Fuel Cell Technologies – 2024

Fuel Cell Technologies Subprogram Overview

Introduction

Fuel cells efficiently convert the chemical energy of hydrogen or other fuels into electricity and are an important part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future. Fuel cells use a wide range of fuels and feedstocks and can provide power for a variety of applications across multiple sectors. The Fuel Cell Technologies subprogram applies innovative research, development, and demonstration (RD&D) to develop a diverse portfolio of low-cost, durable, and efficient fuel cells that are competitive with incumbent and emerging technologies across applications. Subprogram activities align with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap*.

The subprogram's RD&D strategy is target-driven, with application-specific targets developed to reflect the performance, durability, cost, and scale needed to address end-use requirements. In this holistic approach, the subprogram develops targets based on the ultimate life cycle cost of using fuel cell systems in comparison with other technology options. Guided by analysis and fuel cell system modeling, the subprogram develops and refines targets for emerging and high-impact applications. These include heavy- and medium-duty vehicles, stationary power generation (primary and backup), and reversible fuel cells for long-duration energy storage. The subprogram has also developed fuel cell manufacturing capacity targets to facilitate achieving economies of scale. The subprogram's RD&D emphasis is primarily on heavy-duty applications in which significant reductions in both carbon emissions and criteria pollutant emissions can be achieved. Advances in heavy-duty vehicle fuel cells will also offer transferable benefits for medium-duty and stationary applications.

The subprogram engages in RD&D to overcome critical technical barriers to fuel cell development, including the need to further improve performance and durability and reduce fuel cell cost. The subprogram's balanced and integrated RD&D efforts focus on materials, components, and system integration. RD&D also addresses manufacturing and supply chain challenges to accelerate the commercialization and deployment of fuel cell technologies.

Goals

The Fuel Cell Technologies subprogram's goal is to develop fuel cell technologies that are competitive with incumbent and emerging technologies across diverse applications. Specific objectives of the subprogram include the following:

- Develop fuel cell systems—with emphasis on near-term heavy-duty transportation applications—that are highly durable, efficient, and low-cost, while meeting application-specific constraints such as dynamic response, resilience, packaging, and heat rejection.
- Develop new materials and components for next-generation fuel cell technologies in diverse applications for power generation and long-duration grid-scale energy storage, emphasizing innovative mid- to long-term approaches, including reversible fuel cells and hybrid approaches, such as tri-generation, that can use fuel cells to co-produce power, heat, and fuel.

Key Milestones

The Fuel Cell Technologies subprogram has established the following milestones to achieve by 2030:

- Develop a 68% peak-efficient direct hydrogen fuel cell power system for heavy-duty trucks that can achieve durability of 25,000 hours and be mass-produced at a cost of $80/kW.
- Develop stationary fuel cells that achieve 80,000-hour durability at a cost of $1,000/kW.

- Demonstrate heavy-duty fuel cell manufacturing capacity of 20,000 stacks per year in a single manufacturing system.
- Develop reversible fuel cells for energy storage applications that can achieve 40,000-hour durability and 60% round-trip efficiency at a cost of $1,800/kW.

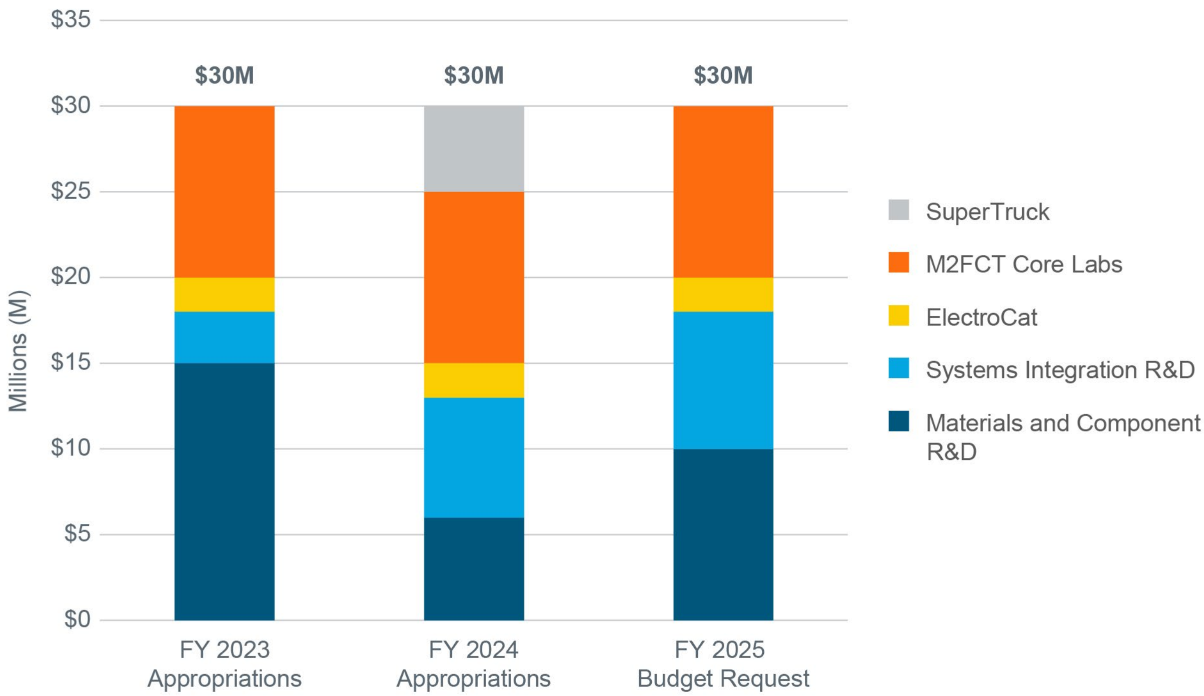
Budget

The Fiscal Year (FY) 2024 appropriation for the Fuel Cell Technologies subprogram was $30 million. In FY 2024, the subprogram funded fuel cell materials and components and systems integration RD&D, with focus on low cost, enhanced durability and efficiency, and a robust supply chain for heavy-duty applications. Funding was also dedicated to the two national laboratory consortia, the Million Mile Fuel Cell Truck (M2FCT) consortium and the ElectroCat (Electrocatalysis) consortium (see the chart below).

Funding for fuel cell materials and component RD&D focused mainly on low-platinum-group-metal (low-PGM) catalysts and membrane electrode assemblies (MEAs), MEAs and stack components with enhanced durability, and PGM-free catalysts and electrodes. Funding for fuel cell systems integration RD&D was dedicated primarily to stacks, balance-of-plant components, and systems analysis.

The Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]) includes $100 million/year for clean hydrogen manufacturing and recycling (Sect. 815). In FY 2024, 16 projects were competitively selected for negotiation with $540 million of total funding to enable 14 GW of fuel cell manufacturing, establish a recovery and recycling consortium for fuel cells and electrolyzers, and strengthen the component supply chain. BIL funding also supported the national-lab-led Roll-to-Roll (R2R) Consortium focused on advancing efficient, high-throughput, and high-quality manufacturing processes for fuel cell and electrolyzer technologies.

The FY 2025 budget request for the Fuel Cell Technologies subprogram is $25 million. Activities planned for FY 2025 include continuing RD&D of low-PGM MEAs (mainly though M2FCT) and PGM-free catalysts and electrodes (ElectroCat), expanding the RD&D efforts on membranes, and meeting durability-adjusted heavy-duty fuel cell cost targets.



Annual Merit Review Results

During the 2024 Annual Merit Review, 55 projects funded by the Fuel Cell Technologies subprogram were presented, and 18 were reviewed (a breakdown of number of projects reviewed by budget category is shown in the table on the right). The reviewed projects received scores ranging from 2.7 to 3.7, with an average score of 3.2. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 18 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Materials and Component R&D	6
Systems Integration	9
ElectroCat	1
M2FCT Core Labs	1
Manufacturing and Recycling	1

Project #FC-160: ElectroCat 2.0 (Electrocatalysis Consortium)

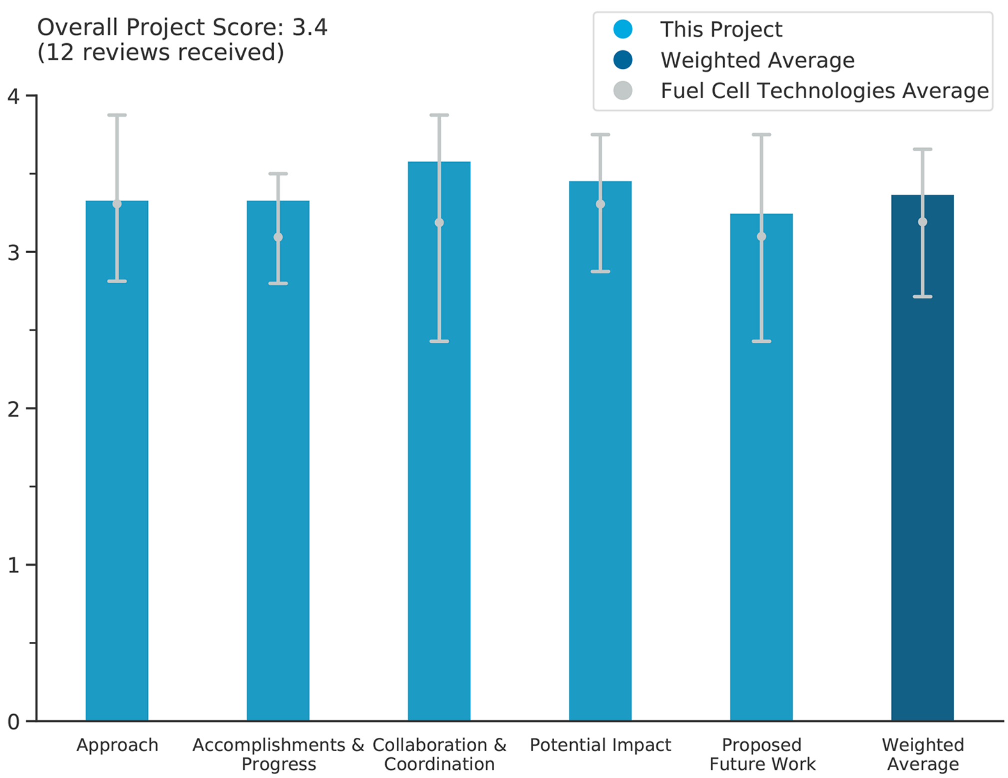
Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory

DOE Contract #	Multiple
Start and End Dates	10/1/2020–9/30/2025
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Cost (catalyst) • Activity (catalyst, membrane electrode assembly) • Durability (catalyst, membrane electrode assembly) • Power density (membrane electrode assembly)

Project Goal and Brief Summary

The Electrocatalysis Consortium (ElectroCat), created as part of the Energy Materials Network, aims to accelerate the development of next-generation catalysts and electrodes that are free of the platinum group metals (PGMs) currently required for good performance and durability of fuel cells and electrolyzers. ElectroCat has focused its efforts on oxygen reduction reaction (ORR) catalysis for proton exchange membrane fuel cells (PEMFCs), as well as the hydrogen and oxygen evolution reactions (HER and OER) for low-temperature electrolyzers. The consortium has established a portfolio of unique synthesis, experimental, characterization, and modeling capabilities to focus on improving catalyst durability and activity. Specifically, ElectroCat is advancing high-throughput catalyst synthesis and characterization capabilities, coupled with machine learning, to achieve durability and activity goals.

Project Scoring



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

Question 1: Approach to performing the work

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

- The ElectroCat team has been working together very effectively for many years and has demonstrated a successful collaborative approach; the team has achieved the vast majority of its quarterly and annual milestones (except for the Data Hub) during the recent review period, with a few on track to be completed, which is impressive and demonstrates a high degree of coordination amongst the team members for both fuel cell and electrolyzer applications. Work is also highly coordinated with goals and research efforts being conducted within other consortia, e.g., Hydrogen from Next-generation Electrolyzers of Water (H2NEW), the HydroGEN Advanced Water Splitting Materials Consortium (HydroGEN), and Million Mile Fuel Cell Truck (M2FCT). The scientific approach is commendable; the team has incorporated many unique, advanced capabilities (the high-throughput synthesis efforts guided by machine learning and density functional theory [DFT] are excellent examples). The safety plan is relatively standard for national labs. The diversity, equity, inclusion, and accessibility plan is pretty “vanilla”; more engagement with Hispanic-serving institutions was expected.
- It is evident that meticulous attention was given to delineating project objectives and addressing critical barriers head-on. The clarity with which objectives were outlined sets a strong foundation for the milestones here completed. The team also had a proactive approach toward recognizing critical barriers, which demonstrates foresight and strategic planning. Moreover, the quality and completeness of the project are commendable. From methodological rigor to comprehensive analysis, every aspect seems thoughtfully considered. This not only enhances the credibility of the research but also augments its potential impact.
- The principal investigators (PIs) among the entire network of national laboratories are executing a well-justified approach in tackling the most challenging topics in electrocatalysis. The PIs implemented cutting-edge characterization tools and rational design of materials that have been evaluated.
- The consortium aims to develop sustainable and inexpensive catalyst technologies for clean hydrogen. Multiple innovative synthesis, characterization, and high-throughput optimization modeling approaches could provide an effective pathway to designing highly efficient catalysts for fuel cells and water electrolyzers.
- Machine learning was used to guide experimental work, which included testing of hundreds of samples over four main categories of catalyst systems. Fuel cell catalyst work is fundamental and a sophisticated blend of computation and experiment. Electrolyzer work is also fundamental and a blend of computation and experiment.
- The project is clearly building on previous results, understanding the limitations and improving results efficiently with appropriate tools.
- The project is focused on advancing PGM-free catalysts for PEMFC cathodes and anion exchange membrane (AEM) electrolyzers, with an emphasis on applying advanced synthesis and characterization.
    - The current strength of the project is the high-throughput synthesis and characterization. The project is establishing a framework that represents a likely future for catalyst discovery, design, and optimization. The use of machine learning in this work is maturing.
    - The fuel cell catalyst development is challenged by the fact that targets are based on fuel cell performance; however, advancing the catalyst into high-performance electrodes is described as being out of the scope of the consortium. As highlighted by the images of ionomer maldistribution and large mass transport losses, there are significant issues with the electrodes.
    - There are promising results with the catalyst development for AEM electrolyzers. One issue with the approach is the characterization of the catalysts and the impact of morphology. It does not appear morphology is being given sufficient attention or characterization. It is unclear how heterogeneous the catalyst particles are within each batch and from batch to batch. The team should consider developing approaches for characterizing electrochemically active surface area (or at least approximations) such that specific activity can be evaluated as the key figure of merit. Currently, morphology will have a dominant impact on mass activity. Using area-specific activity will yield more universal results for catalyst performance that can then be formulated into electrode-optimized morphologies.

