, centralized tri-generation could be a really nice way to kick-start hydrogen production while leveling electricity production.
- It is good to see realistic and thorough costs of the compressor. The total installed capital cost for MCFC seems comparable to other technologies. The EV-charging model, including how it fits into the hydrogen-electricity picture, was unclear.
- The vision for CHHP systems is unclear. Specifically, it is not clear whether they are expected to be attractive to investors in the early market or only once hydrogen has already penetrated transportation to a significant extent.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work to contrast CHP and CHHP and the plans of different sizes will be very important. It is nice to see electrochemical compression in the mix. The final report will be very valuable.
- Sharing with stakeholders is good.
- The proposed future activities appear to be useful and appropriate. One missing area is an investigation of the necessary system configuration of an MCFC tri-generation system during early market with low–Technology Readiness Level (TRL) designs compared with the system configurations of mature-market systems, and the resulting cost difference. Early market systems may be expected to have lower performance in terms of system efficiency, component reliability (leading to higher maintenance and replacement costs), etc. Fuel cell stack lifetime and compressor reliability/uptime are particular areas of concern.
- It is not really clear what comes next, if anything. The project needs recommendations even if it ends.
- The project ends this fiscal year.

Project strengths:

- The project provides a good assessment of MCFC tri-generation systems, which provides useful information on additional avenues for producing hydrogen for FCEVs. Such production leverages other needs (e.g., building heat and electricity) to help provide hydrogen fuel at reasonable cost, particularly during the hydrogen transition.
- The project provides a good survey of not only components, but also processes and equipment in the cost model. The sensitivity model for CHP-only mode and conclusions on key drivers and unknowns are other project strengths.
- This is a good collaborative project with real-world, realistic input into all costs.
- The project uses a good strategy that includes all relevant parameters. The cost model includes all major processes.

Project weaknesses:

- The project would benefit from an examination and comparison to other stationary fuel cell/tri-generation system cost modeling (e.g., NREL's Fuel Cell Power Model) efforts.
- The system was not as well detailed as stack in terms of cost breakdown. It was stated to be similar, but the system cost breakdown was not shown. Collaborators were listed, but partnerships were not fully described.
- Results from the project are hard to understand/display because of the inherent trade-offs between electricity, hydrogen, and heat. Thought should be given to how these trade-offs can be better synthesized into a more readily conveyed format.
- The CHP and CHHP efficiency definitions are confusing. PSA efficiency gets better as compressors get larger. The team needs to further explain CHHP efficiency; it needs careful attention.

Recommendations for additions/deletions to project scope:

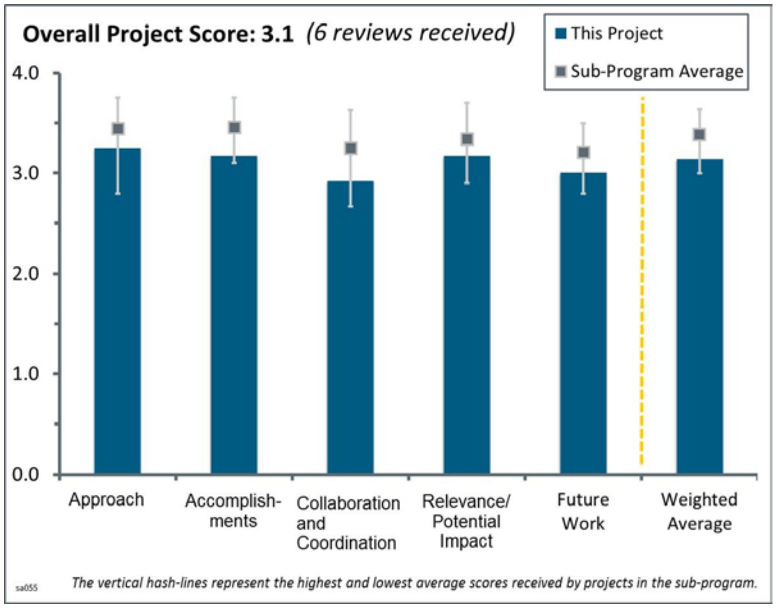
- The megawatt-scale analysis will be useful. Combining a compressed natural gas station with hydrogen can get better values.
- Based on the efficiency discussion, it would be good to discuss metrics with stakeholders from different technologies for consistency across the board. The metrics may need more than one number (fuel efficiency versus "effective").

Project # SA-055: Hydrogen Analysis with the Sandia ParaChoice Model

Dawn Manley; Sandia National Laboratories

Brief Summary of Project:

The objective of this project is to capture the changes to the light-duty vehicle stock through 2050 and its dynamic, economic relationship to fuels and energy sources. ParaChoice occupies a system-level analysis layer with input from other U.S. Department of Energy (DOE) models to explore the uncertainty and trade space (with thousands of model runs) that are not accessible in the individual scenario-focused studies.



Question 1: Approach to performing the work

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

- The project has a great approach to predicting future light-duty markets. By considering all the possibilities and running thousands of parameters, the model gives a good indication of the future and has the ability to react to technology changes and look at the sensitivity of the analysis.
- The approach includes input from other DOE and Annual Energy Outlook models, and it explores trade space parameterizations. The project acknowledges that the results are projections, not predictions. The high-level feedback loop provides a good description of the supply and demand sides. The project addresses state-level variation that is based on natural gas pricing, electrolysis, incentives, etc. and considers one-time (i.e., upfront cost) versus multiyear (i.e., recurring cost) penalties.
- The approach to develop a methodology to assist in decision-making is sound, but the model is dependent on a number of variables that are subject to change.
- The ParaModel appears to apply Monte Carlo simulation to base DOE models and data parameters.
- Building off the existing ParaChoice Model is a project strength. However, the model is only as good as its inputs, and there are multiple parameters that are not clearly defined regarding how they are handled (or what their numerical assumptions are):
  - It is unclear what cost of delivery was added to the hydrogen prices. It is not clear whether it is based on the Hydrogen Analysis (H2A) model/Hydrogen Delivery Scenario Analysis Model.
  - The assumed cost of distributed steam methane reforming (SMR) was not stated. H2A estimates are based on more than 100 units per year of production. It is not clear whether the station capital cost was modified for production rate.
  - It is not clear how consumer vehicle buying preferences were affected by the distance to the dispensing station. It is not clear whether a “standard” method already exists in ParaChoice. It would seem that this factor would affect the hydrogen station quite a bit in the early years.
  - The assumptions regarding initial station density were not clear.
  - This is a national model, but there does not appear to be any discussion of geographic effects or city versus county variation.
- It is not clear how this approach is distinct from or adds value to other choice modeling projects and methods.

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

This project was rated **3.2** for its accomplishments and progress.

- The major accomplishments were inputting hydrogen production, refueling pathways, and fuel cell electric vehicle (FCEV) data into the ParaChoice model and aligning the ParaChoice model with the Macro-System Model. The ParaChoice model findings and results are consistent with similar DOE analysis efforts.
- A lot has been achieved, and certainly many scenarios have been examined. The analysis of the hydrogen price dropping in response to demand was particularly interesting and pertinent.
- The project provides a realistic picture of electrolysis, SMR, and other technologies on an equal basis. It is interesting that in the case of a world without FCEVs, internal combustion engine vehicles only had 4% greater sales share. It is not clear what impact this may have on policy. Electrolysis may not get there with market forces alone (or other product efforts); it may need incentives/compensation. Hydrogen becomes far more renewable with electrolysis.
- Implementation of hydrogen FCEVs into the model appears to have been accomplished well for a first-year project.
- The model seems broad and comprehensive in scope, but it is unclear how inputs translate to market share.
- The modeling tool was developed to project market penetration.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- There are nice collaborations with national laboratories, but the project needs real insights from vehicle original equipment manufacturers (OEMs) and industrial concerns that may produce hydrogen.
- Collaboration is satisfactory, but it might be improved with additional collaboration with market penetration models from others, including the National Renewable Energy Laboratory.
- Incorporation of existing data sets and parallel modeling efforts require close coordination with others. The project received support from two major automotive OEMs. It is assumed there was occasional collaboration with them as well.
- There were no other funded partners for this period; all collaboration was informal. This is because of the scope of the project, but perhaps there should be more industry/stakeholder engagement.
- Further peer review would strengthen the project.
- It is not clear that the model has been reviewed by any outside party.

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

This project was rated **3.2** for its relevance/potential impact.

- It is very helpful to see the requirements to get to low/no greenhouse gas (GHG) emissions and the incentives needed to push hydrogen production to a cleaner pathway. Also, the model showed the need for state "initiatives" such as California's "100 station" goal.
- The project allows DOE to explore the sensitivity of costs of FCEVs and hydrogen to predict behavior and identify where research and development should be implemented.
- The project's relevance is good, but it could potentially become quickly outdated and/or misleading due to changes in variable inputs, including vehicle costs, alternative vehicle costs, fuel and alternative fuel costs, and the regulatory environment (e.g., mandates and incentives). Nonetheless, the model will have a positive impact for the projection of the market and preparation for market entry.
- The topic is relevant, but considering other models in the DOE portfolio, it is not clear how ParaChoice reveals anything relevant that other models are not already addressing.
- This new project appears to provide a duplication of other DOE models and work involving the market penetration and mix of FCEVs and the resulting reduction in petroleum and GHGs.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is important and focuses on parametric assessments. However, it should not necessarily emphasize conferences; there should be a few select forums that have high impact.
- The proposed future work represents a logical extension of the current analysis work.
- It is good to see more sensitivity analysis, and it will be interesting to get this team’s perspective on the levers for FCEV adoption.
- Additional model refinement with refinement of variables is appropriate.
- The model does not seem ready in terms of capability and sophistication to address market levers. The model does not feature enough significant predictive capability or novel/realistic causal mechanisms.

Project strengths:

- ParaChoice explores the uncertainty around FCEVs and hydrogen infrastructure that other DOE models and analysis do not address.
- Project strengths include the neutral, powerful analysis tool that can look at thousands of scenarios and seems to have some very nice predictive capabilities.
- Project strengths include the objectivity for forward-looking projections to prepare for market entry with infrastructure.
- Project strengths include the use of an existing model that highly leverages past work.
- The production pathways seem appropriate for technical maturity.

Project weaknesses:

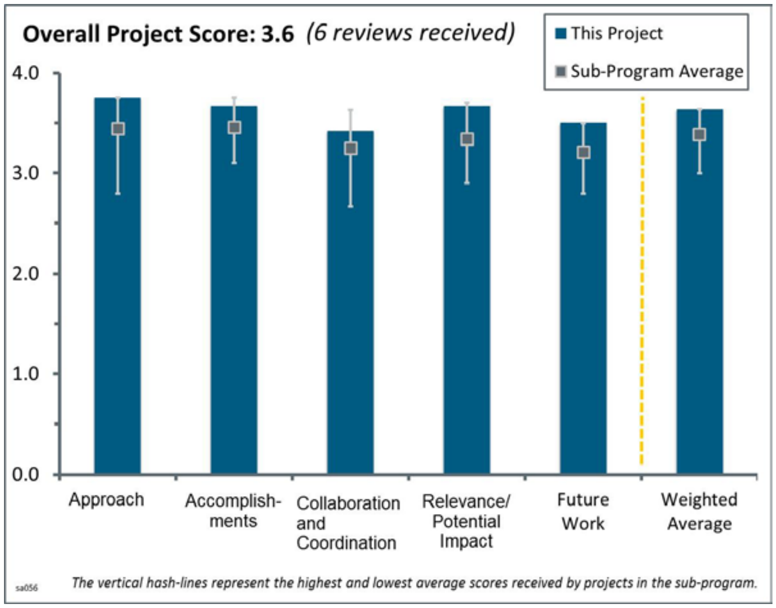
- Complex models such as this are difficult to analyze. Consequently, transparency of input assumptions is critical. Further description of inputs and selection basis would boost confidence in the model’s output. The model outcome is quite sensitive to FCEV pricing assumptions, and the two versions of pricing considered would lead to significantly different results. This should be explored further.
- Creating another model to determine the effect of FCEVs and hydrogen adoption on petroleum use and GHG emissions is a project weakness. There are too many DOE models addressing this same subject matter.
- The model appears to need additional refinement of variables, including vehicle costs. There is possibly a need for a sensitivity analysis for variables related to fuel costs that are reliant on U.S. Energy Information Administration data.
- There is no direct input from industry.

Recommendations for additions/deletions to project scope:

- The project should consider transformative technology breakthroughs in hydrogen production; i.e., a potential method to produce hydrogen for a lot less per kilogram delivered.
- Full disclosure of all variable data, an internal peer review of such variable data, and a sensitivity analysis for fuel and vehicle cost data for input into the model are recommended.
- DOE should consider reducing the number of models and analysis involving FCEV market penetration and the resulting reductions in petroleum use and GHG emissions.

Project # SA-056: Status and Prospects of the North American Non-Automotive Fuel Cell Industry: 2014 Update

David Greene; University of Tennessee



Brief Summary of Project:

The objective of this project is to contribute to the formulation of effective and efficient policies for deployment of fuel cell technologies and development of a sustainable fuel cell industry. The project will assess the impacts of American Recovery and Reinvestment Act (Recovery Act) deployments in the fuel cell backup power (BUP) and material handling equipment (MHE) industries, as well as reassess the effects of key policies on the sustainability of the non-automotive fuel cell industry in North America.

Question 1: Approach to performing the work

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

- The work represents a very pragmatic approach and demonstrates understanding of how market incentives can excite disruptive technology in new markets. The analysis is valuable in assessing the success of current and future policy in supporting the commercialization of new fuel cell technology and products.
- The project has a good strategy to provide feedback from key stakeholders and partners. Forklift and BUP are more near term than automotive application. The project provided great feedback on Recovery Act investments and the Recovery Act's impact, which includes the creation of new opportunities in the United States. Tax credit impacts and phase-out strategies are critical to commercial deployment of stationary fuel cells. This project builds on a previous study and updates it.
- The approach is outstanding. Appropriate tools were used, enabling adjustments to previous model estimates. Evaluations of money already spent are often the best way to assess future expenditures on similar projects.
    - This work applies to the non-automotive industry (MHE and BUP applications). It entails an update on a 2011 report. The report update addresses Recovery Act effects.
    - The work assessed Recovery Act effects on reducing technology costs and increasing technology deployment, and it considers reassessment policy goals concerning non-automotive applications.
    - The work considers the phase out of the investment tax credit.
    - The team looked at developments since 2011. Interviews with original equipment manufacturers (OEMs) were conducted.
    - It is not clear whether the cost predictions are for the future or current year.
    - It is not clear whether the sales data supports the fact that the Recovery Act helped sales.
    - It is not clear whether sales are going down. If sales are going down, it is not clear whether it is only those linked with the Recovery Act.
    - It is not clear whether there is a tax credit for electric vehicle (EV) forklifts.
    - Interviews with customers were conducted. EVs were covered in the work.
- The project goal is to assess the impact of Recovery Act funds to accelerate implementation of fuel cell power systems in BUP units and MHE. Specifically, it assesses whether Recovery Act-assisted purchases of fuel cells reduced costs through economies of scale and promoted additional sales above and beyond sales expectations without support from the Recovery Act. It is an interesting project; it is not addressing

any technical challenges, but more than likely it provides a methodology to judge the return on investment (ROI) of Recovery Act funds.
- Analyzing the effect of the Recovery Act stimulus on fuel cells for material handling and BUP was a really nice way to see whether government incentives work.
- The approach to isolate the impact of the investment tax credit (ITC) and incentive funding is of significant value to understanding the potential outcome for technology commercialization.

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

This project was rated **3.7** for its accomplishments and progress.

- The project provides a good update on the status of stationary fuel cells. The results on the cost reduction due to market support are encouraging. The model results are very useful. Technology progress is better than predicted, demonstrating good results from DOE investments. MHE has done better than BUP. The gradual phase out of the ITC is a great strategy outcome. Uncertainty analysis results are quite relevant and useful to OEMs and stakeholders.
- The project showed that the Recovery Act incentives not only worked but also accelerated development by allowing developers to actually scale up system buildup. The analysis of the phase out of the tax break should drive policy to continue the jump-started progress.
- The results of this work provided good market research on the effect of market incentives on the adoption of new disruptive technology for two very large markets. Analysis outcomes provide good insight on the early market behavior of two diverse industries and the industry’s acceptance of new technology that without market scale is relatively more expensive than the incumbent battery technology.
- This will help DOE assess future investments and help develop the non-automotive fuel cell industry.
- The model is appropriate and understandable. The model generally under-predicted the outcomes, but this conservative approach is reasonable.
- The model is simple; however, it is subject to large uncertainties in its projections.

Question 3: Collaboration and coordination with other institutions

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

- This small project was able to get accurate and honest data from the developers. The researchers talked to all the right people and were able to adjust their model accordingly.
- The project work involved a good deal of market research that required collaboration and persistence with most of the industry stakeholders.
- Outside experts were used in the assessment of this industry, adding to its value.
- Collaboration and partnerships appear appropriate, and there is adequate input of reliable data.
- The project had good collaborative efforts. Plug Power input would have been more valuable.

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

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

- This market research provides a valuable ground-level view of the market behavior of the material handling and BUP markets, their acceptance of fuel cells, and the impact of the Recovery Act market incentives. The work should be valuable to DOE because it provides an understanding of the commercial success for products resulting from previously funded research and development projects. Furthermore, the work provides an understanding of the effect of federal policy in jump-starting new fuel cell markets.
- Using the real-world experience of the Recovery Act incentives, it is now clear what the impact of future government intervention will be.

- This will help adjust policies, and it provides a compelling argument for phasing out funding rather than ending it abruptly.
- The project provides very important feedback for DOE to use in planning activities. The ITC and Recovery Act impact analysis is useful.
- This relevant work to project and predict pathways for commercialization with isolation of the impact of the ITC and incentive funding is very significant in understanding whether and how to provide incentives and in understanding the potential outcomes of technology commercialization with and without assistance.
- There is little value in projecting sales of fuel cell power units.

Question 5: Proposed future work

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

- The future work recognizes the current level of market research, and the model can be further refined and developed through additional market research, market segmentation, and model development. It is great that this work is externally focused and involves a market survey and close contact with industry players.
- All proposed work is appropriate, including refinement of "learning curves" with data and calibration. Additional attention to supply chain, export markets, and market segmentation is appropriate.
- Future work, including conducting more customer surveys, is in line with the findings and project needs.
- Surveying customers is a great activity.
- No future work was presented.

Project strengths:

- The project provides a way to estimate the impact of the Recovery Act in accelerating fuel cell deployment and reducing costs. The project has a good approach to justify the ROI on the Recovery Act support.
- The project provides a valuable ground-level view of the market behavior of the material handling and BUP markets and the impact of Recovery Act market incentives.
- The project used a real-world case and excellent collaboration to determine Recovery Act outcomes.
- The project is built on experience and a previous study. The project uses the choice model very well.
- Evaluation of past policies and adjustments to assumptions are beneficial to good decision-making. Concrete recommendations on phasing out versus ending funding are useful.
- Project strengths include the use of an objective model to isolate the impact of the ITC and incentive funding to understand potential technology commercialization.

Project weaknesses:

- The project could incorporate the value proposition of EV forklifts. Hydrogen forklifts may be not as cost competitive as they once were. The drivers for past and future demand are not clear.
- The project could include all stationary fuel cell projects and their status. Other fuel cell groups and trade associations can provide synergistic data to make the study more useful.
- One project weakness is the inherent need to calibrate the model with new data.
- Plug Power was absent from the list of OEMs providing data and information supporting this work. Data from Plug Power, a major recipient of the Recovery Act funding of fuel cells for the material handling industry, should have been incorporated into this work.
- Large uncertainties in the predictions make the results of little value. Authors indicate that Recovery Act support reduced annualized costs by economies of scale effects and that, as a result of the support, sales of units deployed for MHE and BUP increased by 1,500 and 3,000 units, respectively. It would be interesting to compare the additional sales derived from the support to the actual amount of support and how this cost (per unit) compares with the reduction of costs incurred per unit.
- The project is not continuing.

Recommendations for additions/deletions to project scope:

- The project has done good work in assessing the further impact of current fuel cell investments. It would be beneficial to analyze the combined effect of the Self-Generation Incentive Program (SGIP) and the ITC. Adding renewable identification number credits from the U.S. Environmental Protection Agency would also be useful.
- The team should consider expanding the scope to include vehicle markets for fuel cell EVs and hydrogen infrastructure.
- The project scope should explore the effect of state market incentives associated with the material handling market, along with California SGIP and other funds related to the BUP market.
- The team should expand the project to assess potential future government incentive programs.
- The project should incorporate the competition: EV forklifts.

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Sub-Program Comments Provided by Reviewers

Hydrogen Production and Delivery Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- This was an excellent overview of the sub-program, which is challenging to do because of the technical breadth. The current sub-program manager is technically and scientifically highly skilled, and this comes across in his presentation. With his background, he is more than capable of understanding and conveying the intricacies of the sub-program, from the engineering and technical end of the spectrum to the deeply scientific reaches of the sub-program.
- Yes, the sub-program was clearly described. The overall strategy was focused on delivery (including the cost of production, storage, and transfer) of hydrogen at <$2/gasoline gallon equivalent (GGE). The presentation highlighted that natural gas reforming is already able to deliver hydrogen at less than $4/GGE. Thus, the focus of the sub-program is on hydrogen production from renewable energy sources and improving delivery.
- Yes, the sub-program was adequately covered.
- The sub-program was adequately covered. The presentation was perhaps too detailed; it is not necessary to cover as much as was included in this presentation, which was clear at the end when the presenter ran out of time. (An additional note: as in the project review sessions, the moderator should start on time regardless of whether the audience is ready.)
- The sub-program was covered thoroughly. However, there was way too much information to be conveyed and absorbed in 30 minutes. The presentation deck will be a good reference document, but it was difficult to get that much out of the presentation itself because it was so rushed.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, there is an appropriate balance between near-, mid-, and long-term research and development (R&D).
- The sub-program is very well balanced both in terms of technology development and R&D.
- The portfolio is well thought-out and well managed. It is underweighted on near-term opportunities for early wins.
- Yes, near-term efforts focus on lowering the cost of delivery using established methods of production (e.g., natural gas reforming). Mid-term projects revolve around emerging technologies, including electrolysis, for large-scale production. Long-term efforts are in photoelectrochemical (PEC) and solar thermal hydrogen production.
- Yes, there is an appropriate balance, although it is not always clear what topics fall under long-term research—this could be clarified in the presentation.
- Yes.

3. Were important issues and challenges identified?

- Key challenges were highlighted, including the durability of hoses, the cost of the delivery station, and electricity cost as a driver for the production of hydrogen via electrolysis.
- Yes, the need for reducing the cost (dollars/kilogram) of hydrogen dispensed at the nozzle was identified.
- Yes, all major issues were identified.
- The challenges in this area were very thoroughly described and clearly presented.
- More thought should be given to identifying key challenges to "bridging" production technologies that would lower the cost of hydrogen and expand availability in the near term, which could accelerate the growth of fuel cell electric vehicles (FCEVs).
- Yes.