- Although PGM-free catalysts are still far from meeting the targets that enable their application in either light- or heavy-duty vehicles, PGM-free catalysts are critical for fuel cell applications in vehicles because of limited PGM resources. It is critical for DOE to continue to support this activity to have at least an alternative for the future catalyst on a low-cost basis.
    - Understanding the project is target-driven, the project needs to have some more in-depth study on the activity and stability of PGM-free catalysts. The current incremental improvement seems to meet the milestones of each year, but the rational approach is more important for this project. For example, the current PGM-free catalyst is Fe-N-C-based. It is unclear what the critical properties are in deciding the activity of the catalyst and whether active site density is one. The strategy to increase the activity is unclear. It is unclear what the root causes of PGM-free catalyst degradation are and whether carbon corrosion or loss of active sites is among the causes. It is unclear what the strategy is to overcome these issues.
- ElectroCat has an effective combination of experiment and both DFT modeling and machine learning to help guide the experimental work for both the fuel cell and electrolysis work. The approach to target a completely PGM-free electrolysis system is commended. The consortium appears to have increased its efforts related to improving durability, which is to be commended. However, the large majority of the ORR work is still focused on Fe-based systems, despite industry concerns about the impact of leached Fe on membrane durability and performance. ElectroCat has some efforts with non-iron systems, but the amount of effort on these systems appears minimal compared to the amount of effort on the Fe-based systems. An increased amount of effort in non-iron ORR catalyst systems seems warranted. It may be beneficial to revisit targets and revise targets based on updated cost analysis with current state-of-the-art (especially for electrolysis, given recent advances in AEM) and projected future components for specific applications of interest.
- Nice progress was made on the Fe-based ORR catalyst development. This is a very difficult subject on which to work, and the team has made some important progress. However, taking a step back, it is very unlikely for Fe-based PGM catalysts to be applied to heavy-duty (HD) truck transportation in the foreseeable future. Using Fe/Co-based ORR catalysts as a support for precious metal catalysts to decrease PGM content is suggested. Good progress has been made on the NiFe-based catalyst for alkaline OER applications and Ni/C HER catalysts, but probably more focus on durability is needed, especially in alkaline membrane electrode assembly (MEA) electrolyzer configurations.
- The rating of 3.0 is given as an average of the two areas: 2.0 for PEMFC and 4.0 for AEM water electrolysis (AEMWE). Both areas used a range of advanced capabilities to accelerate the material discovery, including high-throughput screening, synchrotron techniques, machine learning, etc. Many of the promising candidates were evaluated with relevant tests. The low rating for the PEMFC area is due to the sole focus on the Fe-C-N system, which by itself is unstable in PEMFCs and includes Fe, which is incompatible with PEMFCs. Both areas need more focus on durability.
- In the summary presentation, the team identifies the project goals and milestones and high-level barriers to adoption of PGM-free catalyst technology. However, the high-level objectives of the project were not explained clearly. For example, other presentations reviewed waterfall graphs and explained the key objectives relative to a specific use case. It was not clear whether this project is targeting adoption of PGM-free materials for HD fuel cells or electrolyzers or is merely conducting fundamental research.

Question 2: Accomplishments and progress

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

- ElectroCat has increased PGM-free ORR activity by 20% over the last year and by more than 90% compared to three years ago. ElectroCat has exceeded its milestones for decreasing OER catalyst degradation rate, decreasing the rate to 0.25 mV/hr compared to its milestone of 0.45 mV/hr with its NiFeCo catalyst, while also achieving better performance than commercial catalysts (almost double the current density at 2 V compared to a commercial Co_3O_4 catalyst and ~66% higher current density than a commercial $NiFe_2O_4$ catalyst). ElectroCat has achieved over 2.4 A/cm^2 at 2.0 V with a totally PGM-free AEM electrolysis cell.

- The integrated teams clearly demonstrate significant progress in exploring novel catalyst formulations and demonstrate promising catalyst performance. In particular, developing highly efficient high-throughput synthesis methods is very unique, capable of greatly accelerating catalyst optimization and establishing structure–property correlations. Modeling and machine learning efforts also present clear pathways to elucidate catalyst active sites and desirable rational design of catalysts.
- The project comes with significant accomplishments for the previous year, as demonstrated by lead PIs. They keep adding to fundamental understanding of the electrocatalytic processes while improving practical performance of materials by implementing critical physical properties into the design of active materials.
- The presentation and accomplishment slides very clearly showed the project is on track and is completing milestones that are advancing the state of the art.
- Fuel cell catalyst work met its annual current density target. Fuel cell catalyst work fell short of its durability targets. Electrolyzer work examined 30 sample catalysts. The project demonstrated improved electrolyzer OER performance with synthesis directly on the nickel foam porous transport layer (PTL). Electrolyzer work using machine learning developed a new adaptive learning framework.
- While the accomplishments and progress toward the overall project goals are undeniably impressive, it is unfortunate that performance indicators for alkaline electrolyzers were not well-defined from the outset. Key performance indicators (KPIs) for liquid alkaline single cells at larger and more representative single-cell platforms are essential for gauging progress accurately and ensuring alignment with the liquid alkaline water electrolysis (LAWE) overarching objectives already demonstrated by the industry and other research and development labs outside North America. Metrics for LAWE should not, for instance, be merged into those for AEM that operate at much lower KOH concentration and with different and more robust cell–stack architectures. Moving forward, refining these indicators for LAWE will be pivotal for maintaining the project's trajectory and optimizing resource allocation. The advances made in addressing critical barriers to achieving the final project goals are noteworthy. The proactive identification and systematic approach toward overcoming single-cell performance using advances in OER and HER electrocatalysts reflect quick adaptability from existing alkaline fuel cell expertise by the different labs. The teams have not only demonstrated their commitment to success but also showcased their ability to pivot and innovate as needed. As the project progresses, refining KPIs and figures of merit and maintaining momentum in addressing critical barriers will be key to sustaining the exceptional level of achievement witnessed thus far. With continued dedication and strategic focus, development of LAWE in the United States will reach its full potential and make a significant impact in the field of hydrogen generation using such technology more traditionally used in Europe and Asia.
- Reasonable progress was made on both sections of the project with new materials and synthesis method development. The performance and durability of Fe-based ORR catalysts are quite impressive. It was good to see some progress on Co-based catalysts for ORR as well. It would be useful to make these Co-based catalysts a more mainstream approach in ElectroCat and make progress on that. It is refreshing to see H_2/air polarization data on these catalysts. Good progress was made on the PGM-free catalyst inks. The progress on Ni-based catalysts for alkaline HER is not satisfactory. Just changing the carbon support and showing higher activity is not so useful for the consortium. Good progress was made on the Ni-based alloy catalysts for alkaline OER applications, but these materials appear not very durable, even though they might meet the "target" (for instance, see slide 30). More focus on the durability in alkaline MEA electrolyzers is recommended.
- The rating of 3.0 is given as an average of the two areas: 2.5 for PEMFC and 3.5 for AEMWE. Both areas showed impressive progress on mass activity year over year. Progress on higher power and durability are unclear and need more focus. This year, progress on durability, shown on slide 9, cannot be justified, as the fuel cell performance at 0.8 A/cm^2 was poor at beginning of life. Decay rates of both PGM-free PEMFCs and AEMWE are still at least an order of magnitude too high to be practical. It may be time to cut losses and investigate a different family of materials.
- The high-throughput synthesis and characterization with machine learning analysis is showing good progress. In the future, it would be nice to see the team increase its capability to include automation that integrates real-time learning. The progress and accomplishments on the fuel cell cathodes are meeting targets. However, there have not been significant advancements in approach or performance in the last 3–4 years. In terms of fuel cell performance, there are concerns that lessons previously learned about electrode

integration are not being incorporated into the fuel cell fabrication and testing. The electrolyzer progress and accomplishments are very good.

- For the most part, the project appears to be on track to achieve the end-of-consortium goals for both fuel cells and electrolyzers. That being said, there are still major concerns about these catalysts ever being adopted by industry; the research remains highly fundamental, which is of great interest to the scientific community, but since the technology readiness level (TRL) is low, it is unclear if the research will actually impact fuel cells for HD transportation and the very near-term needs of electrolyzers.
- This is a challenging materials development project, and it is understood that practical know-how on ink preparation and coating deposition is critical to measure true material performance progress. The role of using machine learning could be explained more apparently and the gain in efficiency quantified.
- The project meets the DOE goals for PGM-free catalysts. Since this is the only DOE-funded PGM-free catalyst project, it should provide more in-depth study and guidance and insight on the direction of PGM-free catalyst research.

Question 3: Collaboration and coordination

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

- Collaboration within ElectroCat between the synthetic groups, the testing and characterization groups, and the machine learning and DFT modeling groups has been excellent and has resulted in improved understanding of PGM-free ORR catalysts and their degradation, and the machine learning suggested catalyst synthesis conditions resulting in improved activity and durability. ElectroCat has visible collaborations with outside groups.
- Both the fuel cell work and electrolyzer work draw on the expertise of four national labs. The combined capabilities and integrated analysis are impressive.
- This project has an excellent collaboration network across national laboratories, academia, and industry, which also comes with great visibility.
- An extensive network of collaborators is in place, which has contributed to the success of the research.
- The project has great collaboration between national laboratories.
- This project has a broad list of collaborations with diverse expertise.
- There is good collaboration with a world-class team.
- The individual contributions are not mentioned, but the results complement each other.
- There exists a strong collaboration between Los Alamos National Laboratory (LANL) and Argonne National Laboratory (ANL) that is a strength of this consortium. For the AEMWE catalyst development, it would be useful to see more integration with the HydroGEN Advanced Water Splitting Materials Consortium (HydroGEN). It is recommended that a more integrated/formal approach between ElectroCat and HydroGEN be established for the AEMWE component of those consortia. In the future, the project could benefit from additional funded collaborations outside of the consortium. This could be an opportunity to explore a wider variety of alternative catalyst chemistries and integration support.
- There is outstanding coordination and collaboration at the national level, especially between the two leading labs, LANL and ANL. However, little collaboration was demonstrated between the project and more experienced labs, original equipment manufacturers (OEMs) that can supply well-established liquid alkaline components, and the LAWE industry in either Europe or Japan. This could have remarkably changed the entire project in a very positive way. It may still be doable, especially now in the latest part of the project.
- Overall, multiple national labs closely work together, focusing on synthesis, modeling, characterization, and MEA fabrication/tests. In the meantime, the role and contribution of National Renewable Energy Laboratory is not clear.
- Collaboration is good, but there is very little interest from industry.

Question 4: Potential impact

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

- The potential impact of the project is substantial, particularly in its contribution to advancing the progress toward both ElectroCat's specific performance targets and the broader DOE Hydrogen Program (Program) goals and objectives. While the performance targets were not initially well-defined, the project's accomplishments, coupled with its proactive approach in addressing critical barriers, have positioned it as a significant driver of progress. ElectroCat has effectively leveraged resources and expertise to propel advancements in hydrogen generation technology, paving the way for a more sustainable energy future. The LAWE industry is very resistant to change, as it relies on stacks and systems with a high degree of maturity and robustness. Hence, the highlights demonstrated will have very little impact on "real life" devices, as these materials and their correspondent performance and durabilities have not been demonstrated at a significant scale that could be recognized by commercial units and traditional manufacturers. However, some of the project's innovations may have ripple effects across related research initiatives and industry practices. Overall, it is evident that the project has made a solid contribution to advancing the goals of the Program, with crucial efforts and accomplishments for a follow-up phase of five years or more after this project is completed.
- The cost of the PGM catalysts counts for 59% of the total cost of the PEMFC systems, and even with massive production, 0.5 million units/year, the relative ratio of the PGM catalyst cost will increase rather than decrease because there is only limited PGM catalyst reserve on Earth and the price of PGM keeps rising. Hence, PGM-free catalysts are critical for the PEMFC massive market application. Although there are many challenges, it is critical for DOE to continue to support this activity to have at least an alternative for a future catalyst on a low-cost basis.
- The broad goal of a non-PGM fuel cell catalyst is a good one, and the project is clearly focused on development of such a system. In that sense, the project is well-aligned with the DOE goals. Elimination of precious metals in HD vehicles' fuel cell stacks could reduce costs by up to $20/kW, a significant reduction. Elimination of PGM metals for AEM electrolyzers will be a significant step toward achievement of broader DOE goals.
- Developing efficient and low-cost catalysts is the key to clean hydrogen technologies. The potential impact of the consortium on catalyst development is significant, which is relevant to the mission of the Hydrogen Shot.
- The development of non-PGM-based catalysts is a holy grail for all in the industry, and clear progress is being made in the right direction.
- This project has already made a profound impact on the field. It is considered to be the world-leading project on PGM-free materials.
- The project is very important to improving efficiency and reducing dependency on PGM.
- ElectroCat's work is at a lower TRL but has potential to have a large impact on fuel cell and electrolyzer costs by eliminating high-cost PGM from both fuel cells and electrolyzers. The electrolyzer work is likely closer to application.
- Alkaline OER and HER catalyst development is likely to have some tangible impact on the industry, particularly for catalyst developers.
- While catalyst performance improvements have been demonstrated through novel synthesis methods (with impressive high-throughput techniques and adaptive learning guiding these efforts), concerns remain about the durability of the PGM-free catalysts and progress that has been made. It is evident that most of the work is fundamental in nature (excellent science is being conducted by the team); however, this is also leading to skepticism within the community about the reality of such catalysts ever being adopted. Without a clear timetable or summary showing exactly how the performance/durability efforts have evolved during the course of ElectroCat since its inception and a roadmap of expectations for the future, the future of this technology is in doubt. This is especially true for electrolyzers, which are new to ElectroCat.
- Regarding fuel cell catalysts, there are questions about the applications suitable for PGM-free ORR catalysts. With the current emphasis on HD vehicles and the commensurate need for very high catalyst stability and activity, it is highly unlikely that PGM-free catalysts will be useful in the application, given

the reduced emphasis on PGM loading and capital cost. The most significant impact of the consortium is in advancing the AEMWE catalysts. This is significant from both a viewpoint of reducing costs by thrifting out PGM material and also enabling electrolyzers that do not use per- and polyfluoroalkyl substance (PFAS) electrolytes. This work has the potential for significant impact on the production of low-carbon hydrogen.

- The work being conducted on this project is fundamentally interesting, and the modeling and characterization techniques could prove to be useful for other applications. The fuel cell work seems to be far from commercially relevant because of durability challenges, so it is not certain the material development will have a significant impact on the fuel cell industry or Program goals. The electrolysis work appears to be closer to impacting Program goals.

Question 5: Proposed future work

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

- The plan to expand the HER development work and include phosphide, sulfide, and selenide catalysts is commendable.
- The team presents a good plan and a comprehensive list of future project plans.
- The plan is clearly described and involves continuation of current approaches.
- The future work plans suggest an increased focus on durability for the ORR catalyst work. Greater effort directed toward durability is encouraged. The future plans to apply adaptive machine learning and high-throughput synthesis to the OER development work are commendable. Future work plans do not mention work developing non-Fe ORR catalysts. With concerns about Fe leaching into the membrane and acting as a degradation catalyst, catalysts based on other, more benign metals should continue to be explored. The proposed future work focuses on addressing the remaining barriers associated with insufficient performance and durability.
- The project has a very clear scope for the proposed work in the next period. A clearer roadmap is suggested for the progress expected in the LAWE space versus AEM.
- There are vast experimental matrixes unfolding with the use of quaternary metal catalyst compositions, when considering ink composition and application as well. It will be interesting and difficult to navigate and correlate good results to a fundamental explanation, where machine learning cannot provide all answers if the data are not “on the same page.”
- Using boron to mitigate carbon corrosion is an interesting approach for ORR catalysts. Other than that, it is not really clear what specific fundamental approaches are being taken to increase active site density and site accessibility. Using a Pt catalyst supported on the PGM-free catalysts is suggested. More emphasis on durability is required for the alkaline OER catalyst applications in alkaline MEA electrolyzers.
- For fuel cell catalysts, the future integration of boron for fuel cell testing to inhibit carbon corrosion is interesting. The remainder of the planned future work is not overly ambitious and focuses on advancing existing activities. The electrode ink and computed controlled deposition raises questions of whether scalable approaches to making PGM-free electrodes are being pursued. The future work on the AEMWE catalysts is more promising, with a focus on high-throughput approaches and new chemistries. The future work on operating on pure water should include significant coordination with the HydroGEN activities since the electrolyte and electrode, as well as the operation of the cell, will have a significant impact, perhaps greater than the catalyst.
- The vast majority of the presentation was focused on accomplishments during the previous year. One slide was devoted to “Future Work,” and another was devoted to “Challenges,” so it is hard to judge if anything other than “more of the same” will be accomplished in the final year of ElectroCat. Again, excellent science is being conducted, but its impact on the technologies is not evident after 10 years.
- The future work should put more effort on the more in-depth study of the activity and stability of PGM-free catalysts while working on meeting DOE targets. As this is the only PGM-free catalyst project, it needs not only to meet the DOE targets but also, more importantly, to provide guidance for PGM-free catalyst development.