4. Are plans identified for addressing issues and challenges?

- The sub-program features well-thought-out plans that have led to a well-balanced portfolio that seeks to address the short-, medium-, and long-term challenges for hydrogen production and delivery.
- The plans are described in detail in the respective project presentations.
- Yes, plans are identified, but the plans appear largely focused on small stations and small-scale production capacities (even with an acknowledgement that the amount of hydrogen needed for "X" number of FCEVs would outpace current U.S. capacity). In addition, the hydrogen cost-reduction targets are not associated with small-scale production.
- Each of the challenges is being actively addressed with new materials discovery efforts. However, the presentation provided very little articulation of the challenges and innovative efforts in solar PEC production of hydrogen.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes—progress in each of the core areas of solar hydrogen; solar thermochemical; polymer electrolyte membrane (PEM) electrolysis; and compression, storage, and dispensing (CSD) was discussed in detail.
- Yes, progress was clearly benchmarked against the previous year.
- Progress, as usual, was clearly described against prior years' work.
- No, it was not clearly benchmarked, other than via some budgets for fiscal year (FY) 2015 and FY 2016.
- No.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects in this technology area are clearly addressing the broad problems FCTO is trying to solve.
- Absolutely. Development and understanding of this area are critical for the entire fuel cell enterprise to exist.
- Yes, efforts in this sub-program are well aligned with the objectives of FCTO.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is very well focused, even though it is technically very broad, with activities ranging from pipelines and corrosion to hydrogen-producing bacteria. This is a very well-managed portfolio, and the sub-program manager is technically competent and well informed. It is terrific to see such scientifically and technically competent managers running a portfolio in an applied technology office.
- Yes, the sub-program features a blended mix of near- and long-term efforts. The near-term efforts focus on cost-effective storage and delivery, and the long-term efforts focus on solar hydrogen.
- Yes, the sub-program appears to be well managed.
- Yes, it does appear to be focused, but there are some exceptions.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- An example of a project standing out as a strength is the project involving nanosonic and new 700 bar hose development. There is currently only one supplier in the U.S. market. An example of a project standing out as a weakness is the H2FIRST Reference Station Design project. This project clearly showed that at the sizes of stations chosen, \$4/kg will not be achieved.
- The sub-program's projects have no weaknesses. The strength is in a good balance of short- and long-term technology development activities, and a very good medium-to-longer-term R&D component looking at

renewable hydrogen pathways. A key strength is the coupling of technoeconomic analysis early in the project lifetime to maximize impact.
- The solar pathway projects stand out as being innovative and forward-looking.
- One project not even mentioned in the sub-program highlights deserves a higher emphasis—the Lawrence Livermore National Laboratory (LLNL) liquid hydrogen compressor project seems to offer a major solution to the primary cost component of hydrogen stations: compressor capital expenditures and reliability. One weakness is the emphasis on solar thermochemical (STCH) projects. At the current cost of solar heliostat fields (i.e., $4,352/kW average of literature sources), the cost of hydrogen for just the capital recovery of the heliostat and power tower capital costs would be $7.94/kg (assuming 25% annual solar capacity factor and a 12% annual capital recovery factor; this calculation also assumes the STCH electrolyzer is free). However, Savannah River National Laboratory claims it can achieve STCH hydrogen cost of $4.35/kg or less. It was mentioned that this cost assumes heliostat cost reductions under the U.S. Department of Energy (DOE) "SunShot" program. It is not clear whether these SunShot cost reductions are achievable. It is also not clear whether the STCH projects have undergone the rigorous design for manufacturing and assembly (DFMA) cost analysis that most hydrogen research areas have used. It would not be fair if these STCH projects are funded at the expense of other hydrogen production pathways that receive lower funding due to negative DFMA cost estimates. At the very least, the STCH projects should provide the assumed cost reductions in the heliostat and power tower used in deriving their low hydrogen costs.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, they do represent novel and innovative methods to approach these barriers; the solar pathway projects are particularly novel and innovative.
- Yes, they do represent novel and innovative methods to approach these barriers, with the exception of the LLNL liquid hydrogen thermal compressor concept that was not emphasized.
- Given the breadth of the technology represented within this portfolio, this is almost not a fair question. Clearly there are highly innovative approaches being supported in the R&D portfolio; the technology development area is also solid, but of course it may not appear to be as innovative. Integrating such a broad portfolio into an effective overall sub-program is perhaps innovative.
- The approaches are not particularly novel, but the sub-program stresses the discovery and development of novel materials to enable high performance from known device architectures.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has engaged a multiplicity of partners across the breadth of the sub-programs. This collaboration is conducted at a more-than-appropriate level, considering how critical this sub-program is to the overall FCTO goals. Without a solid hydrogen production and delivery portfolio, the rest of FCTO would suffer.
- The sub-program features so many collaborations that it is not clear how it keeps track of all of them. However, it appears the list does not include analogous government efforts in Germany and Japan, which are also doing a lot of work in hydrogen/FCEVs.
- Yes, the sub-program has engaged the appropriate public laboratory and private industry partners.
- Yes, it has engaged appropriate partners, but the collaborations can be expanded. The sub-program is missing collaborations with other federal agencies, such as the U.S. Department of Transportation (DOT), Federal Transit Administration, and U.S. Environmental Protection Agency (EPA), as well as with different departments within these agencies, such as the Pipeline and Hazardous Materials Safety Administration and the National Highway Traffic Safety Administration.
- Yes.

11. Is the sub-program collaborating with them effectively?

- The sub-program appears to be collaborating effectively to continue to make progress across a broad set of technical and scientific fronts.

- Yes, the sub-program appears to be collaborating with partners in an effective manner.
- It appears the sub-program is collaborating effectively.
- It appears the sub-program is collaborating effectively, but it was not clear from the presentation, because of the time limitation.
- One is not able to judge the effectiveness of the collaborations based on the presentation.

12. Are there any gaps in the portfolio for this technology area?

- At present, there are no gaps.
- There were no detectable gaps.
- One gap is mobile fueling at 700 bar (subtopic 1b was missing from the description on slide 32 about the FY 2015 funding opportunity announcement [FOA]). Also, the Hydrogen Production and Delivery sub-program applies mainly to passenger vehicles—it would be good to emphasize medium- and heavy-duty FCEVs in light of increasing market and policy interest in these applications.
- There may be more opportunities to address significant near-term challenges, such as carbon capture for natural gas reforming.

13. Are there topics that are not being adequately addressed?

- There are no detectable weaknesses in the set of topics that this sub-program has elected to support.
- At present, there are no topics being inadequately addressed.
- Topics not being adequately addressed include (1) transit fuel cell bus fueling and the cost of hydrogen in a balanced supply and demand situation, as well as fuel cost targets for this area, and (2) medium- and heavy-duty fuel cell vehicle fueling and fuel cost targets for this area.
- The LLNL thermal compression at liquid hydrogen stations project should be emphasized and given adequate funding—this technology could make the low cost of delivered liquid hydrogen even more competitive by eliminating mechanical compressors, the component with the highest capital cost and highest operations and maintenance cost.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The sub-program appears to be addressing the barriers to hydrogen production and delivery within the bounds of its budget in a rational, well-balanced manner.
- Aside from pipeline cost, the sub-program should consider the feasibility of laying pipelines in urban areas, in light of challenges with “Not in My Back Yard” (NIMBY) and other aspects of implementation. These challenges could be so limiting that DOE should not focus on pipelines as much when determining long-term practical and realistic solutions within U.S. metropolitan regions.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The sub-program should continue on its current path. There are no recommendations that might make a substantial improvement in how the sub-program is going about its business.
- This sub-program appears to be very complete in its coverage.
- The sub-program needs to revisit the cost of liquid versus gaseous hydrogen delivery. It has been calculated that the cost of liquid hydrogen stations is less than the cost of gaseous hydrogen stations, while slide 14 from H2FIRST shows a higher cost for liquid hydrogen stations than for gaseous hydrogen stations. However, in 2013, the National Renewable Energy Laboratory (NREL) estimated that gaseous hydrogen stations cost approximately 60% more than liquid hydrogen stations ($2,190/kg/day versus $1,300/ kg/day), and NREL estimates that the all-in costs of delivered hydrogen from a central biomass plant are higher with gaseous hydrogen delivery than liquid hydrogen delivery ($5.74/kg versus $5.12/kg).[1] Most convincing,

[1] See T. Ramsden et al., *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*, NREL/TP-6A10-60528 (Golden, CO: National Renewable Energy Laboratory, 2013), http://www.nrel.gov/docs/fy14osti/60528.pdf.

however, is the choice made by industry for the fuel cell material handling equipment (MHE) market: most are using trucked-in liquid hydrogen instead of trucked-in gaseous hydrogen. In addition, Linde has chosen liquid hydrogen delivery for five stations in California. If the LLNL thermal liquid hydrogen compressor approach works out, it will further reduce the cost of liquid hydrogen (the previously mentioned liquid hydrogen costs all assume mechanical compressors reach pressures to fill 700 bar tanks).

- The sub-program should increase its engagement with biomass/municipal solid waste (MSW) gasification technology partners—these entities will have to play an increasingly significant role to address the need for renewable content on the desired long-term scale.
- In general, DOE should put more emphasis on supporting the science that will lift all boats, versus applied engineering to bring a particular embodiment to market.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Presently, there are no ways to improve the effectiveness of the sub-program.
- The sub-program should keep adding to the technical prowess of the management team. The management team is working to bring the right mix of skills to address the very broad set of technical, engineering, and scientific challenges of the sub-program.
- Sub-program managers should pressure principal investigators (PIs) to focus all (or nearly all) their effort on key technical challenges—the PIs should identify these challenges and do research to address them. Asking the projects to encompass everything from fundamental science to demonstration units dilutes the effort. Projects end up addressing engineering issues that, while important, are not going to make or break the technology.
- The sub-program should focus more on the solar thermal hydrogen production space. This approach is deserving of higher attention relative to PEC, particularly given the significant PEC efforts in DOE's Office of Basic Energy Sciences (BES) and at the Joint Center for Artificial Photosynthesis (JCAP).
- The sub-program should consider expanding its international partner base and funding two or three shared projects in common-interest topic areas for hydrogen production and delivery.

Hydrogen Storage Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The presentation offered a clear overview of the sub-program strategy and a succinct snapshot of the overall portfolio and future directions.
- The strategy was clearly articulated and justified. The sub-program manager is well regarded internationally, and thus his observations on the "state of the art" are, as usual, well received.
- Yes. Clear, numeric goals were expressed. The presentation did a reasonable job of outlining how the present project mix is aimed at accomplishing the goals.
- The overall strategy—and specifically, the short-term strategy—was well covered and explained.
- Yes, the sub-program was covered very well.
- Yes, the sub-program manager did a very good job in providing an overview of the Hydrogen Storage sub-program's goals and objectives. Additional emphasis could be placed on the need to improve cost, gravimetric and volumetric capacity, with linkage to higher-level vehicle parameters (e.g., range).
- The sub-program has evolved to include an appropriate mix of near- and long-term research. It may be worthwhile to examine the longer-term areas of work (e.g., cryo-compressed, materials, sorbents, and chemical) and consider cutting efforts in areas with little chance of meeting goals and increasing efforts in more promising areas.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. Near-term work appropriately centers on cost reductions for compressed hydrogen storage; in particular, it focuses on the cost of the reinforcing fiber either through cheaper carbon fiber or advances in new generations of fiber glass. Long-term work correctly centers on solid media. Mid-term work centers on cryogenic compressed-gas storage. When questioned whether the original equipment manufacturers (OEMs) would tolerate more operationally complex cryogenic and solid-state systems, the manager stated that vehicle range was still of paramount importance. One other important near-term activity is the use of intermetallic (heavy) hydrides for industrial forklifts.
- Yes, this balance was clearly described.
- The portfolio is well balanced. However, further clarification concerning the future of the chemical hydrogen storage activity would be helpful. Although chemical hydrogen storage is listed as a "longer term approach," it is not at all clear whether there is any interest from the DOE Hydrogen and Fuel Cells Program (the Program) in pursuing this technology in the future. A candid and straightforward statement that expresses the position of the Program on that technology would be useful for the hydrogen storage community.
- Yes, slide 3 provides a clear indication of the near- and long-term research portfolio. It may be helpful to have some simple metrics that indicate the number of projects in the portfolio that are near term versus long term.
- There seems to be good focus on near-term (e.g., compressed) and long-term (e.g., materials, sorbents, and chemicals) efforts. Cryo-compressed appears to be the only mid-term technology. Conformable compressed may also be a mid-term technology.
- The portfolio may be in transition. There is a short-term emphasis on high-pressure tanks. As high-pressure tanks are now becoming commercially available, some shifting away from R&D on carbon fiber development may be warranted because that is clearly in the domain of commercial entities. While some DOE investment is still perhaps warranted for particular aspects of removing the cost barriers, perhaps more funding emphasis could go toward medium- and long-term materials-based strategies that can be potential game changers. The longer-term portfolio is now heavily weighted toward adsorbents and complex metal hydrides. The R&D emphasis on complex metal hydrides is less well justified, because research in this class of materials seems to not be focused on achieving higher kinetics and lower temperature release. Wholly new long-term strategies should be sought, or new perspectives on complex hydrides need to be added.
- Currently, there seems to be more emphasis on meeting short-term targets (e.g., reduction of high-pressure tank cost) and tank engineering led by the Hydrogen Storage Engineering Center of Excellence (HSECoE).

3. Were important issues and challenges identified?

- Barriers and future challenges were well identified, with the current commercial availability of high-pressure tanks driving a reemphasis on higher and higher capacity materials that can meet the targets.
- Yes, important issues and challenges were identified, especially for the materials-based storage initiative.
- Both technical and economic challenges have been clearly understood and explained by the sub-program.
- Yes—cost, weight, and volume were identified, above all others.
- Yes—slide 3 ("…Strategy and Barriers") provides a good summary.
- Challenges were identified. It would have been helpful for the presenter to have shed more light on the "lessons learned" from the HSECoE; for example, the presenter could have highlighted key technology hurdles identified by the HSECoE.
- Yes, the barriers and R&D focus were identified during the presentation. There are certainly many challenges with the hydrogen storage system. In the future, it may be beneficial to highlight a prioritization of the challenges.

4. Are plans identified for addressing issues and challenges?

- Plans were presented to overcome existing challenges.
- Yes, plans were identified quite well.
- Yes, there is a good mix of projects to address the barriers. In the review of project accomplishments, it was helpful to have the summary statements at the bottom of the slides to directly identify the linkage between the projects and barriers.
- This sub-program has a long history of addressing these challenges (which have not changed over the history of the sub-program). Practical solutions have proved hard to find.
- Future approaches to "beat the tank" appear to be largely focused on incremental research on adsorbents and complex metal hydrides. Longer-term research on somewhat riskier, but high-payoff approaches could be sought.
- A plan that identifies issues and challenges was provided only in an indirect way. The presentation summarized the accomplishments, highlights, and plans of current and future projects in the portfolio. It was necessary to "read between the lines" to extract information concerning plans for a coordinated and coherent effort to address issues and challenges.
- Plans are not specifically spelled out for the identified issues; this is normal because the plans are described in the appropriate session presentations and not in this overview.

5. Was progress clearly benchmarked against the previous year?

- Yes, progress with respect to the previous year was indicated; the summary of the past six years of effort on storage by the HSECoE was good.
- The accomplishments were well characterized against prior years' accomplishments.
- Yes, the progress accomplished this year, compared to last year, was clearly communicated.
- Yes, progress was benchmarked in good detail for compressed gas storage. However, there was not much detail for progress in the other technology areas.
- The progress of compressed hydrogen system cost was clearly indicated from the previous 2013 record. It would be useful to identify other metrics to track progress, especially with the material-based storage system. Further highlights on how the DOE portfolio has made a difference in advancing hydrogen storage technology should be included. The metal hydride forklift was a great example of DOE research making a difference in a potential commercial product.
- Progress in all current projects and plans for new project work was summarized in an effective way. However, only very limited benchmarking against progress from the previous year was provided.
- Lowering the costs of carbon fiber is a challenging goal in a mature industry, but the sub-program has made significant progress in reducing costs by using novel precursors and optimizing processing variables. While the HSECoE has made significant progress in understanding the engineering demands of viable storage systems, this effort may have been premature in that as it comes to its planned completion, no workable materials have yet been identified

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects are focused on (1) reducing the cost of the hydrogen storage system to lower the fuel cell vehicle cost and (2) improving storage system performance to meet the important vehicle attribute of driving range.
- Absolutely—the links between the different projects and the problems/barriers are clearly spelled out.
- Yes, the projects address the broad problems FCTO is striving to solve.
- Yes, storage (vehicle range) remains a serious remaining problem within FCTO.
- The Hydrogen Storage sub-program is and has been well focused on the broad and difficult problem of identifying viable hydrogen storage approaches that will surpass the performance of high-pressure storage tanks for onboard applications. The large Centers of Excellence or Center-like activities have led to large gains in understanding the practical limitations of various approaches, and have helped focus current and future research on addressing the remaining barriers. Hydrogen storage is a daunting problem, and the solutions, if they exist, will require a high degree of scientific and technical creativity. The current portfolio could be improved by seeking longer-term, riskier—but high-payoff—research directed by engineering assessments of what materials properties are required to meet the DOE targets.
- In general, yes—a reasonable portfolio of near- and longer-term approaches is in place. At present, there appear to be only two candidate technologies that are attractive in the short-to-mid term: (1) 700 bar compressed gas, and (2) sorbents (and, potentially, cryo-compressed). The other solutions, especially metal hydrides and chemical hydrogen storage, have serious limitations that may preclude their deployment in a practical system (unless major advances occur).
- Storage issues are central to the implementation of fuel cell vehicles. The sub-program has worked hard to find new methods of storing hydrogen. These efforts have not developed viable solutions, and the sub-program has refocused to address lowering costs for traditional high-pressure storage.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is very well managed. The sub-program managers and staff have considerable expertise and experience in all focus areas of the sub-program, and they fully understand the benefits and limitations of specific technology areas. The sub-program effectively addresses FCTO's needs. The recognition by the DOE Hydrogen and Fuel Cells Program (the Program) that additional basic and fundamental materials work is needed represents a departure from the traditional Office of Energy Efficiency and Renewable Energy (EERE) charter. This is a very reasonable point of view, and it should be a sub-program imperative.
- This sub-program continues to be a very well-managed enterprise. The sub-program manager is a well-recognized technical expert in this area, and his reputation and expertise have helped the Hydrogen Storage sub-program. The DOE management team (based in Washington, DC, and the Golden Field Office) is excellent overall.
- Yes, the sub-program is focused on FCTO's needs: lower FCEV cost and improved driving range. The sub-program managers are very effective and focused on managing the projects. This sub-program provides high value to FCTO.
- The sub-program has done a good job of moving from its initial focus on hydrides and materials to a broader approach that includes optimization and cost reduction for compressed hydrogen.
- Yes, this sub-program is focused and well managed.
- The sub-program is well managed and focused.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The progress being made on the alane cost reduction project is noteworthy. The new project on conformable high-pressure storage (ST-126) could be a game changer for onboard 700 bar storage.
- The spider charts summarize each project's status and identify weaknesses in a concise and effective way. The incumbent technology, compressed gas, will never meet the volumetric target; sorbent technology

requires cooling and is costly. Likewise, existing sorbent systems fall short of gravimetric and volumetric capacity goals—material advances are needed. Light-metal and complex hydrides suffer from severe kinetic limitations and, in most cases, limited capacity. Chemical hydrogen storage systems are encumbered with the need for regeneration—the large overhead cost for system regeneration may eliminate this technology from future consideration unless a simple process can be identified.

- Some of the materials-based projects appear to be providing incremental advancements in knowledge of storage materials and are not well poised to create "breakout" advances. The current strength of the sub-program is the engineering assessments area, which is providing guidance to materials and systems developers. An area that has provided recent scientific advances is the area of "metal-assisted" sorption in high-surface-area adsorbents, wherein the included metals act to bind additional hydrogen molecules with somewhat higher binding energies. While this approach may not result in a technical advancement for hydrogen storage, it has shown how far one can go with this approach; from that perspective, it is a strength of the sub-program—the willingness to follow through to ensure that the science indeed is providing evidence of barriers that may not be achievable by certain approaches. Negative evidence is valuable in the daunting search for the hoped-for practical hydrogen storage system.
- Key strengths include the focus on immediate challenges with high-pressure tanks and the understanding of engineering challenges associated with materials-based storage. An area of weakness is that, although the sub-program has recently funded a few projects that address long-term materials-based storage, the attention and funds allocated to long-term materials-based solutions still seem insufficient.
- The key strength is the fact that the near-term projects on compressed hydrogen storage are relatively straightforward relative to the cost and engineering aspects of the technology needed. The inherently weaker projects are those associated with science-based solid-state storage media. The science of these materials is relatively new and requires significant breakthroughs.
- The projects in the sub-program are well balanced. There are a few projects that do not seem to be aligned with automotive applications. Also, there are some projects that have good intentions but may need some redirection to ensure the approach aligns with the most significant barrier for the technology.
- The continuing work on materials-based storage solutions (e.g., hydrides, sorption, and chemical storage) has been disappointing, given the high hopes present in the early days of the sub-program. Given the large expenditures to date and the failure of the sub-program to come up with promising materials, FCTO should consider the desirability of continuing efforts in this area.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- There are many novel and innovative projects in the sub-program. The sub-program managers are very good at selecting projects that target key barriers.
- Yes, the alane and conformable 700 bar projects both represent novel/innovative ways to approach the FCTO barriers.
- The sub-program has used novel approaches to lower costs and improve performance.
- Yes, the projects associated with solid storage media represent innovative ways to approach the barriers. The DOE projects represent a pioneering effort. Unfortunately, solid storage is a very difficult technological subject.
- The projects that compose the overall portfolio generally offer innovative approaches to address the barriers. With one or two exceptions, the new projects provide some interesting options for tackling the barriers in novel ways. The efforts of FCTO to create the Hydrogen Storage Materials – Advanced Research Consortium (HyMARC), comprised of national laboratory partners, is great. With the completion of activities in the three materials centers and with the HSECoE activities drawing to a close, there is a critical need for an overarching collaborative effort that focuses and coordinates R&D activities in hydrogen storage. Without such an entity, the sub-program simply becomes a mix of largely uncoordinated R&D and engineering efforts that lack the cohesion and cooperation that a Center provides.
- In general, the projects present innovative ways to approach the barriers. However, the uniqueness of some of the recently funded projects is unclear.
- While detailed information on several new projects is still to come, from the brief descriptions, these projects would appear to not be particularly innovative, but rather incremental in nature.

10. Has the sub-program engaged appropriate partners?

- The sub-program features good work on leveraging carbon fiber work being supported by other DOE programs, such as the Advanced Manufacturing and Vehicle Technologies Offices, and takes advantage of existing Oak Ridge National Laboratory (ORNL) facilities. Input from OEMs on the U.S. DRIVE Partnership Technical Teams has been valuable in formulating and guiding hydrogen storage projects toward practical goals.
- Yes, the sub-program has engaged a very impressive spectrum of participants: universities, national laboratories, consulting scientists and engineers, industry, OEMs, etc.
- Yes, the sub-program has done an excellent job in engaging partners. In particular, the DOE materials-based hydrogen storage summit was very useful in bringing the experts together.
- The sub-program has continued to be one that attempts to collaborate with other R&D entities.
- The sub-program has indeed engaged the appropriate national laboratory and private partners.
- The sub-program brings together highly competent partners.
- The projects in the current portfolio are highly relevant to the overall goals of the DOE Hydrogen Storage sub-program. However, a formal framework that initiates and sustains collaborations is not currently in place; i.e., cooperation and multigroup interactions are encouraged, but they are only informal. The new HyMARC program could go a long way to formalize fruitful collaborations among national laboratories and industry and academic partners.

11. Is the sub-program collaborating with them effectively?

- There are strong, beneficial connections and collaborations between the sub-program and all existing projects.
- Yes, the sub-program is collaborating with partners very effectively. The communications among the many partners is extraordinary.
- Yes, the sub-program has connections with the industry experts and seeks their input regarding the research.
- The sub-program appears to be collaborating with partners in an effective manner.
- Yes, the collaboration between the sub-program and partners is visible.
- This sub-program, like so many other applied sub-programs, has difficulty crossing the boundaries to the Office of Basic Energy Sciences (BES) "silo" to engage in collaborative longer-term, riskier, but high-payoff R&D in the chemistry and materials studies relevant to hydrogen storage.