- The PIs should keep adding more methods that would elucidate critical processes that enable utilization of PGM-free materials in fuel cells and electrolyzers. That should be related primarily to studies of degradation processes and development of novel in operando methodologies to study catalytic reactions.
- Substantial lists of future activities are stated, but it is hard to assess the relative impact of each idea.

Project strengths:

- This project presents state-of-the-art modeling and characterization of complex and difficult-to-determine active sites for PGM-free fuel cell catalysts. The project is also advancing the state of the art for PGM-free catalyst performance. The project has begun to provide useful evaluation of PGM-free electrolysis materials and characterization of the materials. The project is highly scientific and is leading to fundamental publications that are interesting to the research community.
- The high-throughput synthesis efforts involving machine learning and DFT, as well as the advanced characterization methods employed in the research, are all excellent, and the science breakthroughs are impressive. A highly cohesive, knowledgeable, and collaborative team is in place that works closely to achieve specific goals; significant scientific goals have been achieved.
- One of the most significant strengths is the integration of unique expertise from different national labs. The catalysts being developed at LANL could be immediately characterized at ANL and Oak Ridge National Laboratory using advanced tools, generating valuable understanding and providing timely feedback for further catalyst design and optimization.
- Strengths include (1) outstanding physico-chemical characterization capabilities, (2) wide knowledge on the synthesis of innovative materials, (3) important awareness on the use of machine learning and other innovative information technology (IT) technologies to advance innovation, (4) fundamental understanding of reaction kinetics, and (5) important existing knowledge in alkaline fuel cells.
- Although PGM-free catalysts are still far away from meeting the targets that enable their application in either light-duty or HD vehicles, PGM-free catalysts are critical for fuel cell applications in vehicles because of limited PGM resources. It is critical for DOE to continue to support this activity to have at least an alternative for a future catalyst on a low-cost basis.
- The project PIs are leading experts in the fields, with deep understanding and proven leadership skills and excellent publication records. The legacy of this project is making global impact in the field; the project seems to be the main source of reliable knowledge and achievements in PGM-free catalysts.
- The project's largest strength is the expertise and laboratory capabilities of the team. The use of very specific performance targets is a great strength of the project. This should be the case for all projects but often is not.
- A key strength of the project is the high-throughput synthesis and characterization with the incorporation of machine learning. Another key strength is the effective use of advanced characterization methods.
- Strengths include excellent collaboration within the project and good integration of experiment and modeling. Incorporation of machine learning has been beneficial and resulted in significant improvements.
- A good team with world-class researchers is the major strength of the project. A comprehensive effort is being made based on experimental and theoretical approaches.
- This consortium is valuable in maintaining a scientific edge in catalyst advancement.
- There is a huge amount of experience and competence brought together.
- Strong personnel and teamwork, with good advanced capabilities, are project strengths.

Project weaknesses:

- Given the low TRL of this consortium, focusing on meeting targets may not be the correct approach. Understanding and overcoming fundamental barriers from a conceptual and a phenological sense is required. Use of theoretical and machine learning approaches could be reduced, and more emphasis on experiments under realistic conditions is suggested. More studies incorporating commercially available PTLs and alkaline membranes and ionomers are recommended for alkaline electrolyzers. Focusing on durability of the new materials integrated with commercially available MEA components would be very useful and impactful. Looking at anode ionomer degradation and PTL interfacial resistance issues, combined with the new materials from the project, would be more impactful.

- Understanding the project is target-driven, the project needs to have some more in-depth study on the activity and stability of PGM-free catalysts. The current incremental improvement seems to meet the milestones of each year, but the rational approach is more important for this project. For example, the current PGM-free catalyst is Fe-N-C-based; it is unclear what the critical properties are in deciding the activity of the catalyst and whether active site density is one. The strategy to increase the activity is unclear. It is unclear what the root causes of PGM-free catalyst degradation are and whether carbon corrosion or loss of active sites are among the causes. It is unclear what the strategy is to overcome these issues.
- This project aims to implement PGM-free materials in electrochemical devices with performance that would be commercially acceptable. This project, and the field in general, still struggles to identify critical descriptors, such as the nature of real active sites. Moreover, durability issues remain the main challenge that would determine whether PGM-free materials would ever be applied in real systems. Before making deep impact into commercialization of these materials, it would be necessary to focus on critical barriers. Therefore, this project should evolve into more fundamental-oriented studies, possibly supported by the Office of Science.
- Regarding the fuel cell efforts, the goals of the project are ambitious in the sense that they would greatly advance the state of the art but may still fall a factor or two short of what is needed for economic viability. As there is only one more year left in the project, it appears unlikely that the fuel cell catalysts will reach their end-of-life performance goals.
- A main weakness in achieving a durable catalyst for either HD transportation or electrolyzer applications remains, and a path toward achieving this ultimate goal must be made clear. The foundational scientific efforts are strong; however, the actual integration of the catalysts into real-world applications is unlikely, and a clear path toward such a goal must be demonstrated.
- A key weakness of the consortium is the scope of both components and the emphasis on only catalysts. The impact of electrode structure and electrolyte is significant, and many of the targets for the consortium are based on performance and durability in the devices. Perhaps that should be revised with more catalyst-specific targets and objectives.
- Weaknesses of the project include (1) little collaboration or iteration with industry, (2) no clear understanding of benchmarks previously established by the OEMs and industry, (3) limited capability for single-cell and short-stack testing, (4) limited capability for long-term durability assessment, and (5) non-existing knowledge of accelerated stress test protocols.
- The main project weakness is that the work focuses on PGM-free fuel cell activity, but durability is poor relative to targets for HD applications. It is clear the fuel cell industry is focused on HD applications, so the relevance of the project's fuel cell work comes into question.
- Overall, significant challenges remain, in terms of the project catalysts' performance and durability, to potentially replace current PGM catalysts with the studied catalysts. Novel ideas and concepts are needed to design high-performance catalysts. The critical capability and studies of catalyst scale-up are still lacking.
- The material stability ultimately determines the value of this catalyst development, and the ultimate goal of replacing incumbent PGM materials may never be reached.
- Weaknesses of the project include the approach and lack of interest from industries. Durability is at least an order of magnitude too low to be practical, regardless of activity.
- The ORR work has been narrowly focused on $Fe-N_4$ systems. A broader scope may be beneficial.

Recommendations for additions/deletions to project scope:

- Although the activities were promising at low current density (ORR, OER, HER), the voltages at high current densities were much lower than those of PGM catalysts with comparable mass activity. One should remember that the observed Tafel slope of Pt and IrO_x are intrinsic to the catalysts and reactions. There is no guarantee that one can achieve such preferable Tafel slope with other catalysts. There is a real chance that some very active PGM-free catalysts will have poor Tafel slope and, therefore, will never be able to deliver competitive high current density. Checking a Tafel slope is such an easy measurement. The project should make it the highest priority, in order to eliminate poor candidates before investing time and funding.

- The fuel cell testing is being conducted at 1 atm. That is fine for charting progress. However, current PGM fuel cell stacks operate at elevated pressure. Thus, it would be interesting to see how the new catalysts perform at elevated pressures. As the team is four years into the project, it seems worthwhile to ask them for an assessment of progress and ranking of approaches that might result in radical improvement, not just the incremental improvement demonstrated to date. It would be good to have the researchers' judgment about the impact and likelihood of each proposed future work idea.
- The consortium may consider low-PGM catalyst approaches, as the completely PGM-free formulation cannot meet the performance requirements for fuel cells and water electrolyzers in the short term. The state-of-the-art baseline catalyst also needs to be established for the studied reactions, such as ORR, OER, and HER. In addition to the PGM-free ORR catalysts, the relevant protocols for the OER and HER catalysts are necessary to evaluate their performance and durability in both half-cells and MEAs. The scale-up of catalyst development is critical to the overall impact of the consortium.
- Only one year remains in the current ElectroCat project; the Hydrogen and Fuel Cell Technologies Office should consider expanding M2FCT or another consortium to include some aspects of ElectroCat since there are many challenges faced by PGM-free catalysts, including the unlikely adoption by industry and the low TRL level of the research being conducted. Very nice science has resulted from the consortium over the years, but maybe ElectroCat as a stand-alone consortium has run its course.
- The project should focus more on fundamental understanding of PGM-free material durability, not just active site characterization, for this portion of the project to be relevant to Program objectives.
- It is not clear whether ElectroCat has a high-throughput multi-sample test system suitable for the electrolysis studies. If not, development of a system similar to the 5X5 sample cell used in the fuel cell high-throughput screening would be beneficial.
- Emphasis on machine learning and DFT could be minimized. More focus on actual experimental work is recommended. PGM-free ORR catalysts for HD trucks are unlikely; modifications to suit the appropriate application are suggested.
- Substantial addition of testing capabilities for single cells and short stacks is recommended to more consistently assess performance and durability.
- The most promising materials should be tested in bigger short stacks to make sure practical variability is also captured statistically.
- More coordination with HydroGEN for AEMWE catalyst integration and evaluation is recommended.
- More in operando studies would be desirable.

Project #FC-336: A Systematic Approach to Developing Durable, Conductive Membranes for Operation at 120°C

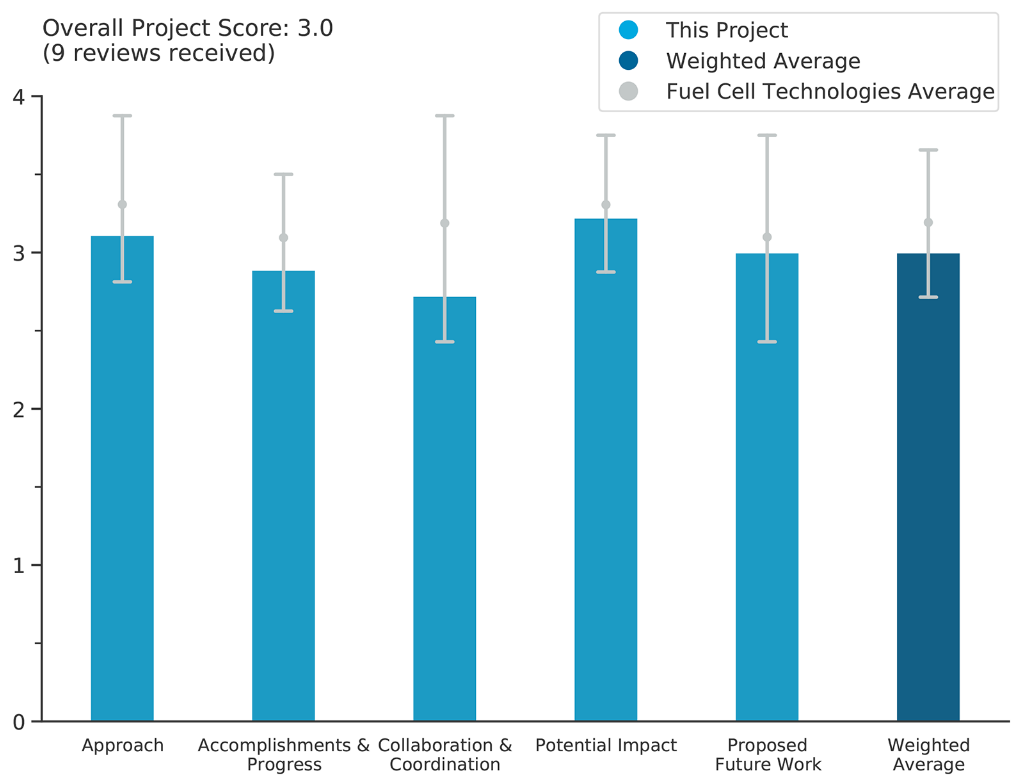
Tom Zawodzinski, University of Tennessee, Knoxville

DOE Contract #	DE-EE0009246
Start and End Dates	4/1/2021–3/30/2024
Partners/Collaborators	Oak Ridge National Laboratory, Akron Polymer Systems
Barriers Addressed	• High conductivity (interim target: low area-specific resistance <0.08 ohm cm^2 @ 120°C, 50% relative humidity) • Durability: on path to 25,000-hour lifetime

Project Goal and Brief Summary

This project aims to develop membranes with sufficient performance and lifetime to meet the requirements of proton exchange membrane (PEM) fuel cells for heavy-duty vehicles. The research team will use background measurements and literature evaluation to inform paths forward for membrane development to meet cell resistance requirements over ranges of temperature and relative humidity (RH) that reflect operating conditions in heavy-duty vehicles. Researchers will then identify and prepare new membrane materials with side chain and polymer chemistry tailored to achieve acceptable conductivity and resistance, with low water uptake and durability on a path to 25,000-hour lifetime swelling. The University of Tennessee, Knoxville (UTK) is collaborating with Oak Ridge National Laboratory (ORNL) and Akron Polymer Systems (APS) on this project.

Project Scoring



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

Question 1: Approach to performing the work

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

- The project strategy involves crafting hydrocarbon composite membranes infused with cerium oxide (CeO_2) nanoparticles to enhance conductivity in environments of elevated temperature (120°C) and low RH. With a specialized proficiency in formulating hydrocarbon-based PEMs and synthesizing inorganic nanoparticles, the team possesses a solid theoretical foundation in understanding proton conduction across membranes at various hydration levels. Drawing from the team's prior work with silica-infused PEMs, this approach presents a promising avenue for exploration.
- The targeted membrane for up to 120°C operation and >20,000-hour durability is critical for economical and reliable heavy-duty fuel cell vehicles. The team is taking a clever approach, combining known conductivity enhancement of additional sulfonic acid groups with durability imparted by radical scavengers such as Ce.
- Project objectives of simultaneously improving water retention and conductivity while maintaining membrane mechanical integrity are in line with current fuel cell membrane requirements for heavy-duty vehicle applications. The presented data suggest that the incorporation of functionalized ceria nanoparticles (CeNPs), if optimized, could address key barriers to the development of fuel cells capable of operation at up to 120℃. An appropriate safety culture exists at UTK.
- The approach has shifted from varying polymer backbone and number and functionality of side chain acid groups to using sulfonated CeNPs to provide conductivity under high-temperature, low-RH conditions. The new approach appears to overlap with some work being done in other projects looking at ceria-based additives, but this project is directed more toward conductivity and performance, while the others are looking more at immobilizing the ceria particles for increased durability. The approach builds on previous work and literature work using sulfonated silica additives to try to provide conductivity at high-temperature, low-RH conditions. The work with sulfonated silica particles had modest success but was never able to reach the area-specific resistance (ASR) or conductivity targets. There does not appear to be any theory or reason to support the thought that sulfonated ceria particles should have a better outcome in terms of enhancing performance under high-temperature, low-RH conditions than sulfonated silica has, though the ceria particles should provide radical scavenging that the silica particles did not.
- Generally, the project has a good approach. The BPSH-35 (sulfonated poly[arylene ether sulfone]) material traditionally has performed well, and this is another unique aspect that was not investigated within McGrath's effort back 10+ years ago.
- UTK has prepared composite hydrocarbon PEMs using legacy polymers of sulfonated polysulfones. Since the last review, the team has sulfonated the CeNPs and has shown that the particles within the polymer matrix are more effective at retaining water at elevated temperatures, such as 120℃ and 50% RH, leading to reasonable proton conductivity under challenging conditions. It seems that the project has struggled with making mechanically robust membranes with particle additives. This is not surprising, given previous work with adding ceria to perfluorosulfonic acid (PFSA) membranes and other work in adding inorganic particles to membranes to prevent methanol crossover. The presentation mentioned this challenge. Backup slides discussing the specifics of the challenges, as well as results, would have helped.
- The project aims to increase the ion conductivity of membranes at high temperature for PEM fuel cell applications without sacrificing mechanical properties or projected durability. The strategy involves incorporating sulfonated ceria particles into a polymer matrix, where composite membranes have reduced swelling and improved mechanical properties, while maintaining reasonable conductivity. It is not immediately clear why the principal investigator (PI) focuses on "McGrath-ion" vs. a more traditional PFSA, as PFSA film formation is well-understood, and it should be relatively easy to demonstrate/scale the chosen solution in a membrane electrode assembly (MEA). It is also well known that hydrocarbon polymer along the lines of those used has poor chemical stability and poor conductivity at low RH. The choice of ceria particles for sulfonation is questionable, as ceria is well-known to dissolve in PEM fuel cell applications. The relative solubility of sulfonated ceria vs. traditional ceria was not addressed.
- The approach is to make new materials and try to make films that are good enough to measure properties; the PI indicates this is hard enough, and it is. The presentation did not react to previous reviewer comments

about considering operating air pressure. There was also no mention of operating pressure during the property measurements, so it is unclear how the material properties of the samples were measured. For example, 100% RH at 100℃ and atmospheric pressure is essentially all steam with no air molecules; 50% RH at 120℃ and atmospheric pressure is essentially a similar operating point and represents essentially all water vapor and no air. If testing was done under these conditions, one could argue, since no air is present and the sample should be under a pure steam environment, there is not really a "drying" effect on the membrane. Thus, a misleading result would be given, even if a system were designed to operate at these conditions.

- The goal is good, but the approach has shifted over the course of the project. The original idea of multiple acid groups per aromatic ring (Balls of Sulfonates) has moved into sulfonate functionalized ceria particles. The PI should spend more time explaining how this approach is better than other strategies such as functionalized silica.

Question 2: Accomplishments and progress

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

- Data suggest significant improvements in conductivity at 120℃ and 50% RH, along with reduced swell and improved water retention, by incorporating CeNPs. There appears to be room for further improvements through optimization. Although material synthesis and processing have been challenging, the author reported that significant progress has been made and that reproducibility has recently been demonstrated in the production of >20 composite membranes with +/-10% conductivity variation.
- The project had a valuable finding in that a modest number of additive particles was sufficient to control swelling. The project also showed progress toward project goals using non-perfluorinated polymers.
- The team was able to greatly reduce swelling with the addition of the sulfonated CeNPs. The project team was able to improve conductivity of the base hydrocarbon membrane at 120℃ and 50% RH by ~ 3× by adding sulfonated ceria particles. The conductivity of the composite membrane is still much lower than target values. Depending on membrane thickness, the conductivity needs to be ~0.05 to 0.1 siemens/cm (S/cm) (assuming a 10–20 micron membrane) to reach the ASR target, meaning a 3×–7× improvement in conductivity is needed.
- The team undertook the task of preparing surface-modified CeNPs for integration into hydrocarbon membranes. Initially encountering challenges in particle dispersion, the team successfully resolved these issues, thereby imbuing the membranes with certain desired properties. Measurements were conducted on ASR, water swelling, and water retention of the composite membranes, revealing promising results presented during the meeting, although complete conviction remains elusive. Consequently, the project has been extended to thoroughly assess these properties. However, the current properties of the proposed materials still fall short of the original target (0.02-ohm cm^2 at 120°C), and a clear path to achieving this goal remains elusive. Crucial properties such as mechanical stability and resistance to radical degradation were not addressed. Despite plans to conclude the assessment of durability against Ce particle loss by March 31, 2024, results were not provided during the presentation.
- UTK achieved the go/no-go decision (Milestone 3). However, data for progress on Milestones 1 and 2 (which had due dates of 03/31/2024) were not seen. Milestone 1 was cerium release from the modified (i.e., sulfonated curie) particles and non-modified ceria particles. Milestone 2 was less than 5% acid loss from modified particles at 80℃ for 1,000 hours under acid hydrolysis conditions similar to membrane acid concentration. Future directions for the project will focus more on conductivity and will deemphasize stability.
- The accomplishments of the project are somewhat muted by the extended illness of the PI, which is, of course, understandable. The demonstration of improved conductivity and reduced swelling in a film, as the PI describes, is a noteworthy accomplishment. However, the reluctance to move forward with any kind of membrane durability testing is confusing. Obvious questions around stability of the particle, polymer, and retained structure after the wet–dry cycle raise issues with the approach. Several times, the PI mentioned the difficulty with forming membranes, which was not well-explained. The choice of polymer may compound these difficulties and is not well-justified. The swelling data for the 5% CeO_2 appear to contain a

power-of-10 error, which if corrected appears to render the swelling trend with increasing ceria content inconclusive.

- Some progress has been made to be able to test new materials, but robust film-forming processes are lacking and are not being addressed by the project; thus, even durability and MEA fabrication are also not addressed.
- The team is making decent progress toward meeting the DOE goals, but it is unclear that there is a true understanding of the data outputs.
- The PI has received an extension because of personal matters, but there looks to be a small number of results for measurements that are fairly easy to complete (conductivity, swell, tensile, thermogravimetric analysis).

Question 3: Collaboration and coordination

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

- Close collaboration with ORNL was in place early in the project until resources were exhausted. Samples of a series of commercially relevant polymers are available through collaboration with APS, and a relationship has been established with a suitable partner (Kodak) for future scale-up demonstrations.
- The partnership between UTK and APS is commendable. While the initial plan involving ORNL has been rendered invalid, this adjustment is reasonable, given the project's funding constraints and requirements. However, there appears to be limited interaction with Million Mile Fuel Cell Truck (M2FCT) or other industrial partners, posing challenges in validating the technology.
- Collaboration exists with a company that has manufacturing experience; however, a collaboration with a systems partner could help with the cell operating conditions trade-offs and give better guidance on the environment to test the samples.
- There is good collaboration with APS for polymer supply. Collaboration with national labs could accelerate progress.
- There is limited collaboration and coordination so far, but based on the progress to date, it is expected to pick up, including engagement with M2FCT.
- UTK has collaborated with ORNL for polymer modification and with APS (a commercial polymer manufacturer). APS provided the polymers used in the hydrocarbon PEMs. It was unclear whether the polymers provided were sulfonated or UTK did the sulfonation. ORNL has exhausted all of the money for the lab's sub-award. It is unclear what the lab actually did in this project. There is discussion about collaborating with M2FCT, but it is unclear whether UTK has a robust membrane for fuel cell testing by M2FCT partners (e.g., Los Alamos National Laboratory or National Renewable Energy Laboratory). The timeline for making MEAs and fuel cell testing is unclear as well.
- The project is relatively small, so the funds available for collaboration are limited. The partnership with APS is reasonable and clearly present. What was done with ORNL is not obvious. No integration with M2FCT appears to have been initiated for any reason.
- There is some collaboration with APS. It seems there are no interactions with other membrane projects, with projects looking at modifying ceria for durability purposes, or with M2FCT.
- This is a small project with a small team. Nonetheless, the project seems to lack coordination. One of the partners is no longer active (ORNL), and the other (APS) is listed as providing polymers but not highlighted as collaborating in any other way.

Question 4: Potential impact

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

- Developing highly conductive membranes capable of withstanding high temperatures is crucial for heavy-duty fuel cell applications. This project directly tackles the demanding requirements of such membranes. While progress has been sluggish, the potential impact on fuel cell technology upon achieving the project goal is considerable. Maintaining high water retention at temperatures exceeding 100°C may still offer significant room for improvement.

- This project directly addresses key challenges for fuel cell operation at 95℃–120℃, namely water management/retention to maintain conductivity under elevated-temperature/low-humidity conditions, while maintaining mechanical stability.
- A membrane that meets all the targets at 120°C and low RH is critical for stack performance and life for heavy-duty and other applications. The principle of sulfonated additives to retain water in dry environments for improved membrane performance is good, if not entirely novel. A successful outcome of this project would benefit the field of heavy-duty fuel cells.
- This project addresses a long-time challenge in the fuel cell industry by attempting to develop membranes that can operate at 120℃. If successful, this will help advance heavy-duty transportation applications.
- While this reviewer is a fan of hydrocarbons, it would be great to finally convince industry that this could be a stronger alternative to Nafion™.
- This project is aligned to several goals in the Hydrogen and Fuel Cell Technologies Office and M2FCT. The project aims to develop proton-conducting membranes under hot and dry conditions (120℃ and 50% RH). Increasing the operating temperature and lowering the RH requirement simplifies heat and water management in large fuel cell stacks that are used in propulsion systems for trucks, buses, etc. Additionally, the project team is developing non-fluorinated PEM materials. This is important for addressing risks associated with potential PFAS regulations. The only deficiency here is arguably the lack of novelty. Ceria particles added to PEMs and sulfonated polysulfones have been researched for decades. It is true that these materials should be in some way revisited. The reviewer is looking forward to the mentioned review article on what has been done, what works, and what does not work. The scope of work could have included other advanced hydrocarbon PEMs such as the ether free poly(phenylenes) (e.g., sold by Ionomr Innovations).
- The project has potential to improve high-temperature, low-RH performance but appears unlikely to be able to reach targets or match the performance of Nafion or other PFSA materials.

Question 5: Proposed future work

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

- The team is realigning the scope of work to focus more on the proton conductivity under hot and dry conditions and will deemphasize stability requirements. The researchers propose to examine the particle loading on membrane properties (presumably, they mean conductivity and mechanical integrity). The team mentions implementing the membranes in MEAs for fuel cell testing. A timeline to achieve these tasks over the next year (when the project ends) would be helpful. It is unclear whether there are any new milestones or end-of-project goals associated with the realignment of goals, for example, fuel cell performance testing or membrane strength.
- The PI has outlined a reasonable set of experiments for the remainder of the project. Earlier in the presentation, the PI highlighted the intention to understand what works and why. The future work appears to be more of an optimization focus and does not include plans to understand why this approach is working or how it differs from other sulfonate functionalized particles. Particle stability in the membrane should be prioritized. Cerium oxide is well-known to dissolve in acid, and it is unclear whether the functionalization is complete enough to prevent this over the expected lifetime of the membrane.
- The project's future plan appears sensible, given the remaining time and available resources. However, obtaining durability data from the M2FCT consortium might prove challenging, given the current pace of progress. Additionally, there is a lack of clarity regarding the strategy for manufacturing MEAs and conducting testing.
- The proposed future work is significant. Much remains to be done to conclude the project as envisioned. The durability tests proposed appear adequate to address the possible limitations of the approach.
- Owing to current demand and interest in non-PFSA-based membranes, focus has shifted toward meeting conductivity targets using hydrocarbon-based membranes at elevated-temperature/low-humidity conditions.
- The project should focus on the fundamentals of the operating environment during testing. It is good to deemphasize durability and MEA testing at this early material study.

- The project is nearing its scheduled completion, and plans are appropriate for the time left.
- This is a good plan for the last year of the project.
- The team should follow through on all the proposed future work.

Project strengths:

- UTK and other project team members have achieved good proton conductivity with their hydrocarbon sulfonated CeNP composite PEMs under challenging conditions (120℃ and 50% RH). The membranes do not suffer from excessive swelling, which is a hard challenge to overcome with sulfonated polysulfones. The team gives some interesting hypotheses to describe the experimental observations—such as water trapping/retention between the particles. Thermal gravimetric analysis data support the better water retention of the composite PEMs.
- The PI and the team boast substantial expertise in hydrocarbon membranes, supported by a strong theoretical foundation. The baseline membranes and Ce particles are both economically feasible alternatives that are free from PFAS. Controlling water retention through nanoparticle interactions is a logical approach for sulfonated hydrocarbon membranes. The concept's validity has been demonstrated through successful validation in terms of conductivity and water uptake. Furthermore, initial hurdles encountered during composite membrane processing have been effectively overcome.
- The project seeks to improve conductivity through increasing the local concentration of sulfonic acid groups. This has the potential to advance the current state-of-the-art fluorine-free membrane technology by enabling ion-conducting channels while avoiding excessive swelling. The experience and insights of the PI are project strengths.
- The project is focusing on an important gap in heavy-duty fuel cell research and development. There are promising results in the fundamentals of improving conductivity while lowering swelling. The team understands the need to evaluate membranes for durability before the end of the project.
- If successful, this approach could be applicable to a range of commercial and developmental membrane chemistries, including PFSA and non-PFSA structures. The authors have intentionally shifted focus toward non-PFSA/hydrocarbon-based membranes in line with current (and anticipated future) demands.
- The experience of the PI is a strength. The use of sulfonated ceria particles to form a composite membrane has potential to provide increased conductivity, improved mechanical properties, and radical scavenging.
- The initial ASR target of <0.080-ohm cm^2 at 10-micron membrane thickness was met. The project looks at many factors affecting membrane performance and how they affect each other.
- There is good work on the development of new materials.

Project weaknesses:

- The main project weakness is the lack of a coherent plan. While every project needs to adapt and change over time, this project seems to have drifted from the original objectives. The project title suggests a systematic approach, but the results to date look to be more of a collection of loosely related ideas. The project does not look to have a strong team or collaborations. One partner has dropped off the project, and the other partner is listed as a polymer provider with no indication of collaboration. Sample nomenclature is confusing and makes it difficult to follow the progress. It is unclear whether all the polymers on Slide 8 were used in the data presented. The number of results seems modest over the course of a year. If polymer synthesis was the main effort, it should have been better represented in the review.
- Attaining high proton conductivity under conditions of elevated temperature and reduced RH raises doubts about the membrane's suitability for fuel cell applications. Moreover, assessments remain outstanding regarding the long-term stability of Ce particles and the mechanical resilience of the membrane during extended operation. Additionally, the absence of significant polymer structural variations beyond the current framework impedes advancements in membrane technology.
- No justification was provided for expecting sulfonated ceria to improve conductivity more than sulfonated silica, which many have used to try to achieve high-temperature, low-RH performance targets. There does not appear to be a path to hitting the target conductivity.

- The author reported processability challenges that could hinder scalability. It is not clear whether functionalization of the CeNPs affects their ability to inhibit peroxide formation and membrane degradation. The likely migration of CeNPs has not yet been addressed.
- The presenter should state the composition of each membrane sample so that reviewers can better correlate the improvements claimed to the sample makeup. Sample sizes used in each case should be listed. Information about sample reproducibility is lacking.
- UTK has not showed adequate progress on membrane and particle stability, as proposed. Given that the project has been going on for at least two years, one would expect more progress to be made, especially given the size of the budget.
- The PI has made life more difficult for himself by returning to two-decades-old polymers known to be inadequate for multiple reasons.
- The material testing environment is unclear.

Recommendations for additions/deletions to project scope:

- The main focus of the project seems to be sulfonate functionalized ceria particles. It is highly recommended that the acid stability work be prioritized. Cerium is easily detected by ultraviolet visible (UV-vis) spectroscopy, x-ray fluorescence (XRF), inductively coupled plasma spectroscopy (ICP), etc., and techniques are available to quickly determine the CeO_2 stability. Methods to consider are those published from Los Alamos National Laboratory to measure mobility under applied potential (Baker et al., *Journal of The Electrochemical Society* 164, no. 12, F1272, 2017), or solubility in acid (Um et al., "Dissolution of Cerium Oxide in Sulfuric Acid," in *Zero-Carbon Energy Kyoto 2010*, T. Yao, Ed., Springer Japan: Tokyo, 2011: pp 165–170), or even putting CeNP composite membranes in contact with a cerium-free membrane for an extended period at high RH, followed by analysis of the membranes. If the cerium is truly insoluble over extended periods of time, then it is unclear what it offers over more easily functionalized particles such as silica. More effort should be spent making connections between ionomer structure, CeNP functionalization, and ultimate performance metrics (conductivity, swell, etc.). While reviewers understand this is a small project with limited funds, it would still be good to more completely address the durability objectives stated in the project title and goals. The PI should make it clear that the goal of this project is a membrane that can perform at excursions to 120°C and not continuous operation at this temperature.
- The upcoming tasks for this project appear to be overwhelming, given the constraints of the current budget and remaining time. While critical tasks—such as ion-exchange capacity determination, conductivity analysis, and assessment of Ce particle stability—must be prioritized, other less crucial tasks could potentially be sidelined. Collaboration with M2FCT should remain a focal point. Additionally, conducting further nuclear magnetic resonance and other spectroscopic analyses would be beneficial for publication and knowledge dissemination, especially considering the PI's expertise in this area.
- The nice particle model on Slide 20 should be expanded to show how an ionically conducting path through the membrane thickness may be achieved. The project should study particle distribution throughout the membrane (e.g., using microscopy) and correlate to performance data. The team should consider measuring through-plane conductivity of membrane samples. The team should also obtain more accurate membrane properties by measuring in an environmental chamber.
- There should have been some collaborations or exchange with projects looking at adding functionalized ceria particles for durability and mobility of these particles in MEAs. The team should do more to look at mobility of the sulfonated ceria particles in an MEA with water gradients.
- Boiling the membrane to ensure retention of CeNPs would be of interest and should be easy with existing unoptimized films. PFSAs should be used to demonstrate the described principle, in lieu of adequately conductive hydrocarbon ionomer.
- The team should do more work on environmental testing conditions at different air pressure–temperature–humidity combinations that can be achievable in a system environment.
- Durability studies are needed to assess the rate of migration/loss of functionalized CeNPs during operation (in comparison to non-functionalized CeNPs under similar conditions).
- There are no recommendations for additions/deletions to project scope.