12. Are there any gaps in the portfolio for this technology area?

- This technology area is adequately covering the problem areas with the current portfolio of projects.
- There are not really any gaps within the known and likely technology. However, any hints of possible new technologies showing any theoretical promise should be carefully considered for the portfolio.
- The sub-program appears to be covering most of the promising technologies in hydrogen storage with few gaps.
- The sub-program managers have acknowledged the critical need for more robust basic/fundamental research activities to address the critical challenges faced by hydrogen storage materials. With the completion of the materials centers, there has been only a very limited opportunity to explore important thermodynamic and kinetic obstacles. The new HyMARC program is a good first step toward providing a framework for obtaining deeper fundamental understanding. It will be essential for DOE to strengthen cooperation across Program offices (e.g., EERE, BES, and the Advanced Research Project Agency – Energy [ARPA-E]) and with other agencies (e.g., the National Science Foundation) to ensure that critical research issues are addressed in the most efficient and effective way.
- The lack of highly innovative longer-term strategies for onboard hydrogen storage is a significant weakness and detracts from the overall effectiveness of the sub-program. There seems to have been a downward trend in the fraction of longer-term R&D in this portfolio in the last several years. However, there appears to be a desire to add more materials R&D back into the sub-program; if more materials R&D projects are selected, there may be a reversal in this trend.

- It appears that cryo-compressed, cold gas, or adsorbents have the potential to be a near-term alternative to compressed hydrogen. Therefore, the development of robust advanced insulation of these systems would be useful.
- More emphasis is needed on long-term materials-based solutions.

13. Are there topics that are not being adequately addressed?

- All topics are being adequately addressed, at least within the spectrum of known technology. New ideas and rational theoretical analyses are needed.
- The development of innovative materials-based long-term solutions is not being adequately addressed.
- At present, all topics are being adequately addressed.
- The boundary conditions on materials that can meet the targets are now better understood and are very constraining. The solutions to these conditions will require new, “out-of-the-box,” and perhaps risky R&D. The sub-program is encouraged to find ways to encourage those not entrenched in the “business as usual” approaches to storage, and to attempt wholly new approaches to the storage of hydrogen in a manner that has a chance of meeting the targets.
- The Program is encouraged to make a more definitive and straightforward statement to the research community about its future plans for chemical hydrogen storage.
- In projects that include a significant amount of modeling, validation of or reference to the model assumptions would be useful for observers to gain confidence in the project teams’ predictions.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- At present, there are no other areas the sub-program should consider funding to meet overall programmatic goals.
- No additional noteworthy areas are recommended for funding.
- There are two possibilities, both of which were briefly considered for the storage problem decades ago:
    - (1) Rechargeable Liquid Organics – Catalytically decompose onboard, then pump out the H-depleted compound(s) for off-board regeneration. Perhaps a new generation of organic chemists can come up with new theoretical possibilities.
    - (2) Liquid Anhydrous Ammonia (17.7 wt.% H) – The direct burning of NH_3 was demonstrated in internal combustion engines at least a half century ago. Perhaps NH_3 can be made cheaply and cracked, and then the hydrogen could be purified to the level needed for it to be used in a fuel cell.
- The complex metal hydrides area is largely populated by materials scientists, who are taking a materials science approach to improving the materials. Perhaps adding co-researchers to these teams that have a better understanding of the covalent chemistry of this class of materials would enable different approaches to be utilized to overcome some of the kinetics issues with hydrogen release and uptake, as well as provide a “fresh set of eyes” on the problem. Looking at other covalent X-H compounds may be profitable.
- Efforts could be included to reduce the complexity and cost of the balance of plant (BOP) in all the storage systems. The HSECoE provided a good understanding of the BOP schematics and content. The next step would be to develop opportunities to reduce the number of items and confirm new designs with a complete BOP demonstration.
- Areas that the sub-program could fund include innovative materials-based solutions that are theoretically capable of meeting the DOE targets (as estimated using HSECoE generated models).

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The efforts to establish and fund the HyMARC activity are great. The consortium will provide a solid foundation for conducting collaborative research on important problems. DOE should move to rapidly include academic and industry participation in the consortium.
- Over the past few years, the sub-program has produced modeling tools that allow the researchers to (1) determine upfront whether the materials they propose are at least theoretically capable of meeting the DOE targets and (2) identify the challenges that need to be addressed. That said, if DOE decides to place more

emphasis on long-term materials-based R&D, the researchers should be asked to justify the viability of their concepts using these tools.

- There are a few compounds or classes of compounds that have some promise, but they release hydrogen at too high of a temperature, or too slowly, or both. This may represent an opportunity to better understand catalysis in these condensed phases, which is difficult. Assembling materials development teams that include catalysis and more chemical science-oriented researchers may provide ideas to address the kinetics limitations of certain classes of materials.
- The safety considerations of every new storage technology should be clearly identified and considered both in a normal situation and a failure situation. Projects should make statements about their safety consideration of the technology and attempt to connect with safety organizations.
- The continuing work on materials-based storage solutions (e.g., hydrides, sorption, and chemical storage) has been disappointing, given the high hopes present in the early days of the sub-program. With the large expenditures to date and the failure of the sub-program to come up with promising materials, FCTO should consider the desirability of continuing efforts in this area. It is not clear what the new materials consortium will do that has not been done in the last 10 years.
- At present, there are no recommendations.
- At the moment, there are no recommendations.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The Hydrogen Storage Summit held last January was successful. It provided a forum for researchers to discuss new R&D needs and express their candid opinions about current Hydrogen Storage sub-program directions. A similar summit should be convened every 2–3 years.
- In addition to this written evaluation, DOE should try a short (two hours), open brainstorming workshop at the Hydrogen and Fuel Cells Program Annual Merit Review (AMR). Of course, participants would not likely disclose any new specific ideas of potential patent value, but a discussion of the pros and cons of new scientific and technological areas might be useful to general DOE thinking and also stimulating to the participants.
- The challenges with hydrogen storage systems are daunting, and while high-pressure tanks are important for initial market penetration, long-term solutions need to be developed. Therefore, one suggestion would be to have more frequent workshops or ways to bring together researchers and engineers to discuss these issues and make recommendations to DOE.
- It would be helpful to have "guesstimates" on the anticipated "time-to-market" of the various alternative material storage projects that are being funded, as well as some indicator of the expected impact.
- A red team approach to sorption might be useful. It is not clear whether the existing approaches can really get anywhere. A very hard, critical look at this area may help improve the overall effectiveness of these sorption projects.
- All projects should have a connection to an industry partner, either as a partner or a consultant, to ensure the research is on a path to commercialization.

Fuel Cells Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The highlights from the Fuel Cells sub-program-funded projects were well covered. The overall strategy was also presented well.
- The sub-program covered cost reduction, durability strategies, and projects with various collaborators very effectively.
- Yes, the sub-program covered the fuel cell activities well.
- Yes, the sub-program was sufficiently covered, including the detailed overall strategy.
- Goal and gap analysis was pursued, and focus areas are identified properly. However, information on the approach and how to fill the gaps is not clearly identified. Each Funding Opportunity Announcement (FOA) seems to be ad hoc. A consistent strategic plan was not presented. The sub-program should show its desired research portfolio (what should be) and the gap from the current research portfolio. Future FOAs should be developed to fill the portfolio gap. A review of results from the recent Fuel Cell Technologies Office request for information (RFI) and workshop, which asked for feedback on necessary R&D areas, would have been helpful. It is also important to show the benchmark analysis of foreign governments' funding programs to allow for comparison with the DOE research portfolio. The European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and Japanese New Energy and Industrial Technology Development Organization (NEDO) projects have comparable funding levels and should be benchmarked.
- Yes—this is clearly a large and diverse sub-program, and the topics that were the focus of the past year were presented well. Additional information on topics within the sub-program that were not a focus in this past year could have been covered a little more thoroughly, such as by acknowledging and describing their role in the multiyear effort.
- The sub-program was represented well. While it is clear that automotive targets are well established, the technical targets for non-automotive applications are not provided in detail.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. A lot of this work will take time to achieve success and implementation, but there is an appropriate degree of urgency to the work in order to ultimately facilitate successful commercial introduction of these technologies.
- The balance appears appropriate, even though long-term research only concerns catalysts and membranes for low-temperature PEM fuel cells. Materials for medium- or high-temperature PEM fuel cells or materials and coating for bipolar plates (BPs) may also be included. Because fuel cell cost projections unfortunately remain almost stable since 2011, projects with a high potential of achieving a technological breakthrough—even if they are high risk—might be initiated.
- Yes, the R&D portfolio is adequately balanced between near-term and longer-term impact items. The majority of the funding is focused on longer-term cost-reduction activities and in the pre-integration activities. Technology development and scale-up of the latest generation catalysts, to move these from Technology Readiness Level (TRL) <3 to >5, might be considered medium-term activities.
- The emphasis on cost reduction and performance, based on catalyst and membranes, was well documented in the presentation. It would have been nice to get some information on BP development, because BPs are the next highest cost contributor after catalysts and catalyst application.
- The presentation did not discuss the balance among the different time frames (i.e., near, mid, and long terms). However, research in this area is in the precompetitive phase and is basically mid- or long-term research.
- Yes. *(2 responses)*

3. Were important issues and challenges identified?

- Yes, the sub-program is clearly driven by attainment of the market-driven targets, and the barriers to achieving those targets were presented well.
- Proper gap analysis was done with the U.S. DRIVE Fuel Cell Tech Team. Important issues and challenges were identified.

- Yes, the challenges and issues were identified, and the key focus areas were addressed clearly.
- Yes. Challenges and strategies to address them were well identified.
- Yes, challenges are clearly identified.
- The main challenges remain cost and durability, which are well identified and addressed. The following challenge will be manufacturing with cost and quality targets, and this is addressed in the Manufacturing sub-program. The 70% system efficiency target appears to be a concern. Indeed, taking a 10% parasitic loss leads to an average cell voltage of 1 V, and even taking 0% of parasitic loss leads to an average cell voltage of 0.88 V. Today these values appear to be unrealistic while looking for lower Pt loadings and increased durability. Announcing this kind of over-aggressive target does not contribute to the scientific credibility of the sub-program. Increasing the power density is an important item that was identified—several projects on catalyst, membrane, and membrane electrode assembly (MEA) address it. BP and stack designs also have a big impact on power density, but since they are not addressed in the sub-program it appears that BP and stack design are internal OEM tasks. Therefore, stack data with MEAs developed within the sub-program should be provided by OEMs to better quantify the current situation. Another option might be to use an "open" BP design representative of automotive applications.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes; the sub-program seems to go to great pains to assess multiple potential paths to success, which is necessary and should continue to be reinforced for the heavily R&D-focused work that is included within the sub-program.
- The FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP) is well structured, with clear targets and items to be addressed. The cost drivers to achieve the $40/kW target have been identified, and the funded projects align with this target.
- Yes, high-level plans for gap closure have been identified.
- Yes. *(4 responses)*

5. Was progress clearly benchmarked against the previous year?

- Progress has been presented during this AMR (e.g., platinum group metal [PGM] and non-PGM catalyst performance improvement). The impact of these improvements is still unclear because the fuel cell cost projections have remained almost stable since 2011. Ionomer mapping achievements appear to be a highlight of this year, and ionomer mapping will definitively contribute to improving short-term MEA performance and durability.
- Yes, the progress was clear, and major achievements were comprehensively described.
- Progress over the years was presented; however, a direct comparison between this year and the previous year was not explicitly provided. The one exception seemed to be the work on PtNi nanoframe catalysts.
- No, just the latest highlighted accomplishments are presented. It is a recommended point to track the progress of focus areas, rather than highlight accomplishments ad hoc.
- Yes. *(2 responses)*

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes. FCTO projects are addressing a broad scope of problems that are the highest-cost elements in a fuel cell system.
- Yes, the work appears to be driven primarily by cost and durability targets, which directly address FCTO's work to achieve commercially viable fuel cell systems.
- The projects cover the main barriers. Nevertheless, taking into account the cost drivers to reach the 2020 target, it appears that some key elements (e.g., air compressor/expander module – $5/kW, BP – $2/kW) are only addressed through one project. At least a second project may be initiated to avoid relying on a single potential solution.

- There was not a clear connection between focus areas and the current or future research portfolio. It is very important to make visible how the research portfolio is related to the focus areas (e.g., problems and barriers).
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program appears to be well structured and well-focused.
- Yes, the sub-program was focused and well managed.
- The sub-program seems to be connected to the U.S. DRIVE Fuel Cell Tech Team well. However, the sub-program seems to be managed without a proper research portfolio or strategic plan.
- Yes, the sub-program appears to be focused and well-managed, especially considering there are so many directions for projects to cover within the sub-program's objectives. However, the presentation of the budget and expenditures did not clearly present how project priorities shift from year to year; an alternative method of presenting this information should be developed and pursued in the future.
- Yes. *(3 responses)*

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The projects in the sub-program are well balanced and cover most of the important aspects for FCEV commercialization, which include increasing low PGM utilization; transport issues; low-cost, high-performance membranes, etc. The direct imaging of three-dimensional morphology on Nafion in the catalyst layer stands out among the projects from this year.
- The projects in this sub-program were thoughtfully organized and managed effectively, and they featured extensive collaboration efforts.
- The sub-program's key strengths are the (1) multi-annual working plan with quantitative targets for each component and subsystem, (2) well-balanced academic and industrial partnerships, and (3) ongoing projects on mechanism comprehension and material characterization. The sub-program's weaknesses are (1) basing the fuel cell cost projection on the modeling of a system design that does not exist and therefore has no real validation, and (2) limited experimental validation on even a short-stack level of all the great developments performed on a 50 cm^2 single cell. This validation may be carried out by OEMs, but releasing such results would increase the sub-program's impact.
- The key strengths are the technical rigor and the ability of the sub-program to develop some breakthrough technologies and tools. FC Application Package for Open-source Long-Life Operation (FC-APOLLO), in particular, seems like a project that will have a lasting impact and the potential to drive much future research. One weakness may be that projects are not benchmarked against each other. For example, the sub-program pursues multiple paths to achieving catalyst activity and performance targets, but there was not a clear presentation of these projects' roles within the whole of the sub-program's activities. It would be helpful to have an evaluation of the projects' status, demonstrated potential, and perhaps theoretical potential. If these data were provided for all projects side by side on a consistent basis, the sub-program may be able to gain a more complete view of the projects' effectiveness compared to one another.
- A strength is the sub-program's strong technical capabilities to advance technologies at the research organizations (e.g., national laboratories, universities, and industry). The sub-program features good connections with OEMs via discussions among the U.S. DRIVE Fuel Cell Tech Team. An area of weakness is the sub-program's ability to manage the research portfolio or communicate a strategic plan to fix the research portfolio. For example, the gap analysis showed the total cost is highly sensitive to area-specific power density (performance at the high current density). However, no research projects were funded in this area (mass transport).
- Projects related to reducing the cost of catalyst were very well documented, and various partners were involved. The development of non-PGM catalyst is very promising. Even though the objectives mentioned distributed generation and a micro-combined-heat-and-power fuel cell system (5 kW), there was nothing in the presentation to shed light in that area.

- The key strength of most projects is the ability to generate novel ideas to generate excellent options for highly active catalysts. These catalysts show good promise toward cost reduction if implemented in a fuel cell stack. However, most of these materials are made in very small batches—this might be one of the biggest weaknesses.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The ionomer distribution visualization work is very exciting and would help to solve some mysteries about degradation inside the stack. Work at both Lawrence Berkeley National Laboratory (LBNL) and ORNL in this area is very exciting.
- Yes, there is quite a lot of novel work being completed under this sub-program. Nanostructured catalysts and FC-APOLLO stand out in this regard.
- Yes. However, most of the catalyst development projects are heavily dependent on rotating disk electrode data, and MEA confirmation is of prime importance. Some efforts were made for novel catalysts to be tested in MEAs, but MEA/catalyst layer/catalyst ink optimization is a big research topic, and more efforts should be concentrated in this area for these novel shape, low-PGM catalysts.
- Some of the projects propose novel approaches, but in general, the projects have more of a continuous improvements approach.
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, there seems to be a good deal of industry, academic, and agency involvement.
- The sub-program's collaboration is good; high-quality academic partners and national laboratories are involved in the sub-program. The collaboration with foreign partners is also appreciated because it helps to speed up FC technology development. Collaboration with the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) was mentioned, but the one with the IEA Advanced Fuel Cells Implementing Agreement was not.
- Yes, there is strong collaboration between the various project teams. FCTO is collaborating with agencies outside the United States as well. It might be good to have reviewers from the United States attend similar peer review meetings for Japan, European Union, and other fuel cell funding agencies.
- Yes. It would have been nice to see at least some catalyst manufacturer/developer involved in developing low-cost non-platinum catalysts.
- Yes. *(2 responses)*

11. Is the sub-program collaborating with them effectively?

- Yes, some of the major accomplishments clearly were efforts coordinated effectively.
- Yes. *(5 responses)*

12. Are there any gaps in the portfolio for this technology area?

- There are no evident gaps in the portfolio.
- This sub-program focuses more on material development, but at the end of most of the projects, the researchers fail to realize the project's application in MEAs. Efforts on integrating most of the materials (e.g., low-PGM catalysts, membrane, and supports) in MEAs need to be emphasized.
- While the focus on materials and components is understandable, there does seem to be a notable lack of system-wide technology development and research.
- It did not seem that there is much being done in the area of BP development and/or cost reduction.
- No.

13. Are there topics that are not being adequately addressed?

- No; the work that was prioritized in this past year seems to be thoroughly addressed.
- The sub-program should address the scale-up of highly active catalyst so MEA tests can be completed.

- No. *(2 responses)*

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It was mentioned in the discussion that solid oxide fuel cells (SOFCs) fall under the purview of the Office of Fossil Energy, but the system analysis of SOFC developments from that Office could be conducted in this sub-program. This seems like an area that could use increased attention because the momentum of developments for the technology seems to have slowed in recent years. This sub-program may be able to help return some focus to the technology.
- The sub-program should consider funding MEA integration of all the promising novel catalysts and MEA optimization approaches.
- MEA and BP sealing appears to not be a problem—it is unclear whether that is the case.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Research portfolio—goal and gap analysis was pursued, and focus areas are identified properly. However, information on the approach and how to fill the gap in the focus area is not clearly identified. Each Funding Opportunity Announcement (FOA) seems to be ad hoc. A consistent strategic plan was not presented. The sub-program should show its desired research portfolio (what should be) and the gap from the current research portfolio. Future FOAs should be developed to fill the portfolio gap.
- Regarding benchmarking foreign governments' programs, it is also important to show the benchmark analysis of foreign governments' funding programs to allow comparison with the DOE research portfolio. European FCH JU and Japanese NEDO projects have comparable funding levels and should be benchmarked.
- Regarding fixing the research portfolio, the sub-program should better manage the research portfolio and communicate a strategic plan to fix the research portfolio. For example, the gap analysis showed total cost is highly sensitive to area-specific power density (performance at the high current density). However, no research projects were funded in this area (mass transport).
- This sub-program should summarize and benchmark the status of the materials developed with DOE funding against materials developed by projects not funded by DOE. Many U.S. and international research groups keep publishing results showing high-activity of catalysts; these results need to be summarized to see where the projects under this sub-program stand in comparison.
- At this time, there are no recommendations.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program's impact may be enhanced by a systematic validation of material (e.g., catalyst, membrane, and BP) and component (e.g., MEA and BOP) developments in a stack or even in a system. This will help fine-tune the R&D activities. Air contamination is considered in this sub-program, whereas hydrogen contaminants are considered to be in the Safety, Codes and Standards (SCS) sub-program. There should be a good link between these efforts in order to collect all the results for stack and system component developments and modeling. It was not clear from the AMR whether such a link exists.
- At this time, there are no suggestions.
- No.

Manufacturing R&D Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, the strategy targets identification of the cost drivers in the manufacturing process, with a specific focus on decreasing process steps, increasing automation, decreasing waste, increasing yield, and facilitating scale-up of laboratory advances. These strategies are appropriate for this sub-program.
- Yes, the sub-program was defined clearly, and the overall strategy for the objectives was covered in detail.
- Yes, the overview gave a clear picture of the action(s) that address each barrier.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, the sub-program targets integration of advanced manufacturing techniques to existing membrane electrode assembly (MEA) technologies, as well as forward-looking approaches, to speed the development of high-volume production of emerging MEAs, cell components, and delivery infrastructure.
- The sub-program was balanced relatively well between near- and mid-term R&D.
- There is less long-term emphasis. However, this is understandable because this is a crucial time and immediate issues must be resolved to facilitate market penetration and commercialization.
- In general, there does seem to be a good balance; however, it seems like the timeline for how soon some of these developments and capabilities will be necessary is a little bit longer than industry stakeholders may consider. There may be a need to provide additional funding to accelerate some of the near- and mid-term projects.

3. Were important issues and challenges identified?

- Key challenges were highlighted, including the lack of high-volume manufacturing processes, the low levels of quality control, and a lack of standard BOP components.
- Yes, key issues and challenges were clearly identified.
- Yes, key issues and challenges were identified, although there seems to be a very narrow focus on MEAs. Expanding the sub-program to work on more components simultaneously will help broaden the impact and possibly help avoid a potential delay in achieving the sub-program goals, in case projects in the highly focused areas encounter unanticipated obstacles.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes, the sub-program targets the development of in-line, real-time tools for diagnosing quality control in MEA production. The sub-program also targets expansion of the domestic supply chain for fuel cell components.
- Yes, the presentation highlighted an extensive amount of recently commenced work that will address the sub-program goals, especially concerning supply chain issues.
- The future plan was clear and focused.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, the efforts related to manufacturing and quality control of MEAs and components showed progress. The new collaboration effort with industry supply chains and the global competitiveness assessment seemed to be important achievements.
- The presentation was not strong in this regard. Some major accomplishments were announced and thoroughly discussed, but the timelines of the projects were not clearly presented. It was not clear how much of the total work was completed in the past year.

- No. A number of initiatives were outlined, but there was no clear delineation of what was accomplished in the prior year, relative to what is being proposed for the following year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, high-volume manufacturing, quality control, and reliability are the key drivers for market penetration of fuel cell technologies, and this sub-program targets advancements in all of these areas.
- Yes, cost and supply chain issues remain high-priority issues in FCTO, and this sub-program addresses them well.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is well managed and broadly focused. The limited budget restricts the use of multiple approaches.
- Yes, the sub-program was thoughtfully planned and well managed.
- Yes. The targets and initiatives are not overly ambitious and are well matched to the needs of the industry sector.
- Overall, the projects do seem well managed and focused. However, they are only now commencing, and there was not a strong sense of DOE oversight and guidance for the more outreach-based projects (i.e., the Opportunity Center and the Regional Technical Exchange Centers). There very well may be detailed plans and processes for how the contracted entities will carry out these projects and coordinate with third parties while coordinating with DOE, but this was not thoroughly presented.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The extensive collaboration efforts are the key strength of this sub-program. The projects for supply chain development and competitiveness analysis appear to be nicely and thoughtfully planned.
- The projects focusing on technical capabilities are rather excellent and were clearly presented. The amount of detailed work provided confidence in the significance and utility of the developments. A key strength is the development of efficient large-area tools for assessing quality control in real time by infrared (IR) spectroscopy. The key weakness is the lack of focus on what manufacturing techniques will remain constant as the MEA technologies change. A key concern is that the efforts toward additive manufacturing or accelerating scale-up will need to be revisited as the underlying catalysts and materials are further developed. Some analysis of what will remain constant and what will change will allow this sub-program to better direct its resources.
- A weakness in the manufacturing defects projects is that the researchers do not seem to establish the character (i.e., size) of the defects that compromise performance and/or durability.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, the projects represent novel and/or innovative ways to approach the barriers, especially in the outreach and supply chain-based projects. This type of coordinated effort is necessary and has probably been necessary for some time now. The new projects seem to address the gap that had existed.
- Yes. The projects bring together advanced spectroscopy, additive manufacturing techniques, and robust modeling to address these challenges.
- Yes. *(2 responses)*

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program has forged relationships with industrial OEM manufacturers and national laboratory partners to develop new technologies and gather data on real-world problems along the supply chain.
- Yes—the partners include market experts, manufacturers, and developers.
- Yes, the sub-program has strong engagements with regional, national, and industry partners.
- For the most part, yes, the sub-program has engaged appropriate partners. In terms of developing new knowledge, and to address most of the need to disseminate that knowledge, the sub-program has formed the appropriate collaborations. The only addition that could be suggested is to increase dissemination of the information to agencies at the state and local levels, and then to use these voices to help determine additional sub-program goals. As presented, the collaborations did not have a strong government coordination aspect.