Project #FC-337: Cummins Proton Exchange Membrane Fuel Cell System for Heavy-Duty Applications

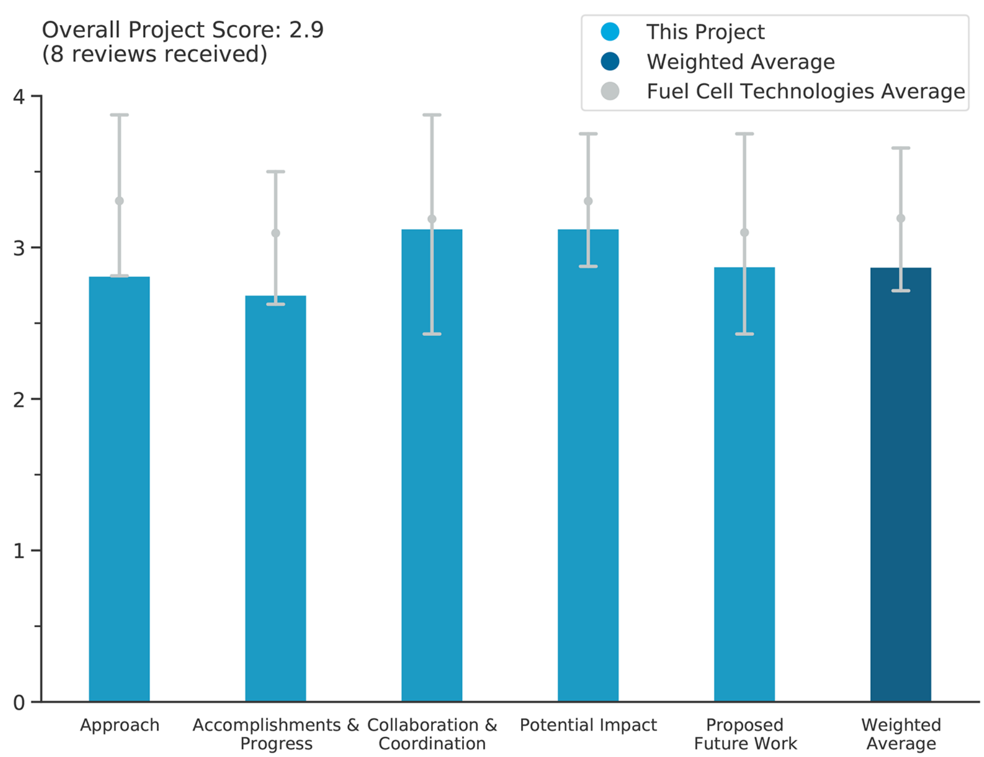
Jean St-Pierre, Cummins Inc.

DOE Contract #	DE-EE0009247
Start and End Dates	7/8/2021–7/31/2024
Partners/Collaborators	Cummins Accelera, Cummins Turbo Technologies, Dana Incorporated, W.L. Gore & Associates, Inc., Argonne National Laboratory, Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Cost: \$80→\$60/kW fuel cell system cost enabled by a smaller radiator, high-volume manufactured bipolar plates, and a smaller, higher-efficiency system

Project Goal and Brief Summary

The objective of this project is to develop and demonstrate a new standardized, modular, and scalable 100 kW proton exchange membrane fuel cell (PEMFC) stack that meets performance, efficiency, durability, and affordability requirements for heavy-duty (HD) applications. Membrane electrode assembly (MEA) and bipolar plate (BPP) development efforts will be undertaken and demonstrated in progressively larger stacks. The stack will be designed to run at higher pressure and tolerate high temperatures (≥100°C) during peak power excursions. A key metric is the system cost of \$80/kW at a production volume of 100,000 units per year. To achieve this objective, the team will undertake a study on advanced manufacturing methods to reduce production costs. This project is a collaboration between Cummins Inc., its Fuel Cells and Hydrogen Technologies division (comprised in part by Cummins' acquisition of Hydrogenics), Cummins Turbo Technologies, Argonne National Laboratory (ANL), W.L. Gore & Associates, Inc. (Gore), and Dana Incorporated (Dana).

Project Scoring



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

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is generally quite good. The goal is to design first a 1 kW and then a 100 kW stack, both of which will be able to operate at >100°C so the radiator size can be reduced. In parallel, testing is being done at elevated pressures. The first period focuses largely on membrane/electrode material selection and BPP design leading to a 1 kW stack. The second budget period focuses on 1 kW evaluation, 100 kW development, and system modeling.
- Developing PEMFC MEAs and stacks that operate at high temperature would provide significant advantages and help reduce system complexity and cost. The project addresses a major materials issue with operation above 100°C, which is the membrane. The focus on the compressor is also relevant, as at temperatures above 100°C, the high water partial pressure can dilute reactants and have a substantial negative impact on fuel cell performance. Operating at increased pressure can help mitigate this effect. BPP design is critical for operating at higher temperatures and pressures. The use of design of experiments will help reduce the number of experiments needed and should lead to more efficient use of resources. The project does not address catalysts and/or catalyst durability at the elevated operating temperature, which is expected to be an issue. The project's target stack power density of 0.8 W/cm^2 is lower than the DOE target. This may be okay, as the coolant system size can be reduced and the total system power density may be higher than a proton exchange membrane operating with a maximum temperature of 90° or 95°C, but the researchers do not provide any calculation or projection of the total system power density to show whether they would meet or exceed that of the 1 W/cm^2 system with a maximum temperature of 95°C.
- The practical approach to build up from single-cell to stack, and then integrate with a dedicated system, is logical and just. However, depending on the amount of material, design, and system operation challenges encountered, this could be a long road.
- The original approach outlined is sound, with clearly defined objectives. However, the project is falling behind the timeline and has yet to make a full stack; barriers and mitigation strategies should be more clearly identified.
- The project aims to produce a robust and economical PEMFC stack and system capable of operating at temperatures exceeding 100°C. The project coordinator acknowledges that MEA, ionomer, and electrode design are critical to durability but has not carried out accelerated stress tests (ASTs) at operating conditions relevant for high-temperature applications to a significant degree (the 48 hours used during potentiostatic hold [VAST, or voltage AST] tests is not adequate). Other elements of the fuel cell system were also identified as key components for high-temperature operation: turbo-compressor, radiator, and BPPs. Sufficient progress has been made in the design of the BPPs, but modeling efforts have not been confirmed because the project was held up by a lack of MEA materials, due to their unique size. A more typical BPP and MEA design with smaller active areas may have been a better approach to keep the project moving forward. The other components mentioned above have not been worked on because the Cummins team is awaiting stack data. The safety plan looks like the bare minimum. No existing or newly developed standard operating procedures were identified, but a review of lab sites is ongoing.
- This project is focused on high-temperature operation of an HD vehicle stack to decrease radiator size and improve efficiency. However, it is unclear if there is a systematic approach to address the key durability issues of operating at 110°C. The safety plan was too vague. It would have been good to see more of the safety panel recommendations for the project and more details on the outcome of the review (not just the few highlights listed in the slide). There was no information on any diversity, equity, inclusion, and accessibility work associated with this project.
- The first objective of this project is reasonable, namely, to "reduce the size of the radiator." However, it is not clear if the approach being pursued here will actually achieve this objective since the team is proposing elevated operating pressures (higher parasitic loads) and cell performance that is likely to be lower than conventional PEMFCs. Overall, one would also expect decay mechanisms to be mostly accelerated at elevated temperatures. The second objective is stated to be "lower activation losses." Although activity may be higher at higher temperature, it is likely that the decay will be higher. It is not clear that the net result will be an improvement. Slide 29 states that the results are "suggesting catalyst degradation is not a

primary concern," but it is unclear if it is actually better at 60° to 80°C. In short, the overall objectives sound good, but the principal investigator (PI) should strive to demonstrate that the approach is on a path to actually enable these objectives.

- A major portion of this project is operation at high temperatures, e.g., 110°C. This would be a big benefit to vehicle heat rejection. However, it appears that this project is using standard near-commercial materials, which are perfluorosulfonic acid (PFSA) membranes supplied by W.L. Gore at 15 and 8 microns. The strategy to make these membranes work at 100°C/110°C is both unclear and potentially non-existent, other than increasing stack operating pressure to 250 kPA. During Period 1 (ending January 2023), the project was supposed to build a 1 kW stack and verify performance. No stack build was presented; if this was constructed, it is unclear. The presentation now lists this as Quarter (Q)6. The MEA was down-selected (for the 10 kW stack test, according to the presentation). The MEA down-selection appears to have been conducted on beginning-of-life performance, although most HD vehicle targets are end-of-life (EOL). The project did select the membrane based on the current density cycling highly accelerated stress test (HAST) membrane durability test, although this seems like it might have been obvious, as the researchers chose the thicker membrane with "enhanced stabilizer" as opposed to the thinner membrane with "stabilizer." The performance target (0.75 V at 0.3 A/cm^2) seems low, especially considering that Million Mile Fuel Cell Truck (M2FCT) showed >1.5 A/cm^2 at 0.7 V.

Question 2: Accomplishments and progress

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

- The project has been able to meet cell voltage and performance targets at 0.7 V while at temperatures above 100°C and relative humidity (RH) of 50% and less. The project team was able to perform ASTs on the membrane and select a membrane that has chemical durability of >1,000 hours in these tests at >100°C. The results show no increase in H_2 crossover or fluoride release rate (FRR) for the Gore-1 membrane under HAST cycling for over 1,000 hours at 110°C, which is encouraging. The project team decreased total platinum group metal loading by ~20% from 2023 to 2024, with no apparent increase in degradation rate and only a minor (~10%) reduction in power density. The dependence of membrane FRR on the variables, particularly temperature and potential, is expected to be important in determining durability and conditions to avoid. The large error bars on slide 27 make it difficult to determine if there are any trends, if the differences are due to scatter in the measurements at these low levels, or if there are other uncontrolled variables. It is not clear how many samples these graphs represent. Getting good measurements on many samples to get good statistics of the dependence of the membrane FRR on temperature (and potential) would be very useful and could enable one to extrapolate membrane lifetime over a drive cycle.
- Between the 2023 and 2024 DOE Hydrogen Program Annual Merit Reviews (AMRs), additional MEA HAST/VAST tests have been completed, as well as development of a (non-optimized) Pajarito Powder MEA. Additionally, stack hardware was acquired, including partially characterized BPPs. An abbreviated testing plan was also developed for the 10 kW stack to reduce testing time. However, during the last year, a 10 kW stack was supposed to be fully assembled and tested, with those tests providing important inputs for modeling results and techno-economic analysis. While only a third of the budget has been spent, the project is falling fairly far behind, and the Q6 go/no-go milestone has not been passed yet.
- While work has continued, it appears that the best data to date still stems from the prior year's work. Additionally, there are delays in completing the final tasks (1 kW stack) due to MEA availability. The team continues to evaluate new materials, some of which will require additional optimization to meet the performance targets.
- Clearly, there has been progress with making better-performing MEAs and characterizing the cell hardware. The difficult part comes when both are put together and performance of the full-scale short stack should match the small single-cell screener, with the complexity of adding more variabilities and non-uniformities. Planned variations in operating protocols will highlight the sweet spot of selected materials.
- It appears that the team has generated a great many data, but the presentation of the results does not demonstrate clear and measurable progress, with the exception of the summary on slide 21. The PI should spend more time on communicating what has been learned and how the performance improvements shown in this summary were realized. The "factorial design" result matrices can be omitted.

- The Cummins team has performed operating condition sensitivity tests at the 10 kW short stack level that should help identify the needs from balance-of-plant components for efficient operation of a full fuel cell system. Complete experimental design is still in progress. General Motors (GM) HAST at 110°C shows durability in excess of 1,000 hours for the down-selected membrane. The researchers "expect" that they can meet DOE goals for EOL performance with their down-selected membrane and catalyst layers, but sufficient in-house durability data or M2FCT AST data were not provided to support this claim. One attempt to explore an alternative electrocatalyst failed because of an invalid recipe for high-temperature operation. A bulk of spending is likely planned for system development, but a project in its last year would likely have less than $2 million of cost share funds available.
- It seems like very little progress was made last year, and that is not surprising, given the very low spend rate of the project from March 2023 (presented in last year's AMR) to December 2023. Although the test matrix listed in slide 9 shows several more experiments as completed this fiscal year, the conclusions from these do not seem to be much improved. It was already clear from the last AMR that Gore-1 had better durability than Gore-2. It is unclear what the impact of temperature, RH, and pressure are on membrane durability. If the main conclusion after all these tests is that Gore-1 is worse under three different conditions and Gore-2 is worse under some other condition, it adds no value to the understanding of membrane durability at high temperatures. There needs to be a more systematic analysis of these experiments that results in a better understanding of what factors affect the durability of these membranes at these elevated temperatures.
- The first high-temperature testing on the membrane was shown. This testing was considered "somewhat variable at 110°C." This seems in contrast to what the PI said in fiscal year (FY) 2023, when he seemed confident that the membrane/materials would be durable at 110°C. The BPP design appeared to previously have been the rate-limiting step; this seems to have been solved primarily with the BPPs acquired. Although operating at a higher pressure (250 kPa versus 150 kPa), the performance is lower than other performance. The presentation shows higher performance at lower pressure by others. To justify the high-temperature operation, this project should provide some sort of trade-off between the lower-performance, higher-pressure, and higher-temperature system compared to the higher-performance, lower-pressure, and lower-temperature system. The design of experiments was conducted on 15–21 cm^2 active area single cells; however, considering that the Achilles heel of this project is membrane durability at high temperature, it would seem that this set of experiments should have been conducted on larger active area. The Fuel Cell Technical Team used to recommend at least 50 cm^2 cells for membrane durability tests. The HAST test was conducted for more hours.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The project is largely internal to Cummins (Technical Center, Accelera, Ending), but the project has partners that include Dana and Gore and is interacting with M2FCT.
- The team appears to be working well with their suppliers and subs, and the contributions of these partners are clear.
- There does seem to be close collaboration between all the parties. Different partners appear to have a balanced impact on the results demonstrated this year.
- Gore and Dana are excellent project partners for the membrane and BPPs. No minority-serving institutions or minority business engagement is listed.
- The coordination within Cummins seems good. M2FCT and ANL collaborators have been identified, with defined requests for characterization delivered to M2FCT. Cummins attended the two M2FCT meetings.
- There are a number of industry collaborators that function as suppliers for different components of the fuel cell system and provide analysis of diagnostic data and ex situ characterization. Cummins should assume a larger role in the analysis of the data the company produces. The team appears to be waiting for M2FCT to identify new AST or new end-of-test targets, as well as modeling results, before moving forward.
- The consortium gives a strong impression, but it is questionable whether the suppliers of membranes and BPPs can adapt their current product range enough to accommodate the high-temperature operation in a

stable manner. Since all components have to work together in synergy, more feedback loops and re-engineering may be required.

- The collaborations with Gore are evident. The collaborations within Cummins are evident. It is not clear how collaborations with R. Ahluwalia/M2FCT are going, and no results were seen—results projecting durability, etc.—from M2FCT modeling of MEAs at high temperature using these data, using Ahluwalia's model, or using data from this project to validate the model, either in this project or M2FCT. Collaboration with M2FCT to measure catalyst durability in these MEAs at high temperature would be beneficial—of particular interest would be catalyst leaching/dissolution experiments at T >100°C (and elevated pressure). It is not clear if M2FCT would have this high-temperature/high-pressure capability or if they could add it.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The goals of this project, if completed, are well-aligned with DOE targets and would be a very nice demonstration of stack-level performance at elevated temperatures.
- A fuel cell stack that can operate at temperatures of >100°C can have a large impact on fuel cell system cost and expand the applications where fuel cells can be cost-competitive. Heat rejection is a key issue for applications such as HD trucking, where the trucks operate at high power for a large percentage of the time and the size of the thermal management system is constrained.
- A U.S. base for fuel cell stack manufacturing is clearly a goal of the DOE Hydrogen Program. A fuel cell stack that operates at high temperatures (110°C) can solve issues with heat rejection.
- While many within the low-temperature proton exchange membrane industry are trying to push the upward limit of PFSA membranes, this project pairs this higher-temperature operation with the use of turbo machinery for fuel cell applications.
- This project has the potential to have a significant impact for the DOE fuel cells program area. Higher-temperature PEMFCs have been seen as desirable by many, especially vehicle original equipment manufacturers (OEMs), and it is good that there is one project that is attempting to demonstrate that higher temperature can be beneficial. The risk here is relatively high, so it is appropriate for DOE's support. However, the real key to how impactful this project will be if the project can either (1) show that high-temperature operation is truly beneficial (this is not clear in the results shown here) and that the durability is acceptable, or (2) if it fails, clearly share with the PEMFC community the root cause(s), such as membrane failure, excessive carbon corrosion, or catalyst growth.
- Stable high-temperature operation could enable simpler thermal solutions and reduce cost.
- Durable high-temperature operation of PEMFCs to improve thermal management is very desirable for both HD and mid-duty fuel cell electric vehicle applications. However, there is no clear set of objectives to be carried out by Cummins and its collaborators to progress at the needed pace and allow time to resolve complications arising from BPP and stack design, MEA durability concerns, and the incorporation of additional balance-of-plant components by the next go/no-go date and project end date.
- This project was funded mainly as a stack development project. However, even after 2.5 years since the project started, no stack has been assembled or tested. The Q6 milestone was supposed to be a 1 kW stack by January 2023, and a 100 kW stack was to be built in budget period 2. However, the current project is focused on a 10 kW stack and claims the project has slipped by only one month for budget period 2, from 17 to 18 months. Perhaps new milestones and dates were negotiated with DOE. If so, those should have been listed somewhere. Even the Q4 milestone is only 50% complete. DOE should very carefully assess this project against the proposed milestones and continue to fund this project only if the team can clearly show that they are making progress not only toward DOE goals but also toward their own stated milestones.

Question 5: Proposed future work

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

- At this point, the future work is geared toward completing the budget period 1 tasks, some of which have slipped because of availability of MEAs for kilowatt-size stacks. Cummins is also proposing replacing duty-cycle testing with an AST as a means of catching up on the delays experienced thus far. While the inclusion of an AST would seem appropriate given the circumstances, perhaps a modified shortened duty cycle could also be included, rather than a full exclusion.
- The future work plan shown (slide 20) is a reasonable set of tasks. However, what is missing are any targets or milestones. It is recommended that these be designed to enable the desired results: (1) show that high-temperature operation is truly beneficial or (2) understand why it fails.
- The stack-testing plan is well-defined and helps mitigate a good deal of time. The proposed plan is well-aligned with the project goals, but it is not obvious it can be completed within the remaining timeframe.
- The list of necessary steps is logical and could well be successful but leaves little time and resources for another iteration loop when issues arise.
- The researchers say that the 10 kW stack is almost ready to be assembled. It is unclear whether they are skipping the 1 kW stack or whether that was done; a 1 kW stack is listed on the summary page, so this would seem to have been constructed, but it is unclear with what materials or whether the design is similar to the 10 kW stack. The Q6 go/no-go was listed as a 1 kW stack. The plan for stack testing is planned out appropriately.
- Cummins plans to finish evaluation of their 10 kW short stack and additional M2FCT-designed ASTs of catalyst alternatives. Cummins needs to devote resources toward identifying a target application for the company's high-temperature system, using their internally available customer data, and designing a drive cycle that best approximates the stresses that will be expected by such a customer. The test should include but not be limited to targets for the frequency and duration of high-temperature exposure, power cycling, and low-power exposure.
- Cummins has proposed changing the work scope to use ASTs on the stack to shorten the test period since the project is behind schedule. Since these tests and the lifetime operation planned will include operation over a temperature range not previously investigated, the correlation between the proposed ASTs and real-life durability is not known. Projections of lifetime durability from accelerated tests will rely on correlations at lower temperatures, and these may not hold. Extending the project and proceeding with tests on a drive cycle (even if some additional funding is needed) would be a much better option and provide more value to the fuel cell community.
- This is almost the same future work as was presented at the last AMR.

Project strengths:

- The team has carried out a substantial design of experiments for membrane VAST tests at various temperatures and pressures using two different Gore expanded polytetrafluoroethylene (ePTFE) reinforced materials. The team has identified that under different conditions, these two membranes show different susceptibility to the fluoride emission rate (FER). The team has also done extensive work to prepare for a 10 kW stack build and has demonstrated excellent leak rates, well below the project targets, when evaluated with N_2.
- Performing MEA and stack tests at 110°C and obtaining durability data from 110°C operation is a strength. A commercial OEM and a commercial membrane/MEA supplier are involved. The team has demonstrated good performance at high temperature and low RH to date.
- The project is actively taking the fuel cell system concept above and beyond current operational window conditions, leveraging the knowledge in the supply chain and the stack/system.
- System/stack component assembly and development, in particular the BPPs, are done well. MEA demonstration at high temperatures is also a strength.
- High operating temperature should reduce the issues with heat rejection.

- Cummins has access to proprietary internal knowledge related to thermal management and compressor systems for HD applications, which will help in those areas of system design.
- The project is led by a HD vehicle OEM that appears committed to developing PEMFC-powered HD vehicles. The truck picture on the title slide is cool.
- The project has great partners and good membrane durability.

Project weaknesses:

- The effect of high-temperature, lower-performance, high compressor load for higher-pressure operation has yet to be presented as an overall benefit. It seems like this should be modeled. The presentation indicated that the high-temperature durability seemed questionable; however, previously the team had indicated confidence about the membrane durability. The catalyst durability has yet to be evaluated for the high-temperature/high-water-content operation. It is unclear what the innovative approach is that allows this project to use high temperature (110°C) when the materials seem quite ordinary PFAS and catalysts. It would be helpful to other projects if this project would define the materials (such as "chemical stabilizer" and "enhanced chemical stabilizer"). The performance targets for this project are low compared to other projects. Maybe this could be justified by comparing the overall system cost by radiator reduction, but that has not occurred, at least in this presentation.
- The overall goals of this project are to develop high-performing stacks that operate at >100°C, but the metrics/targets for assessing high-temperature durability are not well-defined. While development of a high-temperature AST is outside the scope of this project, it is not clear whether running the M2FCT AST at normal operating temperatures (rather than the original 5,000-hour drive cycle) with periodic testing at >100°C will be representative of high-temperature operation and durability. Additionally, all testing thus far has been conducted on MEAs, and it is not clear how this performance will translate to the stack. This is a stack project, but all testing has been on MEAs. Furthermore, the project has not laid out a plan for demonstrating a 100 kW stack.
- Cummins did acknowledge some delays, which have prevented the project from achieving all the budget period 1 tasks, including some of the stack testing. As this is a key task and it appeared uncertain exactly when those MEAs would become available, it is unknown if there will be additional delays in accomplishing the prescribed tasks. There is also apparently significant work needed with the Pajarito Powder catalyst that is being evaluated, as it has demonstrated significantly lower performance than prior evaluations from GM. The team did not outline exactly what changes are expected or how long this re-optimization will likely take.
- The project needs to manage externalities better (procurement delays from suppliers, awaiting data analysis from collaborators, awaiting identification and selection of new ASTs and what those results mean toward achieving 25,000–30,000 hours of operation).
- There are many challenges that could delay the project, and solutions can be found in three dimensions—materials, design, and system operation—greatly expanding the number of variables to "get right."
- The team is a bit behind schedule, causing a shift in plans from running a stack on a truck duty cycle to running it on an AST. The accelerating factor for the accelerated test is not known.
- The project seems to be way behind on milestones and lacks clear focus. The team needs to identify key factors that can degrade the fuel cell under these high temperatures and find ways to mitigate those.
- The team needs to show clearly that the project is on track to meeting the stated objectives: smaller radiator size and lower activation losses.

Recommendations for additions/deletions to project scope:

- The effect of high-temperature, lower-performance, high compressor load for higher-pressure operation has yet to be presented as an overall benefit. It seems like this should be modeled. Little information is given about what materials are being used. The FY 2023 presentation indicated that machined carbon composite plates were going to be used. It is unclear whether that has changed or remains the same. The performance target is low compared to what other projects are presenting. DOE did raise the catalyst target for FY 2024, as per the M2FCT presentation.

- The team should use ANL's PEMFC system model to show that radiator size may be significantly reduced and stack performance targets met, even with elevated operating pressures and reduced cell performance. The team should also compare decay rates of cells at 100°C and more conventional PEMFC operating temperatures.
- Discussions with FC-336 could help with understanding limitations experienced with MEA designs under elevated temperatures and create more focus on a tighter window of potential success by using existing simulation models and know-how from outside of the project.
- Additional AST experimentation with operating condition sensitivities alongside post-mortem analysis would be helpful in identifying possible new/unexpected failure modes experienced from high-temperature operation. A number of non-linearities were observed for the Gore-1 membrane for both hydrogen crossover and FER in the technical backup slides.
- Cummins recommended replacement of duty-cycle development and testing with an AST. Rather than a straight replacement, the AST, while it could have use, should still be paired with at least a modified shorter duty cycle.
- The researchers need to quickly show that they can build a small stack that works reliably at 110°C before they are funded to go to budget period 2.
- The project should more rigorously study the effect of temperature on stack performance, with clearly defined metrics.
- More collaboration with M2FCT would be beneficial, especially in terms of catalyst degradation at above 100°C.

Project #FC-338: Domestically Manufactured Fuel Cells for Heavy-Duty Applications

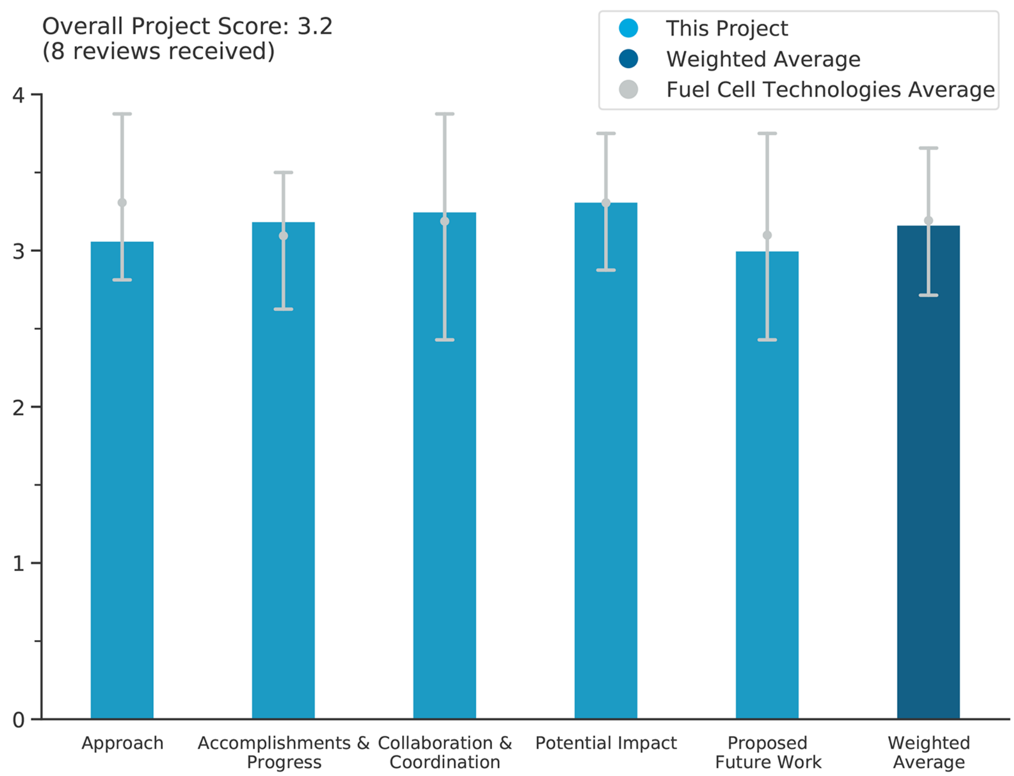
Cynthia Rice, Plug Power Inc.

DOE Contract #	DE-EE0009248
Start and End Dates	10/1/2021–6/30/2024
Partners/Collaborators	Argonne National Laboratory, Million Mile Fuel Cell Truck (M2FCT)
Barriers Addressed	• Performance: High catalyst activity, low mass transport resistance, low electronic resistance interfaces

Project Goal and Brief Summary

Plug Power Inc. (Plug™) is working with Argonne National Laboratory (ANL) to develop a heavy-duty (HD) fuel cell stack that is a suitable drop-in replacement for diesel engine applications. If successful, this project will enable high-volume production of bipolar plates (BPPs) and 100 kW modular stack systems to create a reliable and efficient stack with improved durability, cost-effectiveness, and performance.

Project Scoring



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

Question 1: Approach to performing the work

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

- The goal of this project is to develop a fuel cell stack that can be extrapolated to a 25,000-hour lifetime with only 4µV/hr decay, allowing the technology to achieve DOE targets. Additionally, Plug is focusing on the material supply chain, ensuring that materials are readily available. Modeling will also be used to evaluate performance decay through a drive cycle. The general methodology of acquiring single-cell data and feeding that through modeling efforts at the national labs is appropriate for the modeling/design aspect. Bipolar plates from numerous sources are being sourced to see if they pass key performance indicators during Stage I, and the most promising are then evaluated during additional testing in Stage II.
- The project is focused on identifying a number of sources and manufacturing methods to be used in manufacturing of metal BPP coatings, seals, and assembly methods that can handle materials from several suppliers to reduce line down time. The project has conducted both catalyst- and membrane-focused accelerated stress tests (ASTs) on baseline membrane electrode assembly (MEA) materials at both the subscale and short stack levels. Procurement and durability testing of advanced MEA materials is planned.
- The industrialization of fuel cell stack manufacturing is strongly needed, relying on the maturity of the supply chain, high quality standards, and interchangeability of components. This approach gives a true representation of what problems stack building companies face and need to resolve.
- The goal of domestically producing high-performance, high-durability, heavy-duty (HD) proton exchange membrane fuel cell (PEMFC) stacks is laudable. The testing on bipolar plates is of interest, but it is not clear what types of coatings are being utilized, and with the use of the 316 substrate, it does not appear that these plates would meet DOE cost targets. The approach to investigate recovery protocols could be useful, but the study should be limited to practical steps that can be done in a stack.
- The approach targeting coated metal bipolar plates, roll-to-roll manufacturing, and stack automation to lower costs is excellent. No diversity, equity, inclusion, and accessibility plan or community benefits plan was presented, other than a general statement about Plug's commitment to advancing opportunities to maximize community benefits. The safety plan was adequate.
- Project objectives are well-defined, as are the overall goals of Phases I and II. While some barriers are clearly addressed with appropriate technical questions and plans, some other barriers (particularly for Phase II and the automation plan) should be discussed with proposed mitigation strategies.
- It appears that the major objective of this project is to demonstrate the capability of Plug's high-production-volume-intent PEMFCs to meet HD vehicle targets (e.g., 25,000 hours) in a reasonable timeframe. Understandably, the project is using stress tests to demonstrate durability. However, it is hard to understand the various stress tests. It is unclear why a steady-state hold at 0.6 A/cm^2 is considered to be a stress test. It is also unclear why there are three different stress tests—hold, highly accelerated stress test (HAST), and urban drive cycle—and what will be learned from comparing these results. The Fuel Cell Consortium for Performance and Durability team had multiple ASTs, but the reason was that each was designed to stress different cell components. The Million Mile Fuel Cell Truck (M2FCT) is currently developing a single AST that is supposed to accelerate decay of all cell components and that is relevant to HD vehicle applications. The Plug team should use one of these two types of AST protocols. What the team is currently doing is just collecting great quantities of data with no apparent methodology to draw any solid conclusions.
- Plug is using its own ASTs for this project. While this is understandable, it would be nice if some data were taken with the Fuel Cell Tech Team (FCTT) ASTs and the AST that M2FCT proposed for comparison. Those ASTs were developed so that durability data can be compared. Plug is concentrating on manufacturing and thus, for this project, is using only material available in large quantities.