11. Is the sub-program collaborating with them effectively?

- Yes. Through integrated regional technology exchange centers, the sub-program is able to leverage data from OEMs, connect OEMs with suppliers, and exchange information in working groups to address key challenges.
- Yes, the sub-program appears to be collaborating effectively.
- Yes. *(2 responses)*

12. Are there any gaps in the portfolio for this technology area?

- Work on compressors for infrastructure remains a very high-priority need for the near-term market. It is good to see work on making longer-term solutions such as pipelines potentially viable in the near term, but the compressor reliability issue should probably be a higher priority. Right now, it does not seem to be mentioned in the planned projects.
- The principal gap is the lack of an assessment of what manufacturing advances will be insensitive to changes in the underlying technology (e.g., changes in catalyst composition, supports, or membranes).
- One gap is the lack of quantification of the effect of defects on cell performance and life.
- No.

13. Are there topics that are not being adequately addressed?

- The ongoing work seems to be rather thorough and complete.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It may not exactly fit the goals of the sub-program, but research into reducing infrastructure build/installation complexity may be a useful avenue to explore. More pre-fab, standardized, modular designs and ideas specifically assembled for ease and efficiency of construction could go a long way in helping to roll out the fueling infrastructure at a faster pace and support accelerated vehicle deployment.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- No; the sub-program has a fairly complete set of strategies that appear to be working well.
- The sub-program should assess which steps in the manufacturing process are most likely to benefit from economies of scale. This will allow the sub-program to better allocate resources.
- The sub-program should continue with more emphasis on actual manufacturing hardware and less emphasis on studies.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program needs to reach out to state agencies to get a better sense of the urgency behind all the project goals and to help manage the priorities and focus of the sub-program's efforts.

Technology Validation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, the objectives, metrics, and technology areas were clearly stated. The overall status of the technology was compared against the DOE targets, and future plans were addressed.
- Yes, the overall strategy was clear, and this important sub-program was sufficiently covered.
- Yes, the sub-program and strategy were adequately presented.
- The sub-program was adequately covered. The 80,000 hour target has only been reached by phosphoric acid fuel cell (PAFC) technology and, it was mentioned by the project's Principal Investigator that UTC degraded the performance of the 200 kW fuel cell to 175 kW in order to reach that level. The issue of fuel cell performance degradation in reaching durability targets should be covered in the setting of targets. In addition, the 80,000 hour target was reached with an "old" PAFC design, and there is no indication the new PAFC design will reach 80,000 hours. Other technologies have not shown that level of operation without stack replacement. The commercial power goal may be very difficult to reach.
- At a high level, the strategy discussed provided more of an overview of how the Technology Validation (TV) sub-program fits in with the other sub-programs. The presentation did not, however, really discuss the strategies used within the sub-program in terms of general project types and specifications to meet the goals. These strategies became clearer during the individual project presentations, but the high-level overview could have been more thoroughly presented.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. The sub-program clearly has an emphasis toward the near term, but there are some longer-term projects that are highly valuable.
- Yes; however, it did seem that some of the near-term goals relate to aspects of FCEVs that are near commercial realization.
- The feedback loops provide pathways to communicate identified technical problems back to R&D efforts; however, this was not explained well, and it was not clear how information from the sub-program would get back to the R&D activities. Perhaps there are review committees to evaluate TV sub-program operations and provide feedback, or perhaps this is internal to the projects and therefore was not discussed in the presentation.
- It is clear what the sub-program intends to accomplish in the near future. The sub-program goals and activities up to 2017 were defined, but there was no mention of activities beyond that period of time. It was mentioned that the sub-program will address heavier vehicle classes in the future, but that was the only reference to long-term research. It is unclear what the sub-program intends to accomplish in the long term.
- Yes. *(2 responses)*

3. Were important issues and challenges identified?

- Yes, performance, durability, availability, and operational characteristics were all identified.
- Yes, the key issues and challenges were clearly identified.
- The discussion of the sub-program's accomplishments did not explicitly define the issues and challenges that were being addressed. The work is related to the issues and challenges outlined in the DOE Hydrogen and Fuel Cell Program's research, development, and demonstration (RD&D), but this overview did not explicitly tie the project accomplishments to those issues and challenges.
- No, issues, challenges, and barriers were not identified during the presentation. The presentation focused mainly on accomplishments.
- There was not any statement of challenges. The presentation reported accomplishments.
- Yes.

4. Are plans identified for addressing issues and challenges?

- There did appear to be adequate internal control to manage change. This control will be necessary as certain technologies move forward with commercialization.
- Yes, plans were identified, although it is not clear how large-scale grid energy storage will be accomplished.
- Overall, the projects seem to address the challenges, but a more explicit presentation should be provided.
- The presentation focused on near-term strategies and accomplishments, but it did not describe what issues/challenges are being addressed with the current projects.
- Slide 22 states that the sub-program is "Developing new targets." The presentation did not give any indication of how those new targets (challenges) would be met. Perhaps the planned RFI is the mechanism for achieving new targets.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- In the existing focus areas (e.g., FCEVs and stations), yes, progress was clearly benchmarked.
- Progress was identified.
- The accomplishments are outstanding, and the progress made in all areas in exceeding, meeting, and approaching targets demonstrates a successful sub-program. It did not appear that incremental benchmarking from the previous year was emphasized.
- Much more emphasis was placed simply on the current status and data collection/evaluation over the life of the sub-program projects. There did not seem to be a clear indication of how much more data was collected in the past year or how the status of technologies changed in the past year.
- The current status and goals were clearly defined, but there was no mention of how much the projects in this sub-program have advanced compared to the previous year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes; in particular, there is a widespread lack of information, and the projects of this sub-program are providing a valuable resource for that information.
- Yes, the projects were well selected and represented technologies that required validation.
- The projects are definitely making a contribution to FCTO by validating advances in vehicle range, fuel cell system durability, hydrogen dispensing capacity, and storage using actual numbers instead of engineering calculations. However, fuel cell cost and public acceptance are also listed as challenges in the sub-program, and it is unclear how those challenges are being addressed. Very little cost data was presented, and there was not a clear link between the projects and consumer acceptance (perhaps that is one of the objectives of the [Station Operational Status System (SOSS)] project).
- This presentation is extremely valuable for showing that laboratory R&D can be moved to the demonstration state, and it validates the R&D. This should have been explicitly pointed out in the presentation.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The accomplishments in the TV sub-program clearly demonstrate that it is well-managed and is addressing the necessary issues for moving fuel cell technology to the marketplace. This is a critical sub-program that justifies the approaches taken by FCTO for many applications. It is not clear how the more fundamental FCTO activities, such as catalyst development, help the sub-program. Good performance of fuel cell applications can be achieved with high catalyst loadings or expensive bipolar plates, etc. It is not clear how the R&D achievements help the TV sub-program—perhaps they help through fuel cell buses or forklifts.

- The sub-program was well managed, and meaningful progress was achieved, addressing the important needs of FCTO.
- Yes; the amount of coordination required for the large amount of data that is handled is accomplished very well.
- Yes, the team was thoughtful, focused, and well managed.
- It is hard to assess whether the sub-programs are well managed. That is a question for the people involved in the actual projects. However, it is clear the projects are yielding results, and that the results are moving in the right direction to accelerate the introduction of FCEVs and refueling infrastructure, tackling major challenges such as fuel cell durability, performance of light- and medium-duty vehicles, dispensing, storage, and data collection.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The key strength of this sub-program is the thoughtfully organized validation and demonstration cross-collaboration involving important partners in various scopes.
- The data handling, aggregation, dissemination, and assurance of confidentiality are all particularly well handled in this sub-program. The one apparent weakness from the presentation was the robustness of information for the stationary fuel cell applications and the presentation of the data. The difference in counting methods for units delivered between fuel cell and combustion products was not clearly explained or was otherwise convoluted. Additionally, it seems like there should be much more information and learnings available from stationary applications, based on observations of the current marketplace and the number of commercial products being delivered.
- The key strength of the projects is the teams that have been put together, which feature a combination of industry and national laboratory stakeholders. The fuel cell bus activity stands out for surpassing the 2016 target. The forklift truck project also stands out, but it is not clear how much penetration into the market fuel cell forklifts have made. With the identified benefits of the fuel cell forklift truck, it is not clear why the market penetration is below 5%.
- Key performance metrics and representative projects were clearly identified as a project strength. Comparative analysis with conventional technologies, evolving commercial performance, and new market entries will need to be updated as these technologies advance.
- The fuel cell material handling equipment (MHE) and standby fuel cell power activities are real winners because they have entered the commercial mainstream, which is great. It is not clear how DOE can play a role in the grid storage area; for example, it seems that resources much greater than the DOE R&D budget would be required for a major fuel cell grid storage demonstration.
- One weakness is that it is unclear whether the sub-program is addressing fuel cell cost challenges or consumer acceptance. Strengths include that the accomplishments presented tackle important issues that the industry has been grappling with in terms of demonstrating technology and collecting actual performance data from real systems. There is good collaboration with industrial partners.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, these projects represent novel and/or innovative ways to approach these barriers, especially the project to investigate electrolyzers supporting the grid.
- Yes, objective technical validation is very important and useful. The representative projects, performance characteristics, and goals all appear to be appropriate.
- It is not clear whether the projects represent novel and/or innovative ways to approach these barriers.
- Innovation is not the key to this sub-program; more than that, the sub-program is testing vehicles and infrastructure that have been developed by others. The technology being tested is innovative in many cases, but the role of the sub-program is not to innovate, but to test the contribution of these novel technologies to reaching FCTO targets. In that respect, the sub-program is doing a good job.
- TV sub-program projects tend to be incremental activities and demonstrations. It is not clear what is novel about the sub-program projects, other than they offer demonstrations. No cost numbers are available, so

one cannot judge whether these projects have "novel technology" or represent "brute force" technology at a high cost.
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, the amount of collaboration and partnerships is very extensive and seems to cover all necessary sectors.
- Yes, the partnerships are well structured and productive.
- Yes—OEMs and supply chain and institutional partners have been identified. Increased engagement with supply chain partners—directly or through OEMs—might be a step forward for comprehensive validation to increase opportunities for commercialization.
- Yes, industrial partners and national laboratories are being engaged. Perhaps the sub-program would benefit from engaging the public as well to increase consumer acceptance.
- Yes. *(2 responses)*

11. Is the sub-program collaborating with them effectively?

- High levels of collaboration must be occurring for the reported success to be possible.
- The sub-program appears to be collaborating effectively.
- Yes, it appears to be collaborating effectively.
- Yes, it is collaborating effectively, but there will be opportunities to increase collaboration with supply chain partners, OEMs, and stakeholders.
- It is hard for someone not directly involved in the projects to answer that question. It seems that the collaborations are effective, given that the results are positive; fuel cell durability and fuel economy are improving, more work on the road testing is being performed, additional collaborations are occurring, and future plans include the right stakeholders. Further, data collection and publication are crucial to the success of the FCTO projects; it is great to see that so many partners are on board to provide data and that the Gas Technology Institute and the NREL data center have been effective at consolidating the information in a way that is useful to stakeholders.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- No, the portfolio is well representative of industry and the technology. Note that both industry and the technology will evolve, making collaboration and technology validation an ongoing and changing process.
- There do not appear to be any gaps at this time.
- There is little cost data coming out of the sub-program. Also, it is not clear how consumer acceptance is being addressed. It is not clear whether the results are being integrated into other FCTO sub-programs, or whether there are feedback mechanisms in place to ensure the appropriate bottleneck components are being tested.
- There is a gap related to identifying the cost of the technology validation demonstration of fuel cell systems. It is not clear whether these systems are on a pathway to meet the costs.
- Grid storage and stabilization seem beyond the scope of the DOE Hydrogen and Fuel Cells Program.
- No.

13. Are there topics that are not being adequately addressed?

- The technology and industry are nicely covered. Some suggestions for consideration include the following:
    - Developing some type of simple, consumer-oriented FCEV validation label (similar to the ENERGY STAR label) for range and efficiency.
    - Addressing and contrasting potential voltage drop (or lack of voltage drop) for MHE.
    - Conducting a simple comparative analysis of selected technologies with conventional technologies.
    - Increasing engagement with supply chain stakeholders, either directly or indirectly through OEMs.

- Stationary fuel cell studies do not seem to receive as much emphasis as one would expect. Additionally, the online station status project may soon need to expand to look at other options and methods beyond SOSS. Individual station developers may soon be deploying their own systems for providing consumers with similar information, and the sub-program should look into comparisons among these systems, especially concerning cost, accuracy, and response time.
- Fuel cell cost and consumer acceptance are not being adequately addressed.
- The topic of technology/system cost is not being adequately addressed.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The technology may not yet be ready, but given other sub-program overviews and individual projects presented at this year's AMR, it is likely this sub-program will need to incorporate hydrogen pipeline studies within a short time.
- The sub-program should consider funding DOE certification for performance (similar to the ENERGY STAR program).
- Funding could be directed toward testing tube trailer deliveries as a precompression step to reduce storage and compression at the terminal.
- There is no explanation of how the technology will leave the funding of FCTO and become driven and funded by industry.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Some type of simple, consumer-oriented FCEV validation label for range and efficiency should be developed. A simple comparative analysis of selected technologies with conventional technologies should be conducted.
- The sub-program should approach major utility companies (e.g., Pacific Gas and Electric Company and Xcel Energy) to initiate a major grid storage project. Xcel has been working on renewable electricity projects and might be motivated to pursue energy storage to enable more renewables.
- The sub-program should report the cost of the technologies being tested. It should also test tube trailer deliveries as a pre-compression step. It should test 500 bar refueling systems, including measuring performance and refueling time, comparing the results against 700 bar systems, and calculating e the cost differences.
- The sub-program should reduce funding and determine whether industry is ready to commit to moving forward without RD&D funds. Cutting subsidies is not recommended.
- There are no suggestions.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Overall, this is a good sub-program that will need to evolve as technology evolves.
- The release and explanation of composite data products should be more widely publicized and receive more attention. It has been difficult to keep up with the update schedule and to stay informed of the developing data interpretations.
- The sub-program should build review teams to make lessons learned available to the general public.

Safety, Codes and Standards Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The presentation gave an exhaustive overview of the activities and their link to the overall strategy. This “horizontal” or “crosscutting” sub-program is essential, and its link to the FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP) is clear. The identified priorities are all tackled in a consistent and coordinated way.
- The sub-program’s strategy has been clearly stated. It takes the right approach by starting with fundamental science and engineering in order to develop models and tools (e.g., the Hydrogen Risk Assessment Models [HyRAM]) and disseminating these to end users, both local and internationally.
- Yes, there was a very thorough description of the actions the sub-program takes in order to address its goals and how achievement of a goal affects other goals.
- Yes, the sub-program, including the overall strategy, was adequately covered.
- The sub-program was adequately covered, and within the assigned time available.
- The overall sub-program is covered both nationally and internationally. There is a good focus on the codes and obtaining data. The standards projects need data to provide support for revising standards. There is also good support for participants to participate in the code and standards activities; however, the actual support for the standards development organizations (SDOs) and the work on the SDO/code development organization (CDO) side to support the revision/development of the documents is missing. The work should have some support (cost shared with industry and SDOs/CDOs).
- Yes, the presentation provided a good overview of the sub-program. The presentation could provide a slide that shows all of the existing projects and where they fall in the broader categories. As an alternative, the sub-program could provide this detailed information in each category of the project. This could involve two broad categories—Codes and Standards Objectives and Hydrogen Safety Objectives—that waterfall into three areas: R&D, Codes and Standards support, and Outreach. From the existing presentation, it is quite difficult to tell which specific project example fits in which category, as well as how much of the funding is dedicated to which category, how that changed from previous years, and why that changed compared to previous years (responding to trends, cyclic nature of codes and standards, etc.).

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes; in particular, codes, standards, and field validation (especially for infrastructure technologies) are major areas of need for the current industry, and this sub-program appropriately prioritizes this near-term need.
- Yes, there is a proper balance between near-, mid-, and long-term R&D.
- Yes, there is an appropriate balance, although the presentation does not specifically address the timing of sub-program activities as “near term” or “long term”—the sub-program outlines a cyclical process that includes a very good explanation of research to outreach, as well as continuous improvement. This project appears to have transitioned from a research and document development effort into a more balanced and comprehensive approach to outreach; regulations, codes, and standards improvement; and targeted research.
- At this stage, considerable parts of the codes and standards domain, including safety, have already been covered by previous efforts. Considering the work already done in this area, and the already available sub-program framework, the present strategy is well adapted to the new challenges. On one side, there is the continuous improvement cycle of the sub-program framework, and on the other side, there are more ambitious and more long-term goals, such as the integrated tool and its probabilistic approach.
- Although the presentation did not clearly distinguish between near-, mid-, and long-term R&D, it did show an ongoing effort and emphasis on critical areas that will enable hydrogen to be used as an alternative fuel for transportation. These areas cover, most importantly, safety (e.g., HyRAM), performance, and reliability (e.g., fuel quality/contamination and subcomponent testing).
- It is not completely clear what distinguishes the near, mid, and long terms, but all topics in this topic area are meant for long-term application (but work must begin in the short term).
- Yes.

3. Were important issues and challenges identified?

- All of the issues and challenges associated with safety, codes, and standards were clearly identified and defined throughout all the material presented by the sub-program.
- Yes, important issues and challenges were identified. Collecting hydrogen safety data remains a challenge for all stakeholders.
- Yes, the presentation accurately reflected the need for data to support codes and standards.
- Yes, the description of advantages and challenges at various project scales was particularly well developed.
- Yes; however, the presentation did not address this topic directly. The overall barriers to be addressed were not explicitly described.
- Yes. *(2 responses)*

4. Are plans identified for addressing issues and challenges?

- It is very clear that the sub-program is very aware of the issues and challenges, and the established plan seems very adequate to overcome these issues and challenges. The resources used by the sub-program to execute the R&D really leverages world experts and top facilities.
- The implementation plan embraces two traditionally non-communicating levels of the normative spectrum: (1) the research community and (2) the standardization framework, which is traditionally led by industry. This sub-program is able to align well-identified R&D work—which is needed to deliver science-based evidence supporting continuous development in safety, codes, and standards—with ongoing efforts in regulatory and standardization bodies.
- Yes, it appears that plans are identified.
- Generally, yes, plans are identified.
- Yes, the sub-program identifies a clear plan for addressing challenges; however, it assumes the objectives are solutions to challenges the audience already understands. It might be best to revisit the challenges and issues, particularly to highlight the new challenges faced. This would allow the sub-program to address the dynamic changes the sub-program manager is implementing as part of the management strategy.
- The general strategy for addressing the remaining issues and challenges was identified. However, there was not a lot of specific detail provided in terms of future work to address the challenges. Much more effort appeared to be put toward describing the recent accomplishments. It may be that this work is still ongoing, but it was not explicitly clear how the accomplishments tied into future plans.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, for the new H2FIRST projects, several reports were issued, including a DOE record that demonstrated a 50% reduction in separation distances, shorter response times for the hydrogen quality analyzer, and a commercially ready hydrogen sensor.
- Yes, this project has shown significant results, with great progress in outreach and developing tools such as HyRAM.
- Yes, the progress was clearly benchmarked against the previous year.
- The major accomplishments of 2015 have been clearly and convincingly presented. In general, the multi-year progress is evident. There is only one improvement to make. The sub-program covers a broad range of activities, and it cannot be expected that every single area of progress would be mentioned in a general presentation. For improving future presentations, keep in mind that it is difficult to identify year-to-year progress and realignment of the plans by looking only at the lists of “emphasis” for 2014 and 2015.
- Yes, it was clearly benchmarked, assuming the “progress” and “accomplishments” listed in the project reports are in addition to achievements made during the previous year.
- The progress in projects was specifically discussed in terms of the past year, although there was not a clear indication of how this compared to work done in the previous year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects in this technology area are definitely addressing the broad problems and barriers FCTO is trying to solve.
- Yes, these projects are providing important advancements in the ability to rapidly deploy hydrogen fueling infrastructure and fuel cell technologies.
- Yes, the projects are definitively addressing the broad problems and barriers.
- The projects and activities being managed by the sub-program address the main areas of enabling hydrogen fuel cell technologies. One suggestion would be to fund some R&D work and eventually some demonstrations on hydrogen mass flow metering to improve the accuracy levels of existing metering devices. This is a key area that still needs improvement for current technology and one that will be a significant enabler of hydrogen infrastructure technologies.
- The overall sub-program is addressing both national and international market issues. There is a good focus on the codes and obtaining data. There is also good support for participation to support the code and standards activities; however, the actual support for the SDOs and the work to revise/develop the documents is missing. The roles of national laboratories and private-sector companies that have comparable capabilities need to be better defined. There are real cases where the national laboratories are competing with private industry, and it appears the money being spent to add capabilities duplicates what exists in the private sector.
- The projects are addressing the broad problems to some extent. There are significant concerns regarding the efficacy of the research at NREL, specifically the ongoing testing of pressure relief valves. That work seems highly inconsistent with the work products from materials testing or reference stations where the outcomes have targeted a large impact on the broader community. The outcome and impact of the effort to test pressure relief valves has not been defined, despite several years of review. This reflects negatively on the efficiency and management of the sub-program and the FCTO objectives as a whole.
- Yes.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes, this sub-program is very effective. The evolution of outreach information is a tremendous step forward for the support needed for FCEVs. This sub-program also seems very capable of making timely changes in its activities. The rollout of the new safety tools website is extremely timely and a good indicator of a well-managed sub-program.
- It is clear this sub-program effectively coordinates and leverages the resources and players to address the overarching needs and challenges. Coordination is traditionally difficult in this area, due to the necessity to steer research centers, conduct (pre-)normative activities, and interface with standardization bodies (and specifically their industrial components). One would also expect a certain amount of resistance to this approach by some industrial stakeholders that assume they should be the only players in this space. Despite the possible resistance and management difficulties, the sub-program is well managed and succeeds in achieving its goals.
- Yes, there is a very clear structure to the sub-program's approach to addressing challenges and barriers. The management of the sub-program appears to be well developed, especially considering the multitude of approaches utilized to address the sub-program's goals.
- It is very impressive to see how well the sub-program is currently managed and its collaboration with local and international bodies and institutes in the safety, codes, and standards areas.
- Yes, the sub-program appears to be focused, well managed, and effective in addressing FCTO's needs and goals.
- Yes. *(2 responses)*

8. What are the key strengths and weaknesses of the projects in this sub-program area? Do any of the projects stand out on either end of the spectrum?

- The strength of the projects is their ability to address real-world, current issues with high priority in a timely manner. DOE's partnerships with varied stakeholders and agencies through this sub-program are helping to accelerate timeliness and ensure that focus and attention remains on the most critical issues. The work on hydrogen behavior and risk assessment appears, in particular, to feature a well-developed and confidence-building methodology that will hopefully have a significant impact on industry-wide work, like National Fire Protection Association (NFPA) 55/2.
- Overall, the deliverables of projects in this sub-program represent key strengths. There are no major weaknesses in any of the projects in this sub-program.
- Many of the projects in this area are excellent and strive to achieve science-based evidence and to interface with industrial stakeholders. The achievements in this area show the importance—or better, the essential role—of government and public institutions in shaping the development and deployment of a new, disruptive technology. There were not any weaknesses. However, one would expect a certain grade of competition among the national research centers in terms of covering the major share of the sub-program activities. Slide 6 claims there is a clear and strategic distribution of tasks between Sandia National Laboratories (SNL) and NREL. The slide does not show, however, how the distribution was determined. There was probably something similar to a strengths, weaknesses, opportunities, and threats (SWOT) analysis; if so, that should have been explicitly stated, along with a definition of "subcomponent" versus "component." Otherwise, one could get the impression that NREL's choices for testing valves and SNL's choices on which materials to test are made independently. Finally, slide 11 shows a Los Alamos National Laboratory project on sensor development. This effort seems to be of lower impact in terms of the overarching goals, compared with the other projects presented. The development of a new sensor is an important achievement, but it is not exceptional if considered in the frame of the industrial development of sensors.
- Efforts involving the first responder tools/information are progressing well, and these resources are assisting in education and outreach.
- The sub-program's key strengths include that the overall effort involves all key stakeholders and disseminates the needed knowledge/lessons learned, including on an international level. A key weakness is that the statement of "35,000 first responders reached" does not include enough information to fully understand the context.
- The greatest strength of this sub-program is the role it plays in outreach and code development. One of the sub-program's weaknesses is the NREL effort on codes and standards support and component testing; it is recommended that the sub-program evaluate this effort's long-term focus.
- The actual project portfolio seems very well balanced and robust. The only recommendation is to include a flow metering project(s).

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The most ambitious project, in term of novelty and risk, is the development of an integrated tool for safety design (HyRAM) based also on a probabilistic approach. This is something the international community is dreaming of, and it is very important to enable and facilitate market deployment of the hydrogen and fuel cell technologies. It has a high risk of not reaching the final objective—not because of the lack of scientific quality, which is very high, but because its success depends on its acceptance by a broad spectrum of end users and stakeholders that traditionally do not trust probabilistic approaches. Nevertheless, the importance of the project motivates this effort.
- The sub-program appears to make use of the latest media technology options available to disseminate information needed to the safety, codes, and standards community.
- HyRAM and the new H2 Tools information portal are very good examples of the innovation and creative aspects of this sub-program and its management.
- Yes, each project in this sub-program represents a novel or innovative way to address the hydrogen safety barriers.
- Yes, the projects in the sub-program portfolio all have a strong scientific and engineering background. To expand the innovation aspect of the portfolio, the team should consider funding a project on refueling

protocols as a long-term option to existing standards. Items to consider could include reduction of energy consumption, improvement of equipment reliability, and reduction in cost of required equipment.
- Yes; in some cases (especially the more outreach-oriented projects), the projects borrow from previous or outside work, but there is still innovation in the sub-program's implementation and presentation of that work, and in providing tools that have translated more detailed and complex technical investigations into content that is more immediately accessible to broader audiences (e.g., authorities having jurisdiction and first responders).
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, this sub-program has developed interfaces with all the partners and stakeholders required—from end users to industries, designers to the general public, and (international) scientific communities to governmental institutions.
- The sub-program has absolutely engaged appropriate partners, including national laboratories, industry stakeholders, local partnerships, and international entities.
- Yes, the sub-program has definitely engaged appropriate partners. Each project in this sub-program seems to be well engaged with other institutions.
- Yes, the sub-program has engaged appropriate partners, including international partners.
- The sub-program has generally engaged the appropriate partners; however, the sub-program should clarify the roles of the national laboratories and private-sector companies with comparable capabilities. It is difficult to understand areas when FOAs are announced, particularly when submissions appear to be directly appropriate but are "discouraged" with little to no explanation.
- Yes, the focus on international collaboration needs to be tempered with domestic collaborations. The DOT transport issue (i.e., higher-pressure transport) and bridges/tunnels/parking are going to be ongoing issues with high priority and great importance. With limited time and budget, the sub-program should carefully consider whether the past few years have been "the lull before the storm," and while the international partnership development of the past two years lays good, long-term groundwork, sustaining this level of effort in the next few years may not be the best use of resources. This sub-program has shown good flexibility and has good advisors.
- Yes, there is a high degree of collaboration with outside partners. The only recommendation would be to strengthen the partnership with Korean automotive manufacturers and industry, as discussed in the question-and-answer period.

11. Is the sub-program collaborating with them effectively?

- Yes, the international community speaks highly of the sub-program manager, and there is much less confusion over the direction of DOE and U.S. hydrogen efforts as a whole. The outreach performed by this sub-program over the past few years has been very good.
- The sub-program is definitely collaborating effectively. This is one of the strengths of this sub-program.
- Yes, the sub-program appears to be collaborating effectively.
- The sub-program is absolutely collaborating effectively.
- Yes—the results clearly show the effective collaboration as well.
- It has yet to be determined whether the sub-program is collaborating effectively—a resolution is in progress.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- No, the sub-program's projects are quite comprehensive.
- It does not appear that there are any gaps.
- There are no technology gaps to report.
- There is an appropriate focus in the technology areas; however, the funding for revising codes and standards from the SDO/CDO side should be revisited as a cost-share activity, and the roles of the national laboratories versus the private sector need to be clarified.

- The hydrogen mass flow measurement issue is a gap.
- No.

13. Are there topics that are not being adequately addressed?

- No, all topics are being adequately addressed, especially considering the limited budget available—even though the budget is stable compared to the previous year.
- The sub-program is generally focused on industry priorities.
- There are no topics that are not being adequately addressed.
- There did not appear to be much material covered for stationary applications (although collaborations with the organizations dedicated to this area were noted) or mobile applications, besides the light-duty vehicle (LDV) and LDV fueling infrastructure topics. While these LDV topics need significant attention right now, stationary applications likely could use more attention than they are receiving, and other mobile applications will likely require attention fairly soon.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- There were no identifiable additional areas this sub-program should consider funding.
- Currently, there are no other areas the sub-program should consider funding.
- Yes, this sub-program should address the real problems faced by the industry, such as the development of engineering requirements for minimum standards. This sub-program could study the radiation effects of vent stack releases in relation to the current requirements of API 521, instead of the current path with pressure relief valve testing (it is not clear why researchers are testing the effects of an incorrect part selection).
- The sub-program should consider funding a mechanism to support the SDOs/CDOs in developing documents (in addition to data and providing experts for the work).
- The sub-program should fund an additional project on probabilistic risk assessment (PRA) using a subject-matter expert in this specialized field.
- The sub-program should fund hydrogen mass flow measurement. A recommendation for long term would include an advanced refueling protocol.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The team has demonstrated it has a well-defined approach.
- No; the sub-program implements an array of methods that appear to be working very well.
- The international collaboration framework is very vast, from IEA/HIA for the sharing and collection of R&D results, to the intergovernmental International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), up to the international standardization body the International Organization for Standardization (ISO). All these efforts are practically based on volunteering to share data individually obtained in a single country. Perhaps it would be possible to engage internationally at an operative level by defining joint RD&D programs. This is probably only possible through bilateral collaboration agreements that manage budgets and resources.
- The sub-program should explore new ways of reporting the "number of first responders trained" so DOE and stakeholders better know how and what first responders to reach, as well as what the sub-program has achieved with emergency responder outreach and what is still left to do.
- The sub-program should consider a new project on hydrogen PRA.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- This sub-program could more clearly prioritize the laboratory activities. The sub-program has established the connection between the laboratory, regulations, and outreach. It is not clear how each laboratory activity achieves a given regulatory or outreach goal, and what the anticipated impact is. It is not clear how this sub-program determines those priorities. It is not clear whether all of the top priorities for regulations/codes and standards or outreach are addressed by the current laboratory activities. If not, perhaps a change in laboratory activities is required to address more relevant gaps. It is not clear whether the PIs have been asked to provide the impact of the research on those RCS or outreach goals.

- There is one challenging suggestion that is not easy to implement. Progress in this area cannot be simply evaluated on the basis of progress to a few quantitative targets. Some qualitative indicators are now available, such as the number of downloads of a training package, or the availability of guidelines where none previously existed. However, it is not clear how to evaluate the impact of these achievements, or how to show that specific guidelines have achieved a certain level of improvement. These questions have been partially answered in this area; for example, when showing that science-based release calculation has allowed for a safety distance reduction. Perhaps it is possible to quantify these impacts for the rest of this sub-program.
- The sub-program should consider how California stakeholders (as the first market) can help more with identifying the required target audience and phased outreach strategy.
- The sub-program should consider adding a mechanism to support the SDOs/CDOs in developing documents (in addition to data and providing experts for the work).
- At this time, there are no other suggestions.

Market Transformation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, despite the fact that the sub-program manager was unavailable to present on the topic, the sub-program was clearly defined, both through the presentation and by the team member presenting. This indicates that not only has the sub-program manager effectively refined the purpose of the sub-program in his own mind, but the sub-program manager has also effectively communicated the sub-program goals and purpose to the team. These are the great hallmarks of a well-run sub-program.
- Overall, the sub-program description and strategy are well defined and understood. The presentation adequately discussed the goals and objectives of the Market Transformation sub-program, which include the following:
    - Deploy and demonstrate hydrogen and fuel cell solutions.
    - Catalyze the introduction and deployment of the technology.
    - Perform business case analysis and inform the broad community.
- Yes, the mechanisms by which the sub-program achieves its goals were especially well presented.
- Yes, the strategy, partnerships, and applications were presented very well.
- Yes, the sub-program was adequately covered.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, for this sub-program's scope, the projects are appropriately balanced, with a heavier weight placed on near-term, pre-commercial opportunities.
- Yes; the focus is decidedly on the near-to-mid term, as it should be for market transformation.
- Yes, a good pathway is presented for testing emerging technologies and commercialization.
- Given the nature of market transformation, the balance should be more heavily in favor of high-TRL opportunities and more focused on near-term objectives (1–3 years). The list of activities underway in the sub-program brings that proper balance.
- Near- and mid-term R&D is well represented with existing projects, including the new project modeled on the French experience. Long-term R&D needs to be strengthened; the mobile refueler project, while interesting, is limited to "last-mile" infrastructure issues.

3. Were important issues and challenges identified?

- Yes, the presentation identified the selection of technologies, identified partnerships, and set framework for demonstration and analysis.
- Yes, important issues were identified.
- Yes, the important issues and challenges were identified, but not specifically. The project identifies "challenges in reducing the commercial risk to high hydrogen and system utilization and reliability under mass market penetration scenarios" and "obtain data from operating experience to develop replicable business cases." These may be the important issues, but it is not clear whether these are the challenges. The specific challenges in the near and long terms are unclear. It is not clear what is causing risk in utilization or reliability (e.g., supplier diversity, demand development, or consumer confidence). The graphics in this slide were confusing and did not relate well to the topic.
- Yes; however, the broad challenges that are addressed by the sub-program could be detailed with more specificity. As presented, they seemed to not adequately cover the broad range of challenges that the sub-program should truly address. The individual accomplishments did a better job of being specific in this regard. If the broad challenges are more specifically addressed, it will likely be easier to connect them to the specific project challenges that were addressed. In fact, it would be very helpful if the challenges at the sub-program and project levels could refer to each other more directly or be more clearly parallel in wording.
- Generally speaking, yes, the important issues and challenges were identified. The biggest challenge is to support the faster and broader introduction of hydrogen infrastructure, and that component may be slightly undervalued and under-resourced.

4. Are plans identified for addressing issues and challenges?

- Yes, plans for identification and management of issues and challenges were presented; some of these plans will require ad hoc decision making as issues and challenges are identified.
- There are good plans, but with such esoteric challenges, there is a sufficiently wide umbrella to cover any possible topic. The sub-program should identify the challenges more specifically. The sub-program could do such without identifying—and thus restricting—future opportunities.
- Yes, plans were identified, although the presentation was very broad. A bit more detail than was presented would be very helpful. For example, it would have been good if the presentation addressed what kinds of models, tools, and templates are to be developed in the coming year, what questions they will answer, and who they will be targeted to help.
- Generally speaking, yes, plans were identified.
- The plans are probably described in detail in the specific project presentations.

5. Was progress clearly benchmarked against the previous year?

- Yes, new demonstrations and expectations were presented and appear to be appropriate.
- Yes, there is a very good summary slide that is easy to compare to previous years.
- Progress was clearly benchmarked against the previous year; the only new niche to be identified is the application modeled after the French approach.
- One would expect to see this benchmarking in the specific projects being reviewed. It was not clear that the overall sub-program was benchmarked against last year. The presentation included a good highlight of how the investment in MHE and backup power has potentially served to catalyze the introduction of the technology (5–10-fold).
- This was not very clearly presented. The prior year information was really only presented in terms of appropriation and expenditure.
- No, it was not presented, other than the budgets per year.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, FCEV, hydrogen refueling, material handling, and range extender efforts were all presented and are appropriate for demonstration, and are on the path to commercialization.
- Yes, the projects are addressing the broad problems and barriers for the non-passenger-vehicle markets.
- Yes, the projects address the main issue of getting traction in visible niche markets.
- The broad FCTO goals, especially for building the market and bringing down costs, are certainly addressed by the projects. The sub-program overview also did a good job of showing metrics to success in terms of volume of units delivered pre- and post-DOE projects. However, the same was not done for costs (which is at least as critical). Additionally, some context and perspective should be supplied. For example, it was not clear whether the 5,500 backup power units purchased by industry are a significant number of units in terms of production numbers and power/energy market share.
- The projects are focused on the right type of activities, but a little more focused effort to improve hydrogen infrastructure might be called for in the next five years.
- Yes, this sub-program compensates for a defunct Technology Validation (TV) sub-program, in that it is able to identify project opportunities that would otherwise seem to be covered by the TV sub-program. The Market Transformation sub-program, which has clear leadership and has achieved success, and the issues with the TV sub-program, begs the question of why technology validation efforts are not managed by the Market Transformation sub-program.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes, the sub-program does a good job of clearly delineating the objectives it will work to address, and it seems like most projects are on schedule.

- Yes, sub-program managers appear to be very open and thoughtful regarding moving the appropriate technologies into commercialization.
- Yes, the MT sub-program manager and team have done a very commendable job in identifying and executing projects that help with market introduction.
- Yes, this sub-program seems quite well managed.
- The sub-program is focused and well managed.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The strength of this sub-program is the creative sense of opportunity that it uses to identify and succeed with projects in several application areas with limited funds. This creativity and continued success with strong and well-planned leadership ensures long-term success. The greatest weakness of the Market Transformation sub-program is the structural relationship it holds with technology validation. The inability of the Technology Validation sub-program to produce tangible results restricts the success of the Market Transformation sub-program.
- The MHE fuel cell projects are obviously succeeding, given the large number of industry-funded projects (12 times more industry-funded than DOE-funded fuel cell MHE). Similarly, the backup power systems are succeeding, with a 6:1 industry-funded to DOE-funded project ratio. No data was provided on the other applications. In the future, it might be useful to list the market size in these other areas; for example, the presentation could list how many ground support equipment units (GSEs); refrigerated trucks; trash trucks; and Class 1, 2, and 3 vans there are in the United States.
- The sub-program's strength is that it uses a small amount of funds to help leverage others' investment dollars and help field technology-ready solutions. The main weakness is that the small budget also constrains the number and types of projects that can be considered.
- Project selection, geographic diversity, and technology analysis are all strengths. A weakness might be the budget constraints for sub-program expansion.
- The biggest project-specific weakness seemed to be with the GSE project. The vehicles are to demonstrate real-world capability (and it was mentioned, in particular, that they will need to demonstrate compatibility with the outdoor working environment). However, the project timeline included less than a year for this demonstration and validation. This does not really seem to be an appropriate amount of time to provide a high degree of confidence in the real-world capability of this application. If possible, this evaluation period should be extended, and similar demonstrations in the future should work with a longer period, as well.
- At present, Plug Power's success in MHE (forklifts today, hopefully baggage handling tomorrow) is the only example of traction. Vision Industries' bankruptcy is a case of a fuel-cell-based company failing to achieve traction.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, despite a small number of potential suppliers for equipment, this sub-program seems to creatively develop a project that attracts a diversity of suppliers and a tremendous diversity of project partners. It seems to appropriately leverage opportunity and market need; for instance, the auxiliary power unit for refrigerated trucks features heavy industry participation and seems very close to being a commercial product, whereas the marine generator is much more government-entity-sponsored and represents a longer-term opportunity. Nevertheless, the sub-program is able to prevent the use of a "one-size-fits-all" approach to project development, which would have prevented one of these two opportunities from being fulfilled.
- Yes, the projects appear to be both novel and innovative, and they are clearly ready for demonstration, analysis, and validation.
- Yes; the maritime application, in particular, appears to be a very novel approach. It would be interesting to see this project continue to be refined and potentially expanded for maritime applications with even more stringent operating requirements (particularly the amount of energy storage for the application).
- The funding opportunity announcement (FOA) and the mobile refueler initiative stand out as innovative initiatives.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has absolutely engaged the appropriate partners. The team has interfaced with dozens of federal, state, and local entities, along with commercial partners, over the years. This is probably one of the most collaborative sub-programs this reviewer has ever seen.
- Yes, the sub-program has engaged the appropriate public laboratories and private partners.
- Yes, there is clearly a broad spectrum of partners, especially within various industries.
- Yes, the sub-program features a diversity of project suppliers.
- Yes, the partnerships are appropriate and helpful.
- Yes.

11. Is the sub-program collaborating with them effectively?

- Yes, project managers have gone above and beyond to create effective partnerships and avenues for collaboration.
- Based on its past success and current status, this sub-program has a high likelihood of achieving successful collaborations.
- The deployment and demonstration of the project platforms seems to indicate the sub-program features a very effective collaborative environment.
- Yes, the sub-program appears to be collaborating effectively with partners.
- It is hard to tell whether the sub-programs are collaborating effectively with partners.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- There are no current gaps, but the emerging technology is subject to change as external conditions change. Sub-program managers must be constantly aware of these changing conditions, which may affect the path to commercialization.
- Stationary (non-backup) power applications appear to be receiving no continuing development or attention. While this may have been addressed in the past, the lack of accomplishment metrics (as presented for backup and forklift power applications) seems to imply that perhaps the market has not yet transformed to a sufficient degree. This area seems worthy of a second look. Additionally, ancillary considerations for hydrogen LDVs may need to become a priority for this area, especially concerning safety, codes, and standards. For example, it might be worth considering how DOE can ease the transformation of the FCEV servicing marketplace. It is not likely that the OEMs will remain the only servicers of their FCEVs, and independent businesses not involved in the business of building FCEVs likely need support in this area.
- The gap in pulling technology forward from the other sub-programs seems to be the result of a failed TV sub-program rather than this sub-program’s concern. Despite this issue, there seem to be several infrastructure-related items with which this sub-program is not involved. There is a significant opportunity to develop light-duty fueling infrastructure projects, not just mobile fueling. It is not clear whether this sub-program has done the due diligence with infrastructure providers, or whether this sub-program has developed the relationships and identified opportunities.
- The main concern would be to reexamine the opportunity to catalyze the hydrogen infrastructure industry to broaden and deepen its capability to support vehicle fleets.
- It is not clear whether there are any gaps.

13. Are there topics that are not being adequately addressed?

- The topics, at this time, appear to be adequate and consistent with the budget, but that may change as conditions change.
- Applications that make use of opportunity fuels did not seem to be covered extensively in the review of recent accomplishments or the plan for the coming year. In particular, waste gas to hydrogen, trigeneration, renewable power-to-gas, and the overall intersection of the electric and natural gas grids through hydrogen need significantly more attention than they were given this year. There is a need among stakeholders (including state agencies) to understand the full potential and scalability of ideas such as these. At-scale

demonstrations are consistently called for in stakeholder meetings, although they do not appear to be a priority in this sub-program (which appears to be the most directly applicable sub-program).

- It is not clear how these specific market niche applications have been chosen - there was a systematic screening process or has DOE been opportunistic (in which case, opportunities may have been missed).
- It is not clear what happened to cell phone tower power supplies.
- The only topic not being adequately addressed is infrastructure.
- This question seems redundant with #12.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- At this time, there are no other areas the sub-program should consider funding.
- The major areas appear to be consistent with the budget and sub-program goals. Some additional attention might be beneficial regarding sensitivity to changes in external conditions and the path to commercialization, including a business case without investment tax credits (ITC), periods of low electricity and fuel costs, and reduced financial support for carbon reduction.
- Home power and the intersection of home power and LDV FCEVs seems to be an area that has “fallen off the radar” across the industry. However, there is great promise in integrated solutions that address both the home-based stationary and LDV sectors by more thoroughly demonstrating the possibilities. The number of market drivers could be doubled in DOE demonstration project(s) that provide information to the community on the viability and economic opportunity of these systems. Moreover, the home/auto combined system could help alleviate anxiety regarding the infrastructure being deployed and developed, as well as provide the automotive industry increased assurance that consumer convenience is being addressed, there is ample opportunity for consumer refueling, and there will ultimately be significant market launch volumes of home and vehicle fuel cells.
- The sub-program should consider funding infrastructure-related efforts—specifically, demonstration-scale equipment, suppliers, and support systems.
- The sub-program might want to consider fuel-cell-powered railroad locomotives (perhaps starting with switching yard engines).

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The objective to help market-ready solutions get to market through specific projects is the appropriate method for the sub-program.
- The sub-program should develop a better understanding of the existing hydrogen sources and then develop infrastructure market expansion opportunities around those sources. It should develop infrastructure market demonstration opportunities in un-involved zero emission vehicle (ZEV) and ZEV-leaning states (i.e., Oregon, Vermont, New Mexico, and Washington). It should continue to creatively use the funds available to encourage private and public partners to develop projects that provide an expansion to the established networks in California and the Northeast. It should “nibble at the edges” of the private and competitive markets in California and the Northeast. Perhaps national park destinations could represent opportunities for lower-cost, lower-size demonstration fueling facilities.
- Some current methods could be expanded, including (1) mechanisms to consider sensitivity to changed conditions (e.g., fuel costs, energy output value, ITC, and other incentive loss); (2) increased engagement with the supply chain, either directly or through OEMs, for improved reliability, inventory control, and cost reduction; (3) increased attention to potential cash flow and ability to secure commercial financing; and (4) further engagement to continue developing and maintaining community partnerships for the deployment of demonstration projects.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program should continue engaging other federal partners (e.g., the U.S. Department of Defense, Environmental Protection Agency, U.S. Department of Agriculture, and U.S. Postal Service) for more shared projects. The sub-program should perhaps consider a partnership with the U.S. Department of

Commerce and/or the U.S. Small Business Administration or others for marketing of successful demonstrations.
- Time seems to be running out; after so many years, the only area where traction is visible is the forklift MHE area (in addition, luckily the Nuvera buyout by NACCO Materials Handling Group and Toyota's commitment to supply 400 fuel cell forklifts to Osaka Airport are sustaining the "buzz" in this market). It would be interesting to see whether a solid business case can be made for fuel cells in other niche areas. It is unclear whether there has been a systematic screening of niche areas to identify other traction opportunities. Learning from the French experience is a good idea.
- The only recommendations are to slightly increase funding, if possible, and to refocus some investments on the infrastructure challenge in the next 3–5 years.
- Integrate TV into the Market Transformation sub-program to simplify the FCTO sub-program structure and centralize the point of contact between pre-commercial and commercial opportunities.
- No.