Question 2: Accomplishments and progress

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

- The team has completed the four tasks associated with budget period 1: temperature variation, peak power, estimates of end-of-life stack voltage, and establishment of leak metrics. Additionally, researchers have thoroughly screened different materials from seven suppliers of bipolar plates and continue to make down-selections and conduct additional testing to determine the most viable options. The team has demonstrated what potential cost reductions through automation could represent toward hitting DOE metrics for total cost of system and has identified that work is needed on the impact of automated assembly on stack performance and lifetime. The team is also evaluating whether a voltage hold at low voltage (0.4 V or 0.1 V) can be used as a recovery method following Stress Test 1 (ST1). In general, the team has made substantial progress against the milestones for the project.
- Ultimate project targets align with those established by M2FCT and DOE. The project has demonstrated a robust, full-scale cell design that meets beginning-of-life performance targets. In collaboration with M2FCT, the project analyzed results from ASTs to predict performance at the 25,000-hour end-of-life (EOL) target, and in the process, determined that baseline materials do not meet the EOL catalyst performance target. The project demonstrated the benefit in conducting General Motor's HAST at the full-scale cell level vs. subscale level (the subscale test article was not optimized for mass transport and MEA materials).
- The team has identified four coatings that meet initial contact resistance and corrosion targets. The project team has identified the potential to reduce processing costs ~60% through automation. The project has improved sealing and decreased sealant application time and decreased sealant cost by ~50%. A recovery protocol that can be used in situ has been devised. It is not clear how one would implement the recovery protocol with a 0.4 V hold in a real application. At 0.4 V, heat produced could be considerable, and it is not clear how that heat would be managed in a stack/system or what the heat's impact would be on degradation modes. Different degradation for a single cell vs. a short stack was determined, with the short stack showing minimal transport losses when compared to the single cell.
- Recognized aging protocols have been implemented and results quantified, although specific names of the suppliers are not mentioned. A valuable result is to identify how much performance loss can be recovered through running dedicated operation protocols, mitigating off-spec conditions. Accomplishments would be outstanding if/when there is clear quantification of less sensitive parameters that can be relaxed to achieve cost savings. For example, the principal investigator did clearly show that catalyst loading has a positive impact on resilience.
- All four go/no-go milestones for Phase I were achieved. Significant progress has been made on the short stack testing, with three stress tests and comparison with single-cell results. Cost metrics have not yet been reported. The decay rate does not yet meet the 25,000-hour target.
- Much time was spent on a voltage recovery protocol, which recovers reversible losses. The protocol has a voltage step down to 0.4 V and >100% relative humidity (RH). It seems like this is not plausible on an actual system, and/or it would be expensive to implement. Understanding what balance-of-plant (BOP) materials and systems are needed for this approach could be valuable for developers (e.g., humidification system, direct current–direct current [DC-DC] converter). The frequency at which this recovery step needs to be taken was not mentioned. Some laboratory protocols to measure durability remove the reversible losses daily. The timeframe in which the reversible losses show up should be measured to verify that the timeframe for recovery is not less than a singular drive cycle. In the procedure to remove the reversible losses, the effect on vehicle efficiency should be noted. Four different BPPs have passed the Stage II testing (with one failing and two to be determined); it would be nice to have information about the cost of the materials and whether they will pass a requirement about Fe cation release. It is hard to evaluate the techno-economic analysis with so little information. The one-step temperature cure process for seals (gaskets) seems like a big improvement; however, a cycle time of 60 s seems long for larger commercialization. The durability testing is primarily at low temperatures (60°C for the stationary hold, 80°C for the HAST, 60°C–70°C for the drive cycle). Other projects and developers seem to believe that there will be temperatures of 80°C–90°C regularly and excursions up to 100°C and 110°C. It is noted that the drive cycle is an urban drive cycle, but this does not seem to correlate with DOE on fuel cell HD vehicles for long-haul trucks. It is not obvious what conclusions are made from the catalyst electrochemical active surface area (ECSA) and

fluoride emission rate. The cathode RH at 30% has one catalyst point on it. The stationary hold has a 30% loss, which seems high for that test. The urban drive cycle has 50% loss over 1,500 h, which again seems high for only 1,500 h. These results seem to suggest that there is a catalyst durability issue with the current catalyst being used in this project and, thus, why the catalyst loadings are so high (well above the DOE targets).

- The team shows significant results, which is great, but it is unclear what has been learned. The team shows decay rates as a function of current density, which can be quite insightful, and this appears to be yielding some actual conclusions such as those shown on slide 16. It is hoped that the team also is learning why there are the differences noted on slide 16 (i.e., the responsible decay mechanisms and how differences impacted/mitigated these), although that is not clear. The large-scale active area (LSAA) results on slide 16 are hard to explain. It is unclear why the decay rates are lower at high current densities or why the single cell at 80°C and the LSAA are so much different at low current densities. If these are the same catalyst-coated membrane materials, the activity losses may be expected to be similar since mass transport losses are not significant at low currents.
- It is unclear how Metric 4 (25,000 h estimated durability) is being met. The stress tests listed (ST1, ST2, and ST3) are not accelerated and already result in degradation rates of 10–40 mV/kh compared to the target of 4 mV/kh. It is unclear why the high current decay rate is lower than low current decay rate. More diagnostics to quantify transport property improvement over the course of the test will help answer this question. Correlating low current voltage losses to changes to ECSA and increased diameter of the Pt is critical to understanding degradation and achieving low decay rates. It is unclear why ECSA loss is lower at higher loadings. Normally, ECSA losses are similar while voltage losses are lower at the higher loadings.

Question 3: Collaboration and coordination

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

- Sharing short stack durability data with ANL/M2FCT to improve the durability modeling will be very useful. Plug is collaborating with national labs (Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, ANL, Oak Ridge National Laboratory [ORNL]) and collaborating on developing ASTs. The team is planning evaluation of catalysts from pH Matter.
- Collaboration appears strong within this small group. Plug is responsible for handling the single/stack testing and developing supply chains and automation. ANL is responsible for modeling efforts from performance data and for voltage recovery to assist with cost projections and material analysis.
- The project is reaching out to a range of commercial suppliers and to relevant Roll-to-Roll (R2R) Consortium projects while having a sound foundation of relevant knowledge within Plug.
- This project seems well coordinated with M2FCT regarding stress tests. Discussions have been conducted with ANL, ORNL, and M2FCT regarding future collaborations.
- The project team is working with M2FCT. It would be good to explicitly list the component suppliers as partners, if allowed.
- The project is collaborating with national labs on AST development and modeling. The project has clear and concise requests for each national lab involved in M2FCT. The project has plans to work with suppliers for down-selection of more advanced catalyst materials. It will be important to include post-mortem analysis at the next review from both subscale and full-scale test articles to see what learnings can be applied for predicting subscale vs. full-scale EOL performance differences.
- It appears that most collaborations are with M2FCT and M2FCT labs at this point. Plug clearly must have interactions with its suppliers (but they are not mentioned). While Plug may want to keep its supplier base confidential, the presenter could still say what the interactions are in terms of the suppliers’ contributions (e.g., catalyst, membrane, gas diffusion layer requirements, and improvements desired).
- There appears to be a reasonable amount of interaction with the national labs, but it is unfortunate that Plug does not seem to be benefiting from these engagements with respect to designing a more rational set of stress tests. It is unclear what the meaning or value is of slide 23.

Question 4: Potential impact

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

- The project goal is to meet cost and performance targets for fuel cell stacks. With proper selection of individual MEA components, the project can shift focus to identifying manufacturing methods to produce a sufficient number of stacks at scale to meet cost targets. Down-selection of MEA components and completion of ASTs will also enable the development of operational limits/control strategies to meet degradation targets during simulated drive cycles such as ST3.
- The project is well-aligned with DOE goals, both from a performance standpoint and from the aspect of strengthening U.S. supply chains and manufacturing. Through development of automation for stack/system assembly, Plug is also looking to achieve DOE cost targets that are necessary at volumes of 100,000 systems per year to make HD applications viable. Broad goals outlined on slide 4 are well in line with overall DOE goals.
- Development of a domestically produced, durable HD stack would have large benefits. Providing stack data to M2FCT will have a large impact on the modeling efforts.
- The project aligns well with Hydrogen and Fuel Cell Technologies Office (HFTO) goals, with this stack project having the potential to provide valuable feedback to DOE on durability and ASTs.
- U.S.-manufactured fuel cells and fuel cell stacks for fuel cell HD vehicles are clearly within the HFTO portfolio. The stack operation seems to be at lower temperature than other developers' operations; it seems like the temperature will be an issue in terms of heat rejection. No BOP comments were made.
- The knowledge is highly relevant but could be applicable only to proprietary hardware being used in the project. It is important to publish the protocols and know-how so stakeholders can educate themselves and raise the overall maturity of the supply chain, which benefits the whole community.
- The project is well-aligned with DOE target metrics. However, translatability to other stack systems is unclear.
- The overall goal of this project is outstanding, but the execution is poor.

Question 5: Proposed future work

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

- There is a critical view of the project results from within the participating partners and a clear view of what the market needs from the second part of the project. It is important that the stress protocols have relevance to the real-life conditions, as mentioned in the slides.
- The plan to correlate voltage decay rate to operational conditions is good.
- The project plan builds on progress thus far with 25,000-hour durability testing and characterization. The team will study important metrics, including iron contamination and fluoride emission rate, and understand how operating conditions affect voltage loss. Operating condition protocols should be systematically studied. Additionally, the proposed work of measuring ionomer distribution in the catalyst layer with ORNL seems a little outside the scope—this is a low-throughput and time-consuming endeavor—and it is unclear what science questions are being addressed by this effort.
- The focus on 25,000-hour durability is good. Any details regarding future milestones are absent. The only detail on the milestones is from slide 7 and is only for Phase I.
- The aspirational future goals shown on slide 20 are all good, but it is not clear that the team can actually achieve these goals. How decay rates will be correlated to actual operational conditions in HD vehicles is not clear. It seems unlikely that M2FCT, or anyone else, can actually do that well yet. If the researchers plan to publish any of these results in peer-reviewed journals, they may find that most reviewers are looking for new knowledge, not just data sets.
- For short stack durability tests, it is key to focus on emulating the membrane- and catalyst-related stressors that will be encountered in the design for application. Benign modes of operation should be kept to a minimum for a limited amount of recovery from stressful operation.

- The proposed future work is based heavily on the Phase II emphasis of achieving the 25,000-hour M2FCT goal. Correlations must be made between operating conditions and decay rates. The team will also look at additional material analysis and further automation analysis.
- Not many details were provided on the future work. Understanding the acceptable iron levels, which would be a help to the community, has been only peripherally addressed by a couple of projects.

Project strengths:

- The prime is a viable fuel cell electric vehicle developer with extensive fuel cell manufacturing experience. This experience can help with determining the status of PEMFCs and stacks that are produced using commercially available materials and relatively high-volume manufacturing processes. The project is addressing some of the key challenges with developing high-volume stack manufacturing.
- The team has done substantial testing to determine operational parameters that are viable for the stack. The idea of a low-voltage hold as a recovery method is unusual but seems to demonstrate some promise at this point, based on the preliminary data. The researchers have also demonstrated a cost path forward through automation and are thinking heavily about manufacturability, supply chains, etc.
- The project is aimed at raising the maturity of the supply chain, enhancing robustness of the stack, and highlighting sensitivity to supplier variations. Moreover, the project shows how negative effects can be mitigated and to what degree.
- This project is making good progress and is concentrating on manufacturing stacks in the future. The project has conducted a nice amount of durability testing.
- The ability to build and evaluate stacks with state-of-the-art materials and the willingness to collaborate and share materials and data are strengths.
- The project nicely demonstrates automation capabilities and testing of short stacks.
- Data are presented at multiple scales for multiple degradation modes.
- The project is led by a leading PEMFC developer.

Project weaknesses:

- There are some technical concerns with the data presented. The performance decrease as a function of temperature is as yet unexplained and needs to be investigated, as this goes counter to what is typically seen. The stack voltage, while interesting, may be complicated to implement. It is unclear whether the team has observed any thermal managements associated with low-voltage holds at 0.1 V and 0.4 V. Some increased temperature variation across plates could be expected under those stressors. It is unclear how the team is mitigating carbon corrosion during open-circuit voltage. While that may temporarily improve performance, viability should be evaluated going forward if fundamental changes are occurring to the catalyst. Some of the stress test rates need further investigation. Some of the stacks are showing negative or no decay at high currents, which should be explained.
- This project is simultaneously focused on demonstration of stacks built through automated, high-throughput processes and on diagnostic understanding of the stacks' durability and the impact of the automation processes. However, it is not clear that the effects of automation can be decoupled from material effects and that if a supplier is changed out, or there is batch-to-batch variation, the results here will be translatable in terms of stack degradation predictions.
- The number of variables/combinations can be huge, considering that a number of different suppliers exist for each component in the working stack. The project will have to make preliminary choices while making a selection, which is assumed to be done on the basis of proprietary hardware performance/cost assessment. This decision tree is therefore not objective, but the process of optimization is essential to all in the community.
- The project does not give many details that will help other organizations and the wider Hydrogen Program. As much information as possible about the materials and the directions the project needs to go with materials should be given. Much of the durability testing seems to be at temperatures that are too low. HFTO is concentrating on HD vehicles for long-haul trucking, but this project is using an urban drive cycle, which would seem to be the reason the temperatures are low.

- Better stress tests are needed to evaluate 25,000-hour durability. There is a lack of correlation between EOL properties and performance loss.
- Lack of ex situ characterization is a weakness.
- The correlation between the AST and the real-world lifetime is not clear.
- There is a lack of solid rationale for much of the testing to date.