Systems Analysis Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes. The goals were clearly stated at the beginning of the presentation. The Systems Analysis strategy was also clearly articulated: to develop comprehensive, consistent, and validated data; to obtain or develop models and methods with which to analyze the data; and to carry out a focused set of studies to address questions that can guide and evaluate the DOE Hydrogen and Fuel Cell Program's (the Program's) R&D efforts. Because the data and models have essentially already been developed (updating and checking is still required, of course), the work is now focusing on analysis.
- The strategy for the Systems Analysis sub-program is very robust and employs very well-known tools and models from world-class laboratories. It is also crucial for identifying opportunities for providing direction to overcome barriers and challenges in other sub-programs, such as the Hydrogen Production and Delivery sub-program. The sub-program's extensive collaboration with industry and academia adds a lot of value and robustness to the analysis work performed under the sub-program.
- Yes. The overall goals of the sub-program are well stated. Compared to the 2014 goals, the 2015 goals are more specific about quantifying benefits, such as greenhouse gas (GHG) reduction, and have expanded to cover life cycle analysis (LCA) of water use. Because the Systems Analysis sub-program is relevant to other activities within DOE, coordination was properly mentioned as a challenge/goal (e.g., connecting to the Vehicle Technologies Office models for fuel cell vehicles). The overall strategy and modeling scope was well covered in slides 3–6.
- The sub-program was described very well and seemed to have a good balance of technology analysis, infrastructure analysis, and high-level implementation and market analysis. One area of the strategy that was mentioned as an objective but not discussed was risk analysis and risk mitigation strategies. It was not clear what risks were identified as a result of the analysis and what additional work should be performed to mitigate these risks. High hydrogen utilization and low pressures will reduce cost, but it is unclear what should be done about this because we are headed toward low hydrogen utilization and higher pressures.
- Yes, the objectives, challenges, and strategy were covered adequately.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. There is recognition throughout the Systems Analysis sub-program that the near-term launch of hydrogen technologies has a different set of issues than long-term development of low-net-carbon hydrogen pathways. There are elements of both near- and long-term analysis. Near-term analysis is appropriately claiming significant attention as fuel cell systems become commercial and fuel cell vehicle rollouts begin. This year, the sub-program established an interim (near-term) delivered hydrogen cost target of $7/kg and a long-term target of $4/kg (for automotive fuel). These were revised from previous targets. In the near term early market analysis for FCEVs, especially analysis enabling the commercialization of FCEVs, is stated as an important focus of the Systems Analysis sub-program. Many projects focus on near-term issues, such as infrastructure analysis and financial analysis of hydrogen stations. Long-term issues are also addressed for example, analyzing renewable sources of hydrogen production and advanced technologies (a project in this area analyzed advanced production methods).
- Yes, there is a reasonable balance between the time frames. Projects such as the Hydrogen Financial Analysis Scenario Tool (H2FAST) are useful to activities going on now and in the near future, namely assisting with the deployment of the earliest infrastructure for hydrogen vehicles. Other projects assist in defining targets for 2020 and beyond, while still others assess the long-term potential and conditions for market acceptance, future GHG emissions under different pathways, and so on.
- There is a nice balance between the near-term R&D, such as the efforts to develop an interim hydrogen cost target, and the longer-term R&D, such as the analysis to evaluate the benefits of increased fuel cell efficiency on the storage system and fuel cell. It is good to recognize the benefits of FCTO funding, as was done in the correlation between annual jobs and FCTO funding.
- The sub-program has an appropriate balance: it performs analysis on current hydrogen pathways and early market vehicle penetration while also providing a lot of analytical information to identify the main barriers

to future hydrogen pathways and FCEV penetration and how to overcome these barriers through DOE's R&D efforts.
- Yes, now that the sub-program is incorporating early market analysis, it is more balanced than before.
- Yes.

3. Were important issues and challenges identified?

- Yes. The Systems Analysis sub-program has highlighted the importance of hydrogen delivery and compression, storage and dispensing (CSD), in addition to production and end use. Initially, the importance of CSD to the economics of hydrogen and fuel cell vehicles was not fully appreciated. Analyses by the sub-program have shown how important it is and should help refocus R&D resources toward this critical area. The sub-program has also made an important contribution by highlighting the importance of reducing the costs of low-C hydrogen production. The sub-program recognizes the importance of the transition to hydrogen and fuel cell vehicles, but more needs to be done in this area.
- The sub-program is definitely focused on the main challenges associated with the hydrogen infrastructure development, and this was clearly demonstrated during the presentation.
- Yes, the emphasis is well stated on slides 2, 3, and 9, as well as on the slides for individual projects.
- The issues and challenges for the System Analysis sub-program are laid out in the presentation: market complexities, availability of data, and coordination of analysis. It may be useful to identify the issues and challenges that are identified as a result of the analyses that were performed and to identify approaches the other sub-programs could take to address these challenges.
- Yes, but one of the challenges is understanding market transitions, particularly because consumer behavior is difficult to model.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes. Most plans involve model development and adding to model capabilities (see the list of FY 2015–2017 recent and upcoming activities from slide 20, copied below.)
    - "Diverse portfolio and expanded capability of models developed by the Systems Analysis sub-program are enabling analysts to address barriers to technology development and commercialization.
    - Emphasis on early market and infrastructure analysis. (Comprehensive approach to evaluate portfolio of fuel cell applications for light duty transportation, stationary generation, back-up power, material handling equipment, and the electric sector to realize economic, environmental and societal benefits.)
    - Continue life-cycle analyses of cost, greenhouse gas emissions, petroleum use and criteria emissions, and impacts on water use.
    - Continue to enhance existing models and expand analyses.
    - Assess programmatic impacts on market penetration, job creation, return on investment, and opportunities for fuel cell applications in the near term."
- Yes, by looking at the portfolio, it is very clear that the sub-program has a well-thought-out plan for conducting the proper analysis work, which will provide guidance to DOE's R&D work on hydrogen and fuel cells.
- Yes, the current and planned projects address the challenges identified.
- Yes. However, the Program should pay greater attention to the process of transitioning from petroleum to hydrogen. This is a particularly difficult problem and one that has not been extensively studied in industry, government, or academia. It poses special problems from economic, technological, and public policy perspectives. There are real and large barriers; strong positive feedbacks, including network externalities; and deep uncertainties. There are many important issues about which little is known. It could be argued that because the Program's primary responsibility is R&D, transition issues, especially public policy issues, are someone else's responsibility. Unfortunately, few are taking up that challenge, with the possible exception of the state of California.

- One area of concern is the validation of models. The H2FAST model was impressive. It would be beneficial to now document the validation of this model with available data from hydrogen refueling stations.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Several analyses on hydrogen station costs clearly identified opportunities and options for reducing the costs of dispensed hydrogen. The development and dissemination of H2FAST will be a key enabler to the development of hydrogen infrastructure.
- Yes, progress in understanding impacts on water use, employment, and much more was clearly presented.
- Yes, progress was benchmarked, although the degree of benchmarking shown varied. Progress was clearly indicated for these ongoing projects: Life Cycle Analysis of Water Use for Light Duty Vehicle Pathways, financial analysis for stations, and H2FAST, (Component and Infrastructure Assessment) Station Cost Analysis for Capacity and Fueling Pressure. Also, the following new projects showed results: Hydrogen from Methanol Reforming, Component and Vehicle Assessment, Impact of Fuel Cell System Peak Efficiency, Fuel Consumption, and Cost.
- The status for most of the accomplishments outlined in the presentation was not shown, compared to the previous year, but this is not absolutely necessary, given that the slides show work in 2014/2015.
- There was nothing in the presentation that clearly described how the work performed this year tied back to the work performed last year. This would be valuable to help one appreciate the progress that was made and how work in FY 2015 built on the results of FY 2014. Based on a review of the FY 2014 presentation, there are many areas that did build on previous efforts.
- No, progress was not clearly benchmarked, although there were graphs showing reduction in costs, etc.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The ultimate target of FCTO is meeting cost and performance targets. The sub-program is helping stakeholders understand how far different pathways are from meeting these targets and what barriers/challenges need to be addressed. The Systems Analysis sub-program works with the other sub-programs within FCTO to continuously update assumptions and pathways, and it integrates input from industry. Yes, the sub-program is addressing FCTO's challenges.
- Yes—one project looked specifically at targets for cost and performance, and what they might mean for FCTO goals. A project also looked at job creation associated with hydrogen infrastructure development.
- Yes—the sub-program is definitely in line with DOE's ultimate hydrogen cost targets, and the analysis work is providing significant data and guidance in order to achieve these targets.
- Yes, but the problems are numerous and difficult. The sub-program has done excellent work in benchmarking and analyzing hydrogen production pathways and their costs and benefits, including employment, water, and GHG impacts. The unique and novel problems posed by a major energy transition for the public good need special attention. Hydrogen and fuel cell use by heavy vehicles also deserves increased attention. Some of this is handled by the Market Transformation sub-program, but there are likely important possibilities beyond transit buses, namely medium and heavy duty trucks, that should become a core part of the sub-program's research and analysis.
- It appears the accomplishments from this sub-program address concerns, at least in some degree, for all of the other FCTO sub-programs: Hydrogen Production and Delivery, Storage, Fuel Cells, Market Transformation, etc. Some analysis was done both for stationary and mobile applications. Nothing was presented on the MYRDDP milestone "Complete analysis of the impact of hydrogen quality on the hydrogen production cost and the fuel cell performance for the long range technologies and technology readiness (2Q, 2015)."
- Yes.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO' needs?

- Yes. Systems analysis of hydrogen and fuel cells has proven to be very complex. The sub-program has done an impressive job of building expertise, an information base, models, and analytical tools. Numerous important issues have already been addressed, yielding valuable insights and guidance.
- One of the main reasons this sub-program consistently meets its goals and objectives is the effectiveness of how it has been managed. This particular aspect is very impressive, given the significant number of stakeholders involved in this sub-program.
- Yes. The individual projects addressed important questions. There was good analysis of the impact of the Program on reducing costs for fuel cell backup units and forklifts, and on job creation.
- The Sub-Program Manager presented a set of very clear goals, progress to date, and results for each of the projects funded. It is clear the sub-program has been integrating external input from industry and others, such as the National Academies.
- Because the sub-program has such a wide breadth of areas of interest and such a wide range of time frames, it is difficult to see it as well focused. In general, it appears to be a wide range of disparate projects. It is not clear whether it is possible to tie them together in terms of time frame and model/tool hierarchy.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- One strength is the breadth of issues that the sub-program seeks to address. Another strength is the way the sub-program models draw on and synthesize knowledge across DOE labs and modeling activities. The sub-program tries to make its models as consistent and well verified as possible, which is not an easy task. Collaboration and outreach to stakeholders through model development and workshops are other strong points. Sometimes the sub-program seems spread thin. It would be good to see connections with energy/economic models such as NEMS or others that include multiple sectors of the economy. Particularly excellent projects include the following:
    - The H2FAST project seems very valuable and stands out as useful for near-term studies of a station "business case."
    - The LCA of water use is of increasing interest.
    - There is nice use of the ORNL Market Acceptance of Advanced Automotive Technologies (MA3T) model to assess the impact of cost reductions in storage and fuel cell cost on market penetration.
- The main strengths of this sub-program are probably the models and tools being used to carry out the analysis work. One area in which the sub-program demonstrates its strength is in the understanding of hydrogen refueling station costs and identification of designs and configurations that provide options to reduce costs. There are probably no weak areas, but the sub-program should receive more funding.
- There is a good team of analysts working on these issues to develop things like spreadsheet tools, etc.
- Methanol is an innovative approach to hydrogen delivery. It would be good to have a full cost analysis and engineering assessment of this option, and not just the GHG analysis, to really understand whether it makes sense. Water usage compared to a variety of renewables is a nice addition to the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, although water consumption could be tied to the economics of the approach. The H2FAST model, and its potential utility to determine the economics of hydrogen refueling stations, is impressive. It is good that the analysis of fuel cell efficiency is being tied to fuel cell and storage system cost. However, it does not make sense to tie it to a particular time frame. It highlights the importance of improved fuel cell performance. The vehicle penetration analysis results could be clarified to provide solid conclusions and recommendations that drive some future work.
- Strengths include the expertise and human resources built up, especially at the national laboratories (e.g., NREL, ORNL, Argonne National Laboratory, SNL, and LBNL), but also at universities, especially the University of California, Davis, and the University of California, Irvine. The resources developed by the sub-program like ; the Hydrogen Analysis (H2A) model; and numerous models such as GREET, the Hydrogen Delivery Scenario Analysis Model (HDSAM), the MA3T, other market models, Autonomie,

H2FAST, and more give the sub-program powerful analytical capabilities. The Macro-System model has been developed into a useful tool for linking models together. Strengths also include the contacts and collaboration with industry. Particularly in the area of market models—that include representations of consumers' choices of vehicles,—there appears to be a need to better articulate the purposes of the different models and to understand their particular strengths and limitations. There are many unknown elements, including the following: (1) which models predict initial demand for hydrogen fuel cell vehicles to assist in the deployment of early infrastructure; (2) which models are designed to analyze the co-evolution of the market for vehicles, hydrogen supply, and refueling infrastructure to assess benefits, costs, and policy issues; and (3) which models are for evaluating sub-program goals and assessing costs and benefits.

- Key strengths include the very strong technical expertise, good models, involvement of the right stakeholders, and clear goals. A key weakness is that some of the models are set up to assume that DOE targets are met and only consider high volumes of production for key technical components and high market penetration, which generates unrealistic results. These models need to be coupled with early market assumptions such as low utilization rates and high cost of technology.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes. For example, the addition of H2FAST this year should be helpful to states developing and executing plans for deploying hydrogen infrastructure. It should help in developing policies and evaluating proposals. It is also likely to be useful to early infrastructure providers. Good progress has also been made in the analysis of water impacts and life cycle cost analysis of hydrogen pathways. This work is likely to increase in importance.
- New technology pathways are constantly being integrated into the models. For example, the LCA models now include 700 bar for refueling, and an effort to include 500 bar is on the way; merging hydrogen production technologies are being analyzed; and additional onboard hydrogen storage technologies are being considered. Continuous communication with the U.S. DRIVE Technical Teams, which represent different stages of the value chain, ensures that the latest technologies are being considered.
- Yes, there are projects that represent novel ways to address the key analysis questions. The sub-program manages a number of innovative and useful models that can be used to address questions posed in slides 2 and 3.

10. Has the sub-program engaged appropriate partners?

- Yes. There is good involvement from industry, academia, consultants, and the national laboratories. The sub-program has strong partnerships with industry, which enables valuable input from industry to inform and help target analysis. The national laboratories play a key role as valuable and reliable reservoirs of knowledge and expertise. A sub-program such as the Systems Analysis sub-program cannot function effectively without an array of experts to draw on. Most of these experts reside at the national laboratories. Academia and industry also play a critical role, but the national laboratories perform a core function as the place where expertise can be created and sustained.
- Yes, the sub-program is very engaged with major stakeholders in industry and government, including the national laboratories. The workshops are an effective way to bring stakeholders together around hydrogen issues of interest.
- The sub-program features successful collaborations with partners that provide very valuable feedback to the portfolio of projects under this sub-program.
- The sub-program appears to have engaged a variety of partners that will assist in developing and validating the results. The level of engagement is difficult to determine based on the presentation; however, the multinational workshops with a wide range of industries and laboratories in attendance suggest a strong interested in gathering a wide range of opinions and ideas.
- Yes, industry and national laboratories are involved.
- Yes.

11. Is the sub-program collaborating with them effectively?

- Yes, the sub-program appears to be collaborating effectively. This is not easy, given the rapid growth of activity in the hydrogen and fuel cells space.
- Yes, and this collaboration is clearly demonstrated by the numerous accomplishments and successes achieved.
- It appears that the sub-program is collaborating with partners effectively.
- Yes, the collaborations are effective.
- Yes. It was not possible to determine whether H2USA is making effective use of the capabilities of the sub-program. The presentation was expected to include more details about these interactions.

12. Are there any gaps in the portfolio for this technology area?

- There are no gaps, but there are areas that should probably be given greater attention, such as understanding the transition process. The sub-program has made important contributions by doing analysis and developing resources for early infrastructure deployment, and the sub-program appropriately considers this an area of emphasis. It also emphasizes the interaction between hydrogen supply and vehicle demand. However, the transition includes more than just these issues. There are many unknown aspects of the transition or the conditions for success and the threats. In addition, greater emphasis should be given to heavy-duty vehicles. Heavy-duty vehicles are a diverse segment, and it is not at all clear that in the long run hydrogen and fuel cells could not play a major role as a primary power source for these vehicles.
- No, there are no gaps, but the water consumption numbers need to be scrubbed and compared with the literature on two fronts:
    - Water consumed to make the biomass: One paper estimates that it requires on the order of 3,200 gallons of water per kilogram of hydrogen produced from biomass, assuming a biomass production energy ratio of 0.737.[2]
    - Wind electrolysis: NREL has previously estimated very high water consumption (294 gallons/kg of hydrogen) is needed to cool the electrolyzer.[3]
- In a way, hydrogen FCEVs are similar to compressed natural gas (CNG) vehicles. CNG vehicles have not had significant market penetration in the United States, and they face challenges similar to those of FCEVs. It would be interesting to assess lessons learned from the CNG vehicle industry and understand how they can be leveraged to advance FCEV market penetration. A number of LCAs have been done for GHGs, cost, energy, petroleum use, and water. It would be useful to incorporate criteria air pollutants and show the results of all these parameters for different vehicle technologies for early market and developed markets with the same assumptions in one presentation.
- There are two areas discussed in the MYRDDP that were not addressed in the portfolio: risk mitigation and policy analysis. It would be useful to evaluate what research needs to be done to mitigate particular risks identified with the analyses. It would also be useful to better understand how possible changes in government incentives and regulations could impact the business case for hydrogen, infrastructure development, or fuel cell use.
- There is a need for more transition analysis. Given recent results from the National Academies report on light-duty transitions and others, it appears the benefits of hydrogen outweigh the costs. A better understanding of this issue for different applications would be useful. The sub-program appears to be going in this direction, which is good. It is good to see interest in looking at roles for hydrogen in non-LDV transportation. As scenarios for a low-carbon transportation future are developed, it is important to keep the sub-program closely coupled with activities in other parts of DOE.
- More funding is needed.

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[2] See P.W. Gerbens-Leenes, "The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply," *Ecological Economics* 68, no. 4 (2009): 1052–1060, http://www.sciencedirect.com/science/article/pii/S092180090800339X.
[3] Mark Ruth et al., *Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios*, NREL/TP-6A1-46612 (Golden, CO: National Renewable Energy Laboratory, 2009), http://www.nrel.gov/docs/fy10osti/46612.pdf.

13. Are there topics that are not being adequately addressed?

- The sub-program's portfolio seems well balanced, and it covers the main areas to address the top barriers and challenges currently facing the hydrogen industry.
- Overall, the sub-program is doing a very good job.
- The fuel economy of FCEVs needs to be updated. For example, the national laboratories measured an average fuel economy of 68.3 miles/kg of hydrogen for the Toyota Highlander sport utility vehicle FCEV. As fuel cell technology is migrated into mid-size passenger vehicles with lower cross-sectional area, lower aerodynamic drag, and lower mass, the fuel economy will increase. The following are some examples of increased fuel economy, assuming that the decade-old Highlander fuel cell was packaged into a Prius-like sedan: reducing the test mass from 1880 kg for the Highlander to 1679 kg for a Prius FCEV increases the fuel economy to 76.8 miles/kg, reducing the cross-sectional area from 33 sq. ft. to 28 sq. ft. increases the fuel economy to 77.2 miles/kg, and reducing the drag coefficient from .326 for the Highlander to 0.25 for the Prius body increases the fuel economy to 85.4 miles/kg. Note that this assumes no increase in fuel cell efficiency after 10 more years of development and no increase in specific power of the fuel cell, both of which will increase fuel economy even more. For example, the Toyota Mirai has a reported range of 650 km on 4.3 kg of hydrogen, or a fuel economy of 93.9 miles/kg of hydrogen, indicating that Toyota has improved fuel cell efficiency and specific power since it built and tested the Highlander FCEV more than a decade ago. Thus, the fuel economy numbers that DOE is using for the FCEV (i.e., 50, 55.3, and 68) are way too low and are short-changing the benefits of FCEVs.
- The sub-program is quite comprehensive and addresses a wide range of important issues. It might be useful to develop a clear plan for market modeling, especially models involving vehicle choice. Several models are receiving support, and different scales and scopes need to be modeled using different approaches. However, the presentation did not provide a clear sense of which models address which issues.
- Some of the assumptions in the models are too optimistic:
    - Models that assume that DOE targets are met.
    - Assuming high market penetration.
    - Assuming technology is produced "at volume."
    - All ranges of the spectrum should be considered.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It appears to be a well-balanced portfolio of near- and long-term analyses for the wide range of topics applicable to hydrogen and fuel cells.
- The sub-program should formulate a research agenda for transition analysis. In a way, this is overdue because vehicles are already being manufactured and leased. On the other hand, the transition will take decades, even if it is very successful.
- The sub-program should consider funding projects related to LCA of criteria air pollutants, understanding potential displacement of CNG technologies using fuel cells, and integration of fuel cells to renewable energy sources to address intermittency issues.
- The sub-program should coordinate with the Market Transformation sub-program to document progress as fuel cell and hydrogen technologies are rolled out.
- The sub-program could further fund and perform analysis work on advanced hydrogen technologies in FCEVs, including how these will impact the hydrogen delivery pathways.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The current approach has been demonstrated to be successful over the years.
- Future market behavior is a central issue for the sub-program. Of course, this depends on issues such as the price of oil and how consumers evaluate fuel costs versus vehicle purchase prices in their car-buying decisions. However, it also depends on issues that are mostly unknown, such as the following: (1) the number of early adopters and how willing they are to pay for the first thousands of novel fuel cell vehicles; (2) the risk aversion level of the majority of consumers, and how quickly it can be overcome, (3) the perceived cost of limited fuel availability; and (4) the value of a diverse set of vehicle choices. On the fuel

supply side, it is unclear how important the cost of hydrogen will be to customer satisfaction. It is also unclear what will happen in California if there is no effort to control the price of hydrogen to early vehicle purchasers, or how public policies and business models can be structured to ensure a satisfactory supply of hydrogen at a cost that encourages adoption of fuel cell vehicles. It can be argued that these issues are outside of the sub-program's scope (and budget). However, it is not clear who will do the necessary research and analysis.

- Yes, there are two recommendations for new ways to approach the sub-program's barriers:
    - For barrier "Stove-piped/Siloed Analytical Capability," it may be useful to more strongly encourage activities in other sub-programs to integrate the use of the resources and models that have been developed in this subprogram, especially if the activities are being conducted by different organizations.
    - For barrier "Inconsistent Data, Assumptions and Guidelines," the research organizations associated with the Program should be encouraged to use the information developed by this sub-program as part of Funding Opportunity Announcements or Annual Operating Plans.
- There is a growing focus on understanding consumer decisions and choices around advanced vehicles. The sub-program should encourage continued discussion of these topics with stakeholders.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The Systems Analysis sub-program is making important contributions to guiding DOE's R&D decisions and evaluating the most important costs and benefits of hydrogen and fuel cell vehicles and other applications. The entire Program budget should be increased and, when that happens, the sub-program budget should be increased as well. There is a lot to be done. Recognizing that DOE actively participates in the IPHE, keeping close track of technological progress, policies, and implementation around the globe should probably be a core function of the sub-program effort. There is no doubt this is being done to some degree, but the presentation did not provide much information. Perhaps the United States can learn from what is happening in Germany, the rest of the European Union, Japan, Korea, and China.
- This sub-program is very effective in conducting useful analyses of hydrogen and fuel cell systems. To the extent possible, it should facilitate transfer of the latest knowledge about hydrogen and fuel cells to other groups within DOE and to agencies that model energy systems and futures.
- The only suggestion is to update the fuel economy of FCEVs for passenger sedans, which will improve the benefits of FCEVs compared to other vehicles.
- There are no additional suggestions to make.

Research and Development Project Evaluation Form

This evaluation form was used for the following Hydrogen and Fuel Cells Program sub-programs: Hydrogen Production and Delivery; Hydrogen Storage; Fuel Cells; Manufacturing R&D; Safety, Codes and Standards; and Systems Analysis.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach

To performing the work – the degree to which barriers are addressed, and the project is well designed, feasible, and integrated with other efforts. (Weight = 20%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Approach to performing the work:

2. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 45%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.

1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

3. Collaboration and Coordination with Other Institutions

The degree to which the project interacts with other entities and projects. (Weight = 10%)

4.0 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated.
3.5 - Excellent. Good collaboration; partners participate and are well coordinated.
3.0 - Good. Collaboration exists; partners are fairly well coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.
1.0 - Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. (Weight = 15%)

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.
1.0 - Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. Note: if a project has ended, please leave blank. (Weight = 10%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding

- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

Technology-to-Market Project Evaluation Form

This evaluation form was used for the following Hydrogen and Fuel Cells Program sub-programs: Market Transformation and Technology Validation.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. (Weight = 15%)

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.
1.0 – Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

2. Strategy for Technical Validation and/or Deployment

Rate the degree to which barriers are addressed, how well the project is designed, its feasibility, and integration with other efforts. (Weight = 20%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on the Strategy for Technology Validation and Deployment:

3. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals. (Weight = 45%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair

- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

4. Collaboration and Coordination with Other Institutions

The degree to which the project interacts with other entities and projects. (Weight = 10%)

4.0 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well coordinated.
3.5 - Excellent. Good collaboration; partners participate and are well coordinated.
3.0 - Good. Collaboration exists; partners are fairly well coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.
1.0 - Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. Note: if a project has ended, please leave blank. (Weight = 10%)

4.0 - Outstanding. Sharply focused on critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

List of Projects Presented but Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
PD-038	Fermentation and Electrohydrogenic Approaches to Hydrogen Production	Pin-Ching Maness	National Renewable Energy Laboratory
PD-048	Electrochemical Hydrogen Compressor	Ludwig Lipp	FuelCell Energy, Inc.
PD-095	Improving Cyanobacterial Oxygen Tolerance Using CBS Hydrogenase for Hydrogen Production	Pin-Ching Maness	National Renewable Energy Laboratory
PD-098	Low-Noble-Metal-Content Catalysts/Electrodes for Hydrogen Production by Water Electrolysis	Katherine Ayers	Proton OnSite
PD-100	700 bar Hydrogen Dispenser Hose Reliability Improvement	Kevin Harrison	National Renewable Energy Laboratory
PD-118	New Metal Oxides for Efficient Hydrogen Production via Solar Water Splitting	Yanfa Yan	University of Toledo
PD-119	National Science Foundation/U.S. Department of Energy Solar Hydrogen Fuel: Engineering Surfaces, Interfaces, and Bulk Materials for Unassisted Solar Photoelectrochemical Water Splitting	Tom Jaramillo	Stanford University
PD-120	Accelerated Discovery of Advanced Redox Materials for Solar Thermal Water Splitting to Produce Renewable Hydrogen	Charles Musgrave	University of Colorado Boulder
PD-121	Tunable Photoanode-Photocathode-Catalyst Interface Systems for Efficient Solar Water Splitting	G. Charles Dismukes	Rutgers University
PD-122	Hydrogen Production from Continuous-Flow Bioelectrochemical Systems Treating Fermentation Wastewater	Bruce Logan	Pennsylvania State University
PD-123	High-Performance, Platinum-Group-Metal-Free Membrane Electrode Assemblies through Control of Interfacial Processes	Katherine Ayers	Proton OnSite
PD-124	Solid-Oxide-Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density and Efficiency	Randy Petri	Versa Power Systems
PD-125	Tandem Particle-Slurry Batch Reactors for Solar Water Splitting	Shane Ardo	University of California, Irvine

Project ID	Project Title	Principal Investigator Name	Organization
PD-126	Compressorless Hydrogen Refueling Station Using Thermal Compression	Ted Barnes	Gas Technology Institute
PD-127	Sweet Hydrogen: High-Yield Production of Hydrogen from Biomass Sugars Catalyzed by In Vitro Synthetic Biosystems	Y-H Percival Zhang	Virginia Tech
PD-128	2014–2016 H2 Refuel H-Prize	Jeff Serfass	Hydrogen Education Foundation
ST-007	Chemical Hydrogen Rate Modeling, Validation, and System Demonstration	Troy Semelsberger	Los Alamos National Laboratory
ST-009	Testing, Modeling, and Evaluation of Innovative Hydrogen Storage System Designs	Mei Cai	General Motors
ST-014	Hydrogen Sorbent Measurement Qualification and Characterization	Phil Parilla	National Renewable Energy Laboratory
ST-047	Development of Improved Composite Pressure Vessels for Hydrogen Storage	Norman Newhouse	Hexagon Lincoln
ST-067	Neutron Characterization in Support of the U.S. Department of Energy Hydrogen Storage Sub-Program	Terry Udovic	National Institute for Standards and Technology
ST-095	Hawaii Hydrogen Carriers: Low-Cost Metal Hydride Hydrogen Storage System for Forklift Applications (Small Business Innovation Research Phase II)	Craig Jensen	University of Hawaii
ST-103	Hydrogen Storage in Metal-Organic Frameworks	Jeffrey Long	Lawrence Berkeley National Laboratory
ST-104	Novel Carbon-Boron-Nitrogen-Containing Hydrogen Storage Materials	Shih-Yuan Liu	Boston College
ST-110	Optimizing the Cost and Performance of Composite Cylinders for Hydrogen Storage Using a Graded Construction (Small Business Innovation Research Phase II)	Andrea Haight	Composite Technology Development
ST-119	High-Capacity Hydrogen Storage Systems via Mechanochemistry	Vitalij Pecharsky	Ames Laboratory
ST-120	Design and Synthesis of Materials with High Capacities for Hydrogen Physisorption	Brent Fultz	California Institute of Technology

Project ID	Project Title	Principal Investigator Name	Organization
ST-121	High-Capacity and Low-Cost Hydrogen-Storage Sorbents for Automotive Applications	Hong-Cai (Joe) Zhou	Texas A&M University
ST-122	Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections	Don Siegel	University of Michigan
ST-126	Conformable Hydrogen Storage Coil Reservoir	Erik Bigelow	Center for Transportation and the Environment
BES-001	Complex Hydrides – A New Frontier for Future Energy Applications	Vitalij Pecharsky	Ames Laboratory
BES-002	Elucidation of Hydrogen Interaction Mechanisms with Metal-Doped Carbon Nanostructures	Ragaiy Zidan	Savannah River National Laboratory
BES-003	Activation of Hydrogen under Ambient Conditions by Main Group Molecules	Philip Power	University of California, Davis
BES-004	Elucidation of Hydride Interaction Mechanisms with Carbon Nanostructures and the Formation of Novel Nanocomposites	Pura Jena	Virginia Commonwealth University
FC-049	Open-Source Performance and Durability Model: Consideration of Membrane Properties on Cathode Degradation	David Harvey	Ballard
FC-083	Optimal Stationary Fuel Cell Integration and Control	Genevieve Saur	National Renewable Energy Laboratory
FC-085	Synthesis and Characterization of Mixed-Conducting Corrosion-Resistant Oxide Supports	Vijay Ramani	Illinois Institute of Technology
FC-086	Development of Novel Non-Platinum-Group-Metal Electrocatalysts for Proton Exchange Membrane Fuel Cell Applications	Sanjeev Mukerjee	Northeastern University
FC-088	Development of Ultra-Low Doped-Platinum Cathode Catalysts for Polymer Electrolyte Membrane Fuel Cells	Branko Popov	University of South Carolina
FC-105	Novel Structured Metal Bipolar Plates for Low-Cost Manufacturing	C.H. Wang	TreadStone Technologies, Inc.
FC-117	Ionomer Dispersion Impact on Polymer Electrolyte Membrane Fuel Cell and Electrolyzer Durability	Hui Xu	Giner, Inc.
FC-128	Facilitated Direct Liquid Fuel Cells with High-Temperature Membrane Electrode Assemblies	Emory DeCastro	Advent Technologies, Inc.

Project ID	Project Title	Principal Investigator Name	Organization
FC-129	Advanced Catalysts and Membrane Electrode Assemblies for Reversible Alkaline Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC-130	Development of Non-Platinum-Group-Metal Catalysts for Hydrogen Oxidation Reaction in Alkaline Media	Alexey Serov	University of New Mexico
FC-131	New-Generation P+ Cation for High-Voltage Redox-Flow Batteries	Yushan Yan	University of Delaware
FC-132	Innovative Non-Platinum-Group-Metal Catalysts for High-Temperature Polymer Electrolyte Membrane Fuel Cells	Sanjeev Mukerjee	Northeastern University
FC-133	Non-Platinum-Group-Metal OER/ORR Catalysts for Alkaline Membrane Fuel Cells and Electrolyzers	Nemanja Danilovic	Proton Energy Systems
FC-134	Non-Precious-Metal Bifunctional Catalysts	Paul Matter	pH Matter, LLC
MN-012	Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cell Technologies	Pat Valente	Ohio Fuel Cell Coalition
MN-013	Fuel Cell and Hydrogen Opportunity Center	Alleyn Harned	Virginia Clean Cities at James Madison University
MN-014	U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competiveness Analysis	Patrick Fullenkamp	GLWN – Westside Industrial Retention & Expansion Network
TV-016	Stationary Fuel Cell Evaluation	Genevieve Saur	National Renewable Energy Laboratory
TV-024	California State University, Los Angeles, Hydrogen Refueling Facility Performance Evaluation and Optimization	David Blekhman	California State University, Los Angeles
TV-031	Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation	Robert Hovsapian Kevin Harrison	Idaho National Laboratory National Renewable Energy Laboratory
MT-018	Demonstration and Deployment of a Fuel Cell-Electric Refuse Truck for Waste Transportation	Abas Goodarzi	US Hybrid
ARPA-E-02	A Novel Intermediate-Temperature Fuel Cell Tailored for Efficient Utilization of Methane	Meilin Liu	Georgia Tech

Project ID	Project Title	Principal Investigator Name	Organization
ARPA-E-03	Medium-Temperature Oxygen-Conducting Fuel Cell Based on a Novel Membrane Structure	Ashish Pattekar	PARC
ARPA-E-04	Nanocomposite Electrodes for a Solid Acid Fuel Cell Stack Operating on Reformate	Tom Zawodzinski	Oak Ridge National Laboratory
ARPA-E-05	Low-Temperature Solid Oxide Fuel Cells for Transformational Energy Conversion	Bryan Blackburn	Redox Power Systems
ARPA-E-07	Direct Hydrocarbon Fuel Cell-Battery Hybrid Electrochemical System	Masaru Tscuchiya	SiEnergy
ARPA-E-08	Fuel Cells with Dynamic Response Capability Based on Energy Storage Electrodes with Catalytic Function	Yunfeng Lu	University of California, Los Angeles
ARPA-E-09	A Novel Intermediate-Temperature Bifunctional Ceramic Fuel Cell Energy System	Kevin Huang	University of South Carolina
ARPA-E-10	Development of an Intermediate-Temperature Metal-Supported Proton-Conducting Solid Oxide Fuel Cell Stack	Dave Tew	United Technologies Research Center
ARPA-E-11	Intermediate-Temperature Hybrid Fuel Cell System for the Conversion of Natural Gas to Electricity and Liquid Fuels	Ted Krause	Argonne National Laboratory
ARPA-E-12	Dual Mode Intermediate-Temperature Fuel Cell: Liquid Fuels and Electricity	Carl Willman	FuelCell Energy
ARPA-E-14	Intermediate-Temperature Proton-Conducting Fuel Cells for Transportation Applications	Elango Elangovan	Ceramatec
ARPA-E-15	Methane to Methanol Fuel: A Low-Temperature Process	Chinbay Fan	Gas Technology Institute

2015 Annual Merit Review Survey Questionnaire Results Summary

Following the 2015 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) Annual Merit Review (AMR), all participants were asked for feedback on the review process and meeting logistics. This appendix summarizes the results of that feedback and is organized by type of respondent, as follows:

1. All Respondents
2. Responses from "Attendee, neither Reviewer nor Presenter"
3. Responses from Reviewers
4. Responses from Presenters

1. All Respondents

1.1. What is your affiliation?

	Number of Responses	Response Ratio
U.S. federal government	23	13.5%
National/government laboratory, private sector, or university researcher whose project is under review	24	14.1%
Non-government institution that received funding from the office or sub-program under review	42	22.9%
Non-government institution that does not receive funding from the office or sub-program under review	31	18.2%
Government agency (non-federal, state, or foreign government) with interest in the work	1	<1%
National/government laboratory, private sector, or university researcher not being reviewed	20	11.7%
Other	18	10.5%
No Responses	11	8.2%
Total	170	100%

"Other" Responses

- *From three respondents:* Reviewer
- *From two respondents:* Retired
- *From two respondents:* Contractor
- Consultant to the Vehicle Technologies Office (VTO) and Reviewer
- Consultant
- Engineering Consultant
- Battery Maker
- European Institution
- Foreign Research Institute
- Hydrogen Safety Panel
- Japanese Funding Agency
- Non-Government about to Receive Funding
- Non-Profit
- Public Company

1.2. Purpose and scope of the Annual Merit Review were well defined by the Joint Plenary Session (answer only if you attended the Joint Plenary on Monday).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	1	10	48	48
3%	1%	9%	44%	44%

15 Comments

- Grouping reviews according to the project topic is more efficient and effective from a time standpoint. This helps minimize the reviewers' cost to attend and optimize their time.
- The purpose and scope were very well defined by the speakers at the Joint Plenary at the onset of the meeting, thus setting the stage for the meeting's objectives.
- Having Senator Dorgan speaks volumes on where the two programs are going in terms of impact, especially the Fuel Cell Technologies Office (FCTO).
- The presentations were interesting, in particular the one from Senator Dorgan.
- The purpose and scope of the AMR were very clear.
- It provided an excellent overview.
- Some (not all) were very inspiring speakers, which set the scope appropriately for the AMR.
- In general, it was very good; there was too much talk about limited-access and unproven fuel cell vehicles—it is nice to know that it is coming, but there are still very low numbers available.
- The scope of the sub-programs is well presented. The scope of the review is, however, not clear. One hopes that it is clear to the reviewers.
- The high-level talks are somewhat interesting but do not add all that much to the reviewer's ability to review the overall programs.
- *From five respondents:* This individual did not attend the Joint Plenary Session.

1.3. The two plenary sessions after the Joint Plenary Session were helpful to understanding the direction of the Hydrogen and Fuel Cells and Vehicle Technologies Programs (answer only if you attended either the Hydrogen and Fuel Cells or Vehicle Technologies plenary sessions on Monday).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	0	12	60	37
3%	0%	11%	54%	33%

16 Comments

- This new way of doing plenary sessions is highly appreciated because it allows attendees to have access to the main results of the different programs. Please continue like that.
- The plenary talks are useful in showing the scope of the various sub-programs in VTO.
- Making the plenary presentations available on the USB flash drive will be valuable.
- Very informative overviews by FCTO staff.
- They provided an excellent overview.
- Both sessions were good.
- They laid out the programs and issues well—the only problem was that most presentations really had to cram in a lot in a short amount of time.

- Speakers often had too much text in their slides that was glossed over. Perhaps fewer examples that are explained or put in context would be better.
- Presentations should be more concise, should talk about information that is not online, and do not have to highlight what will be described later.
- There was a lot of repetition between these presentations and session presentations.
- *From six respondents:* This individual did not attend the plenary sessions.

1.4. The sub-program overviews were helpful to understanding the research objectives (answer only if you attended one or more sub-program overviews).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
3	1	5	68	56
2%	1%	4%	51%	42%

16 Comments

- Sub-program overviews are one of the most valuable aspects of the AMR.
- Very well done and informative. Just enough information was presented to grasp sub-programs, goals, progress, and challenges.
- This new way of doing plenary sessions is highly appreciated because it allows attendees to have access to the main results of the different sub-programs. Please continue like that.
- The sub-program overview provided a good sense of the resources and objectives that are assigned to the different DOE agencies involved in the relevant research and development (R&D) areas.
- Informative sub-program review sessions—most sub-programs are doing well on appropriate research areas.
- Very good overview of the Fuels and Lubricants sub-program.
- The updates on program progress are very useful for people outside of the program.
- They provided a good overview of goals and milestones.
- They were very nicely done.
- They were useful.
- The objectives of each project are outlined in the project report. How such objectives meet the program scope is less clear in the presentations.
- Unfortunately, the plenary would be better at the start of each session. This is true for the crosscut sub-programs within FCTO.
- The DOE slides were overly complicated and contained too much text. It was difficult to see.
- They were not very helpful.
- *From two respondents:* This individual was not able to attend.

1.5. What was your role in the Annual Merit Review? Check the most appropriate response. If you are both a presenter and a reviewer and want to comment as both, complete the evaluation twice, once as each.

	Number of Responses	Response Ratio
Attendee, neither Reviewer nor Presenter	92	54%
Presenter of a project	34	20%
Peer Reviewer	39	23%
No Responses	5	3%
Total	170	100%

2. Responses from “Attendee, neither Reviewer nor Presenter”

2.1. The quality, breadth, and depth of the following were sufficient to contribute to a comprehensive review:

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Presentations	0	1	6	53	24
	0%	1%	7%	63%	29%
Question and answer periods	0	2	8	54	19
	0%	2%	10%	65%	23%
Answers provided to programmatic questions	0	1	13	54	14
	0%	1%	16%	66%	17%
Answers provided to technical questions	0	1	4	55	22
	0%	1%	5%	67%	27%

8 Comments

- A lot of data was included in some presentations, and it could not be covered in the time available. This seems a necessary compromise, however.
- Presentations from industry do not have much detail, which compromises the benefit of the taxpayer money spent. Specifically, for the SuperTruck program, as well as the ATP-LD program, all that was given were the percentage numbers and a list of technologies. There are no details that can be transferred within the whole industry. So the company got most of the benefit of funding.
- The presentation template inhibited some presenters from covering their topic in sufficient detail (e.g., having to comment on reviewer questions from the prior year).
- Of course there are some gray areas that could not be specifically answered in the programmatic questions. There is a certain level of uncertainty about the funding and its allocation.
- Out of necessity, the presenters share very little, if any, business-sensitive information.
- “Answers provided to programmatic questions” is a “Disagree” because there was not an opportunity to ask these questions in some tracks.
- Some presentations did not have questions from the reviewers or audience members.
- Could use more time for question and answer (Q&A) for a number of talks.

2.2. Enough time was allocated for presentations.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	5	6	57	15
0%	6%	7%	69%	18%

6 Comments

- It depended on the presentation—the time allotted was balanced.
- It depends on the topics. A longer time is necessary for automotive projects and/or highly funded (i.e., >$3 million) projects. For specific topics (e.g., development of materials), it is enough.
- Twenty minutes is a bit short. Thirty minutes plus questions might be better.
- Several people were cut off. Perhaps five more minutes would suffice.

- Most presentations could have used some additional time.
- The schedule was too tight.

2.3. The questions asked by reviewers were sufficiently rigorous and detailed.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
1	3	17	45	16
1%	4%	21%	55%	20%

6 Comments

- The reviewers cannot—because of their limited expertise and number—cover all possible topics. It is OK to give the reviewers priority to ask questions, but there should be some time “guaranteed” for questions from the general audience. Questions from the general audience should be also formally documented, like the questions from the reviewers. Both the presenters and the reviewers benefit from the questions from the general audience.
- Some reviewers were not very familiar with the field of work being reviewed.
- It seems that a few reviewers never ask questions and are not well qualified to review the topics.
- The questions vary over a wide range of rigor and detail.
- The quality of the question depended very much upon the reviewer.
- Some projects did not get questions.

2.4. The frequency (once per year) of this formal review process for this Office or Program is:

	Number of Responses	Response Ratio
About right	78	46%
Too frequent	5	3%
Not frequent enough	0	0%
No opinion	0	0%
No Responses	87	51%
Total	170	100%

3 Comments

- DOE could consider every other year for this review, with smaller or more targeted or virtual reviews in the other years. This might also allow for other venues or locations, or co-locating with other conferences.
- The projects that have not been working for more than a year should not present. There is typically not enough to report or the teams do not have enough time to draw tentative conclusions on the results.
- Confirming annual progress is important.

2.5. Logistics, facilities, and amenities were satisfactory.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	2	7	35	39
2%	2%	8%	41%	46%

17 Comments

- *From three respondents:* Walking back and forth between buildings is tedious and makes it difficult to hear all the talks of interest. It makes more sense to have VTO in one hotel and FCTO in another.
- The location of the rooms was particularly practical—they were very close to one another so that having a lot of meetings was possible.
- Very well run and organized.
- Breakfast was first-class.
- Meals were satisfactory.
- The hotel was booked, but there were enough other hotels in the area that walking to the AMR was possible.
- The Crystal City hotel was not an appropriate venue. The salons were too small and cramped; during the more popular sessions, there were often people standing. The hotel did not have adequate air conditioning, and the lunch sessions had to be streamed to other facilities. The hotel and general area are perfect for the VTO AMR.
- In the J&K salon where the plenary was held on Tuesday, the podium was back against the wall. The speakers could not see their slides or use the laser pointer effectively. There was no back row, so folks had to cross in front to find a seat. One gentleman tripped on backpacks, etc., crossing in the front, and he fell down. Seats were jammed together like in an airplane, so one could not sit up straight. It is questionable whether the fire marshal would approve. Noise in the hall behind the ballroom was distracting.
- The configuration in the room for the fuel cell track did not initially provide enough aisle space to allow for easy access in and out. This was fixed later in the conference with the removal of a back row of chairs.
- One should be able to register at either hotel (Marriott or Marriott Gateway). This attendee had to register at one hotel and run to the other hotel to listen to the first talk.
- At the luncheon, it was sometimes difficult to hear speakers with the noise generated by a number of attendees in the room.
- The daily rate for hotel accommodation is too high to be accepted as affordable.
- The temperature was set too low, which wastes energy.
- The plenary rooms were very hot and humid.
- The lunches were bad.

2.6. The visual quality of the presentations was adequate. I was able to see all of the presentations I attended.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
2	8	8	38	29
2%	9%	9%	45%	34%

15 Comments

- *From four respondents:* Presenters continue to use too many words and put too many graphs on one slide. Graphs were frequently illegible. The template requires too many words. Presenters should be required to provide graphs and text at a minimum font size of 18 or 20 points. It was hard to see from the back of the meeting room. One had to choose between listening to the speaker and reading the text. A new template is required. General guidance in making AMR slide formatting is recommended.
- *From three respondents:* The screens should be raised; otherwise, only those in the first few rows can see the slides easily.
- For the most part. Having the thumb drive was helpful because one could view the presentation on one's notebook computer.
- All the information technology (IT) parts of the presentation worked very well.
- The presentation format is great.
- The sessions had adequate quality; the lunch presentations in the Crystal City hotel were not adequate.
- DOE should forbid red font on a blue background on the slides. It is impossible to read.

- There were occasional issues with pulling up presentations in the session rooms.
- The rooms were huge, the presentations contained too much information, and the text was too small.
- For the size of the rooms, the screen was small, and certain elements were not quite easily visible.

2.7. The audio quality of the presentations was adequate. I was able to hear all the presentations I attended.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	4	42	36
0%	1%	5%	51%	43%

5 Comments

- Microphones are quickly delivered to the people questioned.
- This was only a problem when one or two of the speakers did not speak clearly, but this was not the fault of the audio equipment.
- This participant did not hear any presentations with audio.
- Noise issues outside of the session rooms need to continue to be monitored and addressed. A large number of people were mingling, and hotel staff were making significant noise in access halls behind the plenary room.
- Sometimes it was difficult to hear clearly.

2.8. The meeting hotel accommodations (sleeping rooms) were satisfactory.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	17	31	25
0%	0%	23%	42%	34%

14 Comments

- *From six respondents:* This participant did not stay at the hotel.
- *From three respondents:* The hotel was very expensive, even at the conference rate.
- Excellent hotel; with the conference rates, it was also a good value for the price (for Washington).
- The conference planner was very helpful, even when this attendee booked a hotel room after the deadline.
- It was too expensive for the value, and there were a few issues with the room that one would not have expected for the price. This participant would have been willing to be further out of town for more economical accommodations, although having a large enough facility is obviously key.
- The hotel rooms were fine. But the Crystal hallway in front of the meeting rooms was very hot—it was uncomfortable for meeting/talking.
- Except the restroom.

2.9. The information about the Review and the hotel accommodations sent to me prior to the Review was adequate.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	11	43	27
0%	0%	14%	53%	33%

4 Comments

- When this participant registered the contingent was already exhausted, but the conference manager was extremely helpful and took care very efficiently so that the participant could still get the rate.
- Very well organized, good job.
- A “conference bag” to hold all the materials throughout the review would have been helpful.
- The hotel information was sent a bit late this year.

2.10. What was the most useful part of the review process?

52 Responses

- *From six respondents:* The technical presentations.
- *From five respondents:* Networking.
- *From five respondents:* The presentations, feedback, and Q&A.
- *From three respondents:* The Q&A.
- *From two respondents:* Plenary session.
- *From two respondents:* Poster sessions. This time was the most effective for learning and networking. It was helpful to speak to the presenters one-on-one as well as mingle informally with the other attendees.
- The detailed breakout sessions; both presentations and poster sessions.
- Hearing the technical progress made by the various teams and hearing the questions the presentations provoked from the reviewers and others.
- Hearing experts (reviewers or audience) pose pointed questions.
- Attending the oral presentations and interacting with principal investigators (PIs) and reviewers.
- Technical content and interactions with peers.
- The presentation of project results in a concise 20-minute presentation is very useful.
- Access to the presentation material (including the technical backup slides) is the most important part of the review process. The verbal presentations by the PIs are a close second.
- Presentation materials provided on a USB memory stick.
- The memory stick of the presentations and the spreadsheet references are very helpful. The plenary sessions helped one to calibrate on the vision and priorities of DOE.
- It was useful to learn about the status and progress of all the projects being funded by FCTO and VTO, as well as the challenges/hurdles being faced by them.
- Gaining a better understanding of the type of projects being funded was useful, as was learning about future development needs that this participant’s company may be able to support.
- Awareness of all R&D funding recipients, national laboratories’ role, and funding levels. Technical progress is very valuable.
- The ability to see the program portfolio and provide interactions between projects that would normally not communicate is useful.
- It was very helpful to see other ongoing research in the area of lubricants, in particular.
- The review provides an opportunity to obtain external feedback on projects.
- Learning about the state of the art among various research groups. The plenary session.
- In-depth questioning with on-site personnel.
- Engaging with the technical experts.

- Being able to talk directly to the project leads.
- The ability to see the status of multiple projects in a short period of time. It is very time efficient.
- The timelines, objectives, and published deliverables.
- The overview of ongoing R&D and the networking.
- The open style of reviewing.
- Electrochemical storage.
- The overview and plenary sessions.
- The overview session.
- Briefings.
- Staying current.
- The reviews were helpful, but there should be more networking time to speak to the different presenters because Q&A is limited. The presenters do not always stick around for the breaks.

2.11. What could have been done better?

43 Responses

- *From eight respondents:* No comments. The event was satisfying.
- *From three respondents:* The presentations from the introductory and plenary sessions should be included on the USB.
- The plenary session needs to be reenergized. Talks are covering much ground covered in previous years with slides that are too detailed—this is great for review offline but not for a live audience. Senator Dorgan's talk was excellent.
- Less time introducing projects and overviews, more technical details and indicators of progress.
- More time on technical progress, less on administrative slides.
- Perhaps an exhibit of the device/technology—an example room or demonstration of a prototype selected by reviewers as the best from the last review.
- More commercial discussion about these projects would be helpful in expediting technology-to-market.
- Laboratory projects occupy prime presentation time. Industry projects, which are orders of magnitude greater in funding and actually get the technology being funded into consumer hands, were tacked on at the end when attendance was poor—late Thursday and early Friday when attendees were trying to get home.
- It seems like the few Friday presentations could have been held on an earlier day(s) to avoid a few people having to stay an extra day.
- The whole event could be condensed to four days, Monday to Thursday.
- Some talks were reviewed although the work was not even started. That should stop.
- Better seating. Attendees were seated too close together, literally rubbing elbows with the person seated adjacent.
- A little bit more space for coffee breaks was needed. It was quite difficult to find the person this participant wanted to talk to because there were so many people in a limited space.
- The luncheons are a disaster. A perfect time for networking is lost, all in the name of having a "working lunch." The current format is stressful and unproductive. It would be better to pay for lunch and meet new people.
- During lunch, the tables should carry a jar of water in case anyone needs to drink more without inconveniencing the serving staff, who are already busy enough.
- This participant brought this up at last year's AMR: It is disappointing that in this day and age, there was not recycling provided. For example, outside of the meeting rooms, during breaks, there were plenty of bottled and canned drinks, but no recycling. It is not good for the earth, and the wrong message is being sent. One hopes next year is better.
- Beverage stations during breaks were too close to the main ballrooms, which led to congestion from too many people. It was too loud to hear anyone.
- Post answers to questions that were asked after the session ended because of time constraints (presenters may choose which ones to post based on how useful the answers may be in terms of clarifying to the technical community certain key information).

- It would be better to have a smaller but more focused review on each subject matter to facilitate more discussions as a group and provide more free flow of interactions among the stakeholders and their peers.
- For those interested in more than one topic (e.g., hydrogen production and fuel cells), the parallel arrangement of the talks is not ideal. Because of the number of talks, this is probably difficult to resolve.
- Create a clear objective statement and be honest about whether the project is meeting it and whether it is going to be a relevant technology.
- Provide more detail on the program, title, and affiliation of the presentation.
- The AMR schedule should be available online rather than just in paper form to allow people to set up their personal review schedule for the week. One possible app is Guidebook.
- Perhaps links could be provided to a summary slide ahead of the AMR to help attendees decide on session priorities. Perhaps this could be made available ahead of the registration process when the memory sticks are distributed.
- Guaranteed time for questions from audience—at least 3 of the 10 minutes.
- Improve the visual quality of the presentations and set the meeting room temperature at about 75°F.
- Please keep the temperature higher during the presentations. Thank you.
- Duplicate registration desks.
- Networking with a board industry group.
- Some of the reviewers should come from an economic perspective and/or social (media).
- Conference locations were a little too far apart. It was difficult to see Advanced Powertrain Technologies and make it back to see Thermal Presentations.
- Keep VTO sessions in one hotel.
- No working lunch.
- Lunch and coffee breaks.

2.12. Overall, how satisfied are you with the review process?

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	7	50	23
0%	0%	9%	63%	29%

3 Comments

- It provided a comprehensive outline of DOE projects.
- It was very beneficial.
- This participant did not hear anyone say that funding decisions would be made based, at least in part, on these presentations/reviews. The quality of the talks is mixed.

2.13. Would you recommend this review process to others, and should it be applied to other DOE programs?

	Number of Responses	Response Ratio
Yes	77	45%
No	5	3%
No Responses	88	52%
Total	170	100%

5 Comments

- There is great value in having projects report out periodically and collecting feedback from qualified reviewers.

- This is the best all-around event.
- It is very key for getting all parties together.
- The review process is still good.
- This is a reasonable forum for the laboratory projects to be reviewed but not for the industry partners.

2.14. Please provide comments and recommendations on the overall review process.

24 Responses

- *From two respondents:* The meeting was well organized.
- The AMR event is fascinating and unique. Although highly technical in nature, it attracts significant interest and participation from industry. Attendees are able to meet with more customers, partners, and collaborators in one event than almost any other event (and definitely more than any other event in the United States).
- The transparent approach to information enables stakeholders to make certain decisions regarding advice given to clients and researchers.
- This review is now the most valuable conference for networking in the fuel cell industry.
- Thanks a lot to the organization committee for its effort.
- This review featured the best time management of presenters ever witnessed at a conference.
- The meeting was informative and well organized.
- The meeting was efficient and transparent.
- It is good that this AMR is open to everyone.
- This participant was not involved in a reviewed project and cannot really comment on this.
- The luncheon speech process was really unpleasant, particularly on Wednesday. The speaker was shouting so the audience continued to speak even louder, so no one could hear anything. Perhaps the luncheon speeches can be eliminated. After all, lots of work gets accomplished during lunch talking to one's seatmates.
- Peer networking is one purpose of the meeting, and lunches should allow for conversation and sharing without other lectures and working sessions, other than awards presentations.
- It is highly recommended that DOE allocate some "guaranteed time" for questions from the audience, while preserving the priority for reviewers. Audience questions are useful for both the presenters and the reviewers.
- It would be good to see more commercial discussions as well as possibly seeking feedback from the industry on the technologies.
- It seems like the few Friday presentations could have been held on an earlier day(s) to avoid a few people having to stay an extra day.
- All VTO projects should be held in one hotel. Too much running through the tunnel was required to see projects.
- Non-DOE people should be charged to support the catering of breakfast, lunch, and poster session snacks.
- Recommend plastic badge covers—this participant's badge got wrinkled/damaged throughout the week.
- One hopes that reviewers are people who are not funded through this program.
- Presentations from the overview sessions should be provided.
- It was not always clear what the review criteria are and how the achievements, completed or failed, are reviewed.
- Additional accountability to the mission and goals initially set would be appropriate.
- It may be better to do a panel discussion to summarize DOE projects.

3. Responses from Reviewers

3.1. Information about the sub-program(s)/project(s) under review was provided sufficiently prior to the review session.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	0	20	14
0%	0%	0%	59%	41%

7 Comments

- All information was provided except for overviews.
- Having one more week for reviewing would be appreciated.
- It might be helpful to have it a little sooner.
- A summary of reviewers' comments from the previous year will also be useful.
- This reviewer did not get the sub-program manager's presentations prior to the meeting, although the project presentations were received.
- One poster was available on PeerNet only a number of hours before the session—the poster was not available during the poster session. Reviewing this poster was, as a result, very difficult.
- No copy of presentation materials was provided either before or during the meeting for one project that this reviewer had to review.

3.2. Review instructions were provided in a timely manner.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	0	14	21
0%	0%	0%	40%	60%

4 Comments

- The reviewer process information was very clear.
- No problem—but this reviewer has been doing it for a number of years.
- Grouping reviews according to the project topic is more efficient and effective from a time standpoint. This helps minimize the reviewers' cost to attend and optimizes their time.
- There were some problems getting the material and video because of internal firewalls.

3.3. The information provided in the presentations was adequate for a meaningful review of the projects.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	3	20	10
0%	3%	9%	59%	29%

7 Comments

- This reviewer has a much better sense of the resources and objectives that are assigned to the different DOE agencies involved in the relevant R&D areas than prior to attending the program overview
- Presenters had difficulty presenting a few of the more complicated projects in the time allotted, but for the most part, information was sufficient.
- Several of the presentations did not provide enough detail for a thorough review. Also, some projects that were reviewed were less than $100,000 in size, and others were several million. The smaller the project, the more sufficient the detail provided. Bigger projects did not have nearly enough information.
- In some cases, the information was perfect, while in others, the information provided by the applicants was weak, was poorly organized, and did not really allow for a complete review of the progress of the work. They were academics who concentrated too much on the technical details and not enough on the management aspects of the work, which is key.
- It would be useful if what was presented as future work from the previous year was used as a basis for the work completed in the current year. There should be a slide from the project's last AMR that says what the team planned to accomplish so that during this AMR they would be able to check off progress—or to understand the challenges that need to be overcome to achieve the planned accomplishments. (This approach works only for multiyear projects.)
- The required format of the presentations puts far too much emphasis on the approach and collaboration sections—both are important, but evaluating the results and their relevance to DOE goals is of highest value and should receive more time.
- In some cases not enough was provided, but that is typical for industry-based development-type projects.

3.4. The evaluation criteria upon which the review was organized (see below) were clearly defined.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	0	1	20	15
	0%	0%	3%	56%	42%
Approach	0	0	0	18	16
	0%	0%	0%	53%	47%
Technical Accomplishments and Progress	0	1	2	17	14
	0%	3%	6%	50%	41%
Collaboration and Coordination	0	1	1	18	14
	0%	3%	3%	53%	41%
Proposed Future Research	0	0	2	19	12
	0%	0%	6%	58%	36%
Resources (for Vehicle Technologies Office Projects)	0	2	6	14	7
	0%	7%	21%	48%	24%
Strategy for Technology Validation or Deployment (for Market Transformation and Technology Validation Projects)	0	1	12	10	6
	0%	3%	41%	34%	21%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential (for Technology Integration/Clean Cities Projects)	0	1	8	11	6
	0%	4%	31%	42%	23%

4 Comments

- All were very well defined; the issue was that some applicants simply ignored the guidelines, and this was reflected in this reviewer's evaluations of their work.

- Resources and the assessment of resources were not clearly quantified in the respective presentations that this reviewer attended. Also, the impact on petroleum reduction was not quantified, other than just a general statement indicating that petroleum consumption will be reduced.
- Very few PIs mention whether resources are sufficient—there is not much incentive for them to raise this issue, because insufficiency is a negative in scoring. Plus, this might not be the forum for the PIs to raise this to the technology managers.
- This reviewer does not recall the last two criteria being mentioned in the reviews.

3.5. The evaluation criteria were adequately addressed in the presentations.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	0	1	19	15
	0%	0%	3%	54%	43%
Approach	0	1	1	16	16
	0%	3%	3%	47%	47%
Technical Accomplishments and Progress	0	1	2	14	17
	0%	3%	6%	41%	50%
Collaboration and Coordination	1	2	3	16	13
	3%	6%	9%	46%	37%
Proposed Future Research	0	2	4	14	11
	0%	6%	13%	45%	35%
Resources (for Vehicle Technologies Office Projects)	0	3	6	16	5
	0%	10%	20%	53%	17%
Strategy for Technology Validation or Deployment (for Market Transformation and Technology Validation Projects)	0	2	13	8	5
	0%	7%	46%	29%	18%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential (for Technology Integration/Clean Cities Projects)	0	2	11	7	6
	0%	8%	42%	27%	23%

7 Comments

- Many projects were ending soon, so future research discussions were limited to work left to complete. A few mentioned follow-on work suggestions, but that was rare. Again, the focus at the AMR is on the specific project and completion of required activities, while future efforts are not that much of a priority at this venue. Perhaps they should be.
- The proposed future research areas were generally only a couple of lines with high-level task descriptions—this is not enough detail for one to judge accurately.
- In some presentations, only a given part of the results has been presented. A general status of all the work done should be given, at least in the Reviewer slides.
- More focus on accomplishments and progress and less on the softer items would be much more valuable for reviewing the projects.
- The range varied between individual presentations; some were more thorough than others. Most made an effort to address how their projects were addressing the criteria for evaluation.
- Very often the “barriers” quoted in the presentations were quite often not “barriers” but goals/objectives.
- These ratings apply only to *some* of the projects this reviewer reviewed.

3.6. The right criteria and weightings were used to evaluate the project(s)/sub-program(s).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance/Potential Impact	0	0	5	16	12
	0%	0%	15%	48%	36%
Approach	0	1	3	17	12
	0%	3%	9%	52%	36%
Technical Accomplishments and Progress	0	1	3	17	12
	0%	3%	9%	52%	36%
Collaboration and Coordination	0	1	4	16	11
	0%	3%	13%	50%	34%
Proposed Future Research	0	0	5	17	10
	0%	0%	16%	53%	31%
Resources (for Vehicle Technologies Office Projects)	0	0	6	14	9
	0%	0%	21%	48%	31%
Strategy for Technology Validation or Deployment (for Market Transformation and Technology Validation Projects)	0	1	13	4	8
	0%	4%	50%	15%	31%
Alternative Fuel Market Expansion and/or Petroleum Reduction Potential (for Technology Integration/Clean Cities Projects)	0	0	12	7	6
	0%	0%	48%	28%	24%

7 Comments

- The criteria and weightings seemed reasonable.
- Most criteria/weightings seemed fine, except for a few issues.
- It is difficult for a reviewer to judge whether the weightings were appropriate—this is more related to the relative importance to DOE.
- This reviewer did not pay any attention to the weightings.
- Technology validation or deployment does not seem to have the required emphasis and weightings.
- The basis/criteria used for proposed future work was unclear.
- One of this reviewer's reviewed presentations (ST-116) was not for vehicles but for other types of applications. The presentation did not clearly indicate this fact, resulting in some confusion on what target parameters (e.g., costs) were relevant.

3.7. During the Annual Merit Review, reviewers had adequate access to the Principal Investigators.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	0	19	15
0%	3%	0%	54%	43%

4 Comments

- This is a particularly valuable element of the AMR.
- Access was OK.

- The poster session was very busy and extremely noisy—this participant did not have sufficient time to talk with the PI, who was constantly distracted/interrupted by others. In general, one had to wait to talk with the PI, and there was always a queue formed, making the discussions somewhat "pressured."
- Some PIs had little time for reviewers.

3.8. Information on the location and timing of the projects was adequate and easy to find.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	1	1	13	20
0%	3%	3%	37%	57%

5 Comments

- It was excellent, like every year.
- The team has the system down.
- Frankly, this participant has usually found the schedule to be complex and a little tough to follow and has often made his own. However, this is a very large and complex event, so perhaps there is not anything that can be done about that.
- Once one found the room designations.
- The crosscut infrastructure session for FCTO was not advertised correctly and probably should not have been in the smaller hotel. Almost all other FCTO projects were in the larger hotel.

3.9. The number of projects I was expected to review was:

	Number of Responses	Response Ratio
Too many	2	1%
Too few	2	1%
About right	31	18%
No Responses	135	79%
Total	170	100%

5 Comments

- It was great overall, and the chair of the session did a superb job of keeping everything flowing along efficiently.
- Four projects seems to be a good number.
- The number of projects assigned to this reviewer is more than normal. This reviewer would not mind doing the reviews but needs more time to complete them.
- This reviewer could have done a few more, but schedule and conflicts made that tough.
- This reviewer did 8 and could have done 10 to 12.

3.10. Altogether, the preparatory materials, presentations, and question and answer period provided sufficient depth for a meaningful review.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	4	18	13
0%	0%	11%	51%	37%

5 Comments

- It was a very good review.
- Yes—the only problem was that some of the presenters did not present what they were asked to.
- It was adequate for the time allotted for the review and the magnitude of projects that were reviewed.
- For the most part, yes.
- Recently, there have been more mandatory slides, such as Response to Reviewers and Collaborations. Therefore, providing a few extra minutes and a few extra slides for the PIs to elaborate on their technical accomplishments would be useful.

3.11. Please provide additional comments.

11 Responses

- This is an excellent platform for DOE, both from an outreach point of view and to get the feedback from non-DOE specialists. This was indeed a well-organized meeting.
- It is an honor and a pleasure to be involved with this excellent process. Thanks so much for including this participant.
- Looking forward to the next AMR.
- Great opportunity to learn about activities—the only problem is too many presentations at once, meaning there can be direct schedule conflicts.
- Not all presentations follow the format suggested, but they supply the information verbally during the presentation. Perhaps it can be made clearer to the presenter that the responses to the evaluation criteria should be included in the presentation in written form.
- While the physical facilities at this location were good, this function should be held within the District of Columbia, which has greater need for the positive economic impact.
- DOE should space out all the presentations by at least five minutes to help allow for (1) the reviewers to change seating and (2) the audience to go to other rooms for different presentations.
- The presentations are becoming too boilerplate to the point that the PIs are not allowed to really show the technical merit of the projects in some cases.
- It was extremely hard to hear what was being said during the lunch presentations—attendees were very rude this year and are getting worse. Perhaps the presentations can be made before the food is served.
- Presentations during the Tuesday/Wednesday lunches did not seem to work well. It is difficult to get and keep the audience’s attention.
- Please provide the program managers’ presentations prior to the meeting if participants are asked to review those presentations.

4. Responses from Presenters

4.1. The request to provide a presentation for the Annual Merit Review was provided sufficiently prior to the deadline for submission.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	1	13	17
0%	0%	3%	42%	55%

4 Comments

- *From three respondents:* The deadline for submission seems early with respect to the meeting. This prevents the project from reviewing progress closer to the meeting, and the material is stale by the time of the AMR.
- Two months beforehand is sufficient.

4.2. Instructions for preparing the presentation were sufficient.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	2	0	12	17
0%	6%	0%	39%	55%

5 Comments

- The instructions were very specific.
- Please consider the trend over the last couple years of continuing to add more and more required slides into the presentation. Presenters still have only 20 minutes, but all these new required slides are cutting down on the time for technical accomplishments, which should always be the meat of the presentation.
- The instructions are very long—the level of detail was great for this participant's first AMR, but after several years, the instructions are just tedious to read. It would be helpful if the organizers also offered a short summary of "what's different this year" so that attendees do not have to reread 70+ slides of instructions every year.
- The instructions were confusing. Without having been to the AMR previously, one would have a hard time knowing exactly what to do given the current instructions. Furthermore, the instructions were onerous to read through.
- The instructions were almost overkill—70 slides of instructions was a lot to wade through (even if most were examples).

4.3. The audio and visual equipment worked properly and were adequate.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

Highly Disagree	Disagree	Neutral	Agree	Highly Agree
0	0	2	11	17
0%	0%	7%	37%	57%

5 Comments

- The audio and visual preparation was excellent and made transitions smooth and easy. This is a rarity among meetings.
- It worked great for preloaded presentations. There were a couple issues with presenters bringing updated slides—this should not have happened.
- This presenter generally likes to use his own laptop for presentations because it is a touch screen, which helps him communicate what is being projected on the screen by drawing on it during the presentation. This presenter is not sure whether the provided laptops were touch screen, but if not, that would be nice.
- Many of the rooms were set up such that the presenter had a very bad angle toward the projection screen; thus, it was hard to use a laser pointer.
- Many speakers had a "reviewers' comments slide." It is unclear whether this was required for the presentation or whether it should be in the backup slides or the reviewer-only slides.

4.4. The evaluation criteria upon which the Review was organized were clearly defined and used appropriately.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	0	0	2	19	9
	0%	0%	7%	63%	30%
Approach	0	1	1	19	9
	0%	3%	3%	63%	30%
Technical Accomplishments and Progress	0	0	2	18	10
	0%	0%	7%	60%	33%
Technology Transfer and Collaboration	0	0	2	18	10
	0%	0%	7%	60%	33%
Proposed Future Research	0	0	1	22	7
	0%	0%	3%	73%	23%

3 Comments

- Having responses to reviewer comments as part of the presentation does not work well. These should be included in the reviewer-only slides or at the end but not directly presented.
- This presenter does not recollect that an emphasis was placed on technology transfer in the slides. Thus, that piece may not have come through as strongly as the others.
- It is sometimes difficult to identify where relevance ends and where approach begins.

4.5. Explanation of the questions within the criteria was clear and sufficient.

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	0	0	2	20	8
	0%	0%	7%	67%	27%
Approach	0	1	1	21	7
	0%	3%	3%	70%	23%
Technical Accomplishments and Progress	0	0	1	21	8
	0%	0%	3%	70%	27%
Technology Transfer and Collaboration	0	0	2	20	8
	0%	0%	7%	67%	27%
Proposed Future Research	0	0	1	22	6
	0%	0%	3%	76%	21%

0 Comments

4.6. The right criteria and weightings were used to evaluate the project(s)/sub-program(s).

The top number is the count of respondents selecting the option. The bottom percentage is the percent of the total respondents selecting the option.

	Highly Disagree	Disagree	Neutral	Agree	Highly Agree
Relevance	0	0	5	18	7
	0%	0%	17%	60%	23%
Approach	0	1	5	18	6
	0%	3%	17%	60%	20%
Technical Accomplishments and Progress	0	0	5	19	6
	0%	0%	17%	63%	20%
Technology Transfer and Collaboration	0	1	7	16	6
	0%	3%	23%	53%	20%
Proposed Future Research	0	0	6	19	5
	0%	0%	20%	63%	17%

2 Comments

- Approach seems underweighted.
- Technology transfer does not always have the same relevance for all projects.

4.7. Please provide additional comments:

7 Responses

- Great meeting. Excellently organized. Providing a flash drive with all the presentations makes life much easier. Thanks for the change from CD to flash drive.
- Clearly a lot of work goes into organizing this review. All the DOE employees and other support personnel should be congratulated for putting together a very good review.
- None. The whole meeting was well done.
- The review uses an effective format for communicating about the project by allowing reviewers and presenters to have back-and-forth communication. It would be nice if the lab call used a similar format to reduce communication issues. Also, the AMR would be much more useful if the comments came back before the lab call submission deadlines.
- The salons that had main entry to the side were set up horribly. The only way to get to the far side was to shove past the reviewers. An aisle from the main entry across the middle of the room would have been exceedingly helpful.
- From past experience, review comments have typically not gotten back to the PIs until about five months after the AMR. It would be much more effective for PIs to receive the review comments one or at most two months after the AMR.
- The only difficulty was in addressing all aspects of each criterion within the allocated page count.