Recommendations for additions/deletions to project scope:

- Some data should be taken with the FCTT ASTs and the AST that M2FCT proposed for comparison. A Class 8 long-haul drive cycle should be examined and used for some of the evaluation. Providing as much information about the materials and directions the materials need to go to improve performance and durability will help the global Hydrogen Program. The catalyst durability seems disappointing compared to other results presented. While Plug concentrates on materials that are already available in commercial quantities, it could be valuable for the team to incorporate some advanced material testing into the project matrix to understand whether it is material or operation (e.g., M2FCT announced that the consortium had 10 g of an advanced catalyst). Some durability testing should be conducted at higher temperatures. Understanding the acceptable iron levels would be a help to the community. It would be good if Plug can do a study on this topic and publish it.
- The team should consider using only one type of stress test (e.g., ST2) and then compare results obtained on the different cell hardware since this appears to be yielding the most informative results. The project should attempt to be more quantitative about categorizing the performance losses going forward. For example, it should be possible to estimate activity loss from the changes in the Pt particle size; it is unclear how this compares with the losses that are independent of current density. Likewise, for mass transport losses, one can try to estimate the impact from various mechanisms (e.g., lower Pt area results in higher flux rates per site and therefore large transport losses, changes in catalyst layer morphology, etc.). It is unfortunate that none of the real-world results from Plug's PEMFC forklift fleets are included here. It seems likely that this database could be helpful in correlating durability in vehicle applications and those obtained on test stands.
- The project should consider collaborations with the R2R Consortium, particularly with regard to MEA fabrication process and automation. More focus should be given to translation of single-cell data to short stack and full stack, and how the cells vary across the stack, perhaps through modeling efforts/collaborations. Quality control metrics should be developed/baselined (especially when considering materials from different suppliers) to make the automation process more robust.
- The project needs to define a clear distinction between what is regarded as inside-specification vs. out-of-specification operating conditions to baseline what requirements the stack should be able to handle or recover from. Then, it is clearer what AST to run and which costs have to be paid to deliver robust stack performance for a dedicated application and secure stack lifetime.
- The team is focused on developing a drive cycle and extrapolating to 25,000 h to demonstrate lifetime viability. Given the recent work from M2FCT on determining full MEA ASTs, it would be good to leverage that work, either at M2FCT or in-house, and additionally use the AST as a proof of concept on the Plug stacks.
- It is not clear whether Plug intends to build fuel cell systems, and it is certainly out of scope for this work but would allow for the development of control strategies for the fuel cell stack and materials.
- More information should be provided on materials used and data generated. It is not clear how the MEA performance and durability compare with DOE targets.
- The project team needs to make sure the project meets clear go/no-go decisions. It is unclear what size stacks will be built in Phase II.

Project #FC-339: M2FCT: Million Mile Fuel Cell Truck Consortium

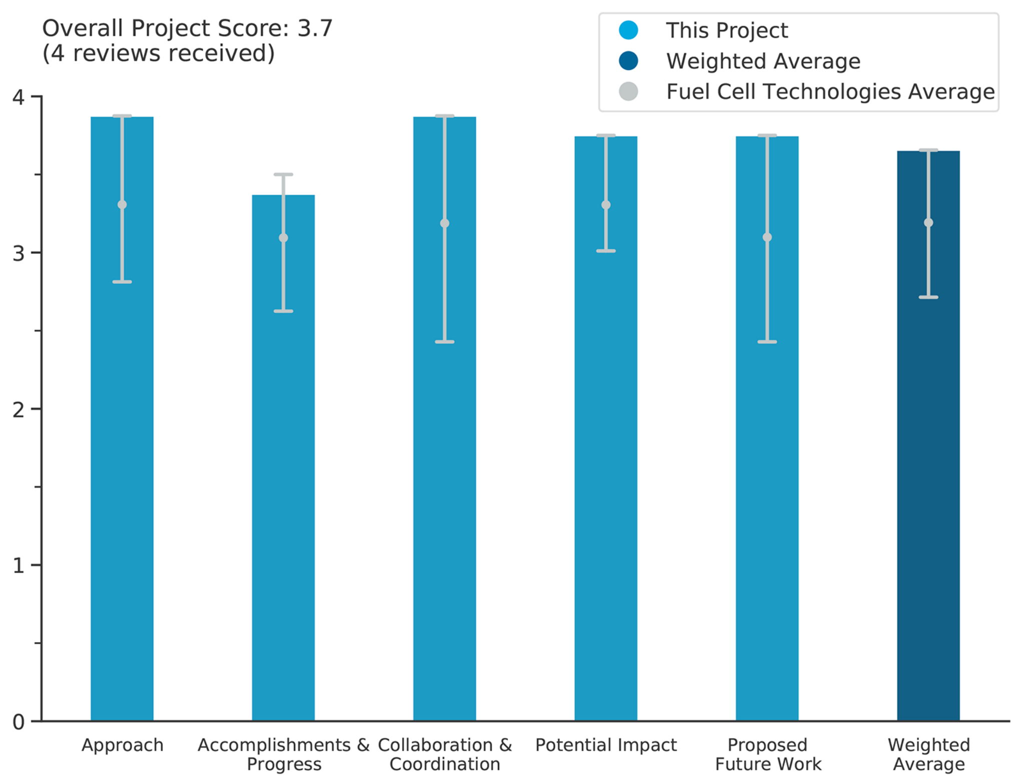
Rod Borup, Los Alamos National Laboratory, and Adam Weber, Lawrence Berkeley National Laboratory

DOE Contract #	WBS 1.5.0.402
Start and End Dates	10/1/2020–9/30/2025
Partners/Collaborators	General Motors, Nikola Corporation, Carnegie Mellon University, 3M, The Lubrizol Corporation, University of Tennessee, Knoxville, Cummins Inc., Plug Power Inc., Raytheon Technologies Corporation, NeoGraf Solutions, LLC, TreadStone Technologies, Inc., Caterpillar Inc., Eaton Corporation, R&D Dynamics Corporation, MAHLE Powertrain, LLC
Barriers Addressed	Cell durability: 25,000 hours (2025), 30,000 hours (2030) Peak efficiency: 68% (2025), 72% (2030) Fuel cell system cost: $80/kw (2025), $60/kW (2030) Overall target: 2.5 kW/g_{PGM} power – 750 mW/cm^2 (1.07 A/cm^2 current density at 0.7 V) – after 25,000-hour-equivalent accelerated durability test

Project Goal and Brief Summary

The project team is working to construct fuel cells that provide 2.5 kW of power per gram of platinum group metal (g_{PGM}) after a 25,000-hour-equivalent accelerated durability test. The purpose is to create durable and efficient fuel cell designs suitable for adoption by the heavy-duty (HD) vehicle market.

Project Scoring



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

Question 1: Approach to performing the work

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

- This year, there are 15 new funding opportunity announcement projects, some of which will be supported by M2FCT. Year 4 is for getting components into a membrane electrode assembly (MEA) for trucks. The team shows a very logical approach. First, the team looks at models to see what to expect. Next, the team examines smaller-component properties. Then, the team puts the MEA together and, finally, puts the fuel cell system together and tests the system to see whether it meets the project target. All of this makes sense. (Both slide 1 and the pdf file have "weber_2023" in the title of the file, although the two files are different. This caused confusion.). Targets are clearly spelled out in slides 2 and 3. Activities addressing diversity, equity, inclusion, and accessibility (DEIA) are listed on slide 64, though the team notes that neither a DEIA plan nor a community benefits plan was required. The team is commended for its work on the Minority-Serving Institution [MSI] Partnership Program. The national labs are not required to submit a safety plan for review by the Hydrogen Safety Panel, as described on slide 9. The main approach is described on slide 8. After looking at the catalyst, support, and membrane material, the team puts everything together to make and characterize the fuel cell (on slide 37); this is straightforward.
- M2FCT is an extremely valuable project with a unique task of bringing all stakeholders in the development of HD applications together, allowing for the development of uniform standards, guidelines, and practices. The barriers associated with the HD technology as a whole, as well as the barriers of unifying processes across the industry, have been very well identified, and substantial progress is being made against those barriers. The DEIA efforts have been thorough to this point, with multiple interactions with MSIs and historically black colleges and universities and through the personnel involved directly in the project.
- M2FCT manages projects and efforts, at both low and high technology readiness levels, that have the opportunity to reduce cost by improving durability, reducing PGM loading, or increasing performance.
- The project summary presentation provided excellent background slides on the consortium's scope and the drivers for the project objectives, goals, and milestones.
- Efforts are needed to establish standards for durability testing among original equipment manufacturers (OEMs), suppliers, and labs, especially with new-generation, state-of-the-art materials.

Question 2: Accomplishments and progress

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

- A spider chart illustrates the 2024 status of various targets (on slide 21), and it shows that various performance and durability targets have been or can be met using system mitigation techniques. However, reducing the error bars and making the model more robust and realistic remain issues. The biggest issue appears to be the high cost of the fuel cell system. Slide 6 shows how the team will reduce the cost of the fuel cell system. From the experiments in the M2FCT project, the team should show how the increased durability, increased power density, and reduced catalyst loading of the fuel cells directly caused a cost reduction of the fuel cells. In other words, the team should explain how the experimental results from this project affect the total cost of the fuel cell system. Moving to the materials development section (slide 23), it looks like the team has found several catalyst samples that will meet the durability (end-of-life) targets, but no mention is made of the sample size. The reviewer does not remember whether the presenters mentioned the size of the samples during the talk, but including that information on the slide would be helpful in determining how difficult it will be to meet the 2024 and final project milestones. On slide 30, the team notes that the project is "on track to deliver 10 g $L1_0$-PtCo/CZIF-8 (carbonized zeolitic imidazolate framework 8) batches" to meet the quarterly progress milestone for the third quarter of fiscal year 2024; this is great. The work on new catalyst supports such as CZIF-8 looks promising for MEA durability. Ellagic acid, especially combined with Ce, looks like a great antioxidant for membrane durability. These studies should definitely continue. As noted in last year's DOE Hydrogen Program Annual Merit Review (AMR) report, some organizations around the world are questioning the use of polyfluoroalkyl substances (PFAS, the "forever chemicals") to make fluoropolymer coatings and products, and the question of using fluorinated membranes in MEAs arises. As noted on slides 33 and 67, the authors plan to look at hydrocarbon membranes without fluorine, and they are urged to continue with those plans.

- The project has demonstrated incredible progress toward its goals, including establishment of MEA, stack, and system targets that must be achieved for viability in HD applications. At this point, the project is shifting toward an increased focus on durability and accelerated stress test (AST) development, which is traditionally something that has not been unified across the industry. The team has a thorough catalyst-specific AST and has now presented an in-progress and under-evaluation full AST that targets potential weaknesses in both catalyst and membrane technology.
- Over the past three years, M2FCT has demonstrated significant improvements in electrode performance, with reduced losses after an AST. A number of these catalyst materials meet the 2024 performance target. Demonstration of membrane durability and extrapolation out to the lifetime target of 25,000 hours seem deficient. Much of the preliminary work and methods have been established, but there is not a clear correlation between membrane durability metrics monitored during ASTs (fluoride emission rate [FER], cerium migration, membrane thinning, and crossover current) and a reasonable Class 8 HD vehicle drive cycle. Obviously, membrane durability tests take a long time, especially for state-of-the-art materials, but this is an area where industry is struggling.
- The primary apparent weakness with the project is that it seems to be moving slowly. The table of milestones was difficult to follow regarding whether milestones were on track or behind schedule. Other presentations at the AMR typically indicated clearly if a milestone was completed, on track, or behind schedule. The accomplishment slides presented did report significant developments, such as MEA durability and system modeling, in advancing the state of the art with respect to HD technology.

Question 3: Collaboration and coordination

This project was rated **3.9** for its engagement with and coordination of project partners and interaction with other entities.

- For years, the team has collaborated with MSIs and minority business enterprises. That work is commendable and deserves continued support. As noted on slide 2, the team is working with many partners, including the national labs, other labs, universities, and industry. In addition, the team developed an AST working group and carries out extensive work with the International Durability Working Group, sharing data, exchanging materials, and promoting the development of AST protocols. Interaction with those groups is applauded and should continue. The principal investigators are the best in the world.
- M2FCT is a unique project not only in the amount of work that is done internally but also in the level of interaction and collaboration across the fuel cell environment. This includes the discretionary projects, as well as direct industry feedback and input. This is vital if the project is to succeed at its goal of developing industry-wide standards and practices for HD application of low-temperature proton exchange membrane fuel cells (LT-PEMFCs).
- The sheer number of individual contributors across multiple institutions and the quality of work produced demonstrate great collaboration. It would be interesting, though, for M2FCT to work with some suppliers and use a non-proprietary short-stack design to analyze variations from subscale to full-scale durability and performance testing.
- The consortium has a strong group of members with varying capabilities and varying roles in the value chain. There do not appear to be any deficiencies in consortium partnerships.

Question 4: Potential impact

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

- As noted on slide 79, medium-duty (MD) and HD trucks generate one-quarter of all CO_2 emissions from the transportation sector—and with far fewer trucks on the road. The HD trucks are on the road more hours than passenger vehicles, so reducing the carbon footprint of HD vehicles is important. The 2025 target of the project is a fuel cell that will generate 2.5 kW/g_{PGM} power (1.07 A/cm^2 current density at 0.7 V) after 25,000-hour-equivalent accelerated durability testing, as projected using M2FCT-developed modeling methodology. The team has provided appropriate quarterly progress milestones and annual milestones that measure progress on the components, and the team is also always looking toward the project end target.

- M2FCT is perhaps the most vital current work on the technical side toward implementing LT-PEMFC technology for HD applications. While that is addressing only one potential use case of hydrogen in the United States, it is a critical contributor in meeting ultimate DOE goals for hydrogen manufacturing, storage, implementation, and use.
- The consortium has a clear focus on HD trucks, which are the clear first step for large-scale hydrogen fuel cell adoption. The background slides and waterfall chart were excellent. The only information that would have also been of interest would have been a clearer picture of where the HD industry is on average in terms of MEA performance, MEA durability, system-level cost, and system efficiency. Although manufacturers do not supply this information, M2FCT could be in a unique position to test OEM technology and anonymize the results for presentation to the industry. This would help to better validate the state of the industry and where improvements are needed to ramp up commercial traction.
- M2FCT focuses efforts where its resources can be best put to use: individual MEA component development and subscale testing.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The future work proposed is quite extensive, covering nearly all areas in need of development for HD applications. On the catalyst side, the primary goals are increased durability and scaling the most promising catalysts to date. For the membrane and ionomers, the focus is based around development of F-free materials, developing key factors such as transport properties and incorporating scavengers to improve durability. The team will also continue to focus on integration of catalysts and ionomers into electrode structures, with a focus on catalyst layer studies. Additionally, as the project progresses, development of full MEA ASTs will continue, as that is a key factor in being able to screen materials in a time-efficient manner.
- With regard to AST development, additional work should be devoted to the generation of a novel test article further optimized and representative of full-scale systems. It is important that these ASTs be run on the most common set of equipment possible across the field to ensure results are comparable, and the resulting data can be solicited and shared with the field. Both labs and industry have a limited amount of testing capacity and their own priority list for workstreams to develop fuel cell systems. ASTs must be shown to differentiate membranes specifically at end of test.
- This project was originally scheduled for completion at the end of the next fiscal year. For the rest of the project, the team should continue to complete tasks, especially to scale up synthesis of the best-of-class catalyst to 10 g batches and integrate into large-active-area MEAs, as well as to develop non-fluorinated hydrocarbon ionomers.
- The plan for future work is excellent.

Project strengths:

- It is difficult to relay succinctly the amount of work that has been accomplished thus far in this project. Catalysts meeting the DOE targets have been identified, and their durability is under investigation and being improved regularly. New synthetic methods and characterization tools are being implemented to better understand the catalyst materials at both beginning and end of life. New hydrocarbon ionomer materials are being evaluated to reduce the necessity of fluorine chemistry as increased regulation becomes prevalent worldwide. Integration of all these materials is being thoroughly studied to optimize electrode development. Materials are being scaled to roll-to-roll coating to evaluate defect-free direct membrane coating. Durability of these materials is being evaluated, and promise is being shown in mitigating carbon oxidation through the use of additives. ASTs to target catalyst degradation have been developed, validated, and implemented. ASTs are in development for full MEAs.
- The team members are extraordinarily strong, with many experts contributing to the project. The team is careful to include efforts to improve all of the important properties of each component, and the team

members always keep their eyes on the target of the entire project. Every time the reviewer identified something that the team should include, the issue was found to have already been anticipated and addressed; this is outstanding.

- The project is squarely focused on addressing targets for HD fuel cell truck adoption. This consortium is critical to DOE Hydrogen Program objectives, as HD applications are the best option for fuel cells to gain commercial traction, and the project enables decarbonization of a heavily polluting sector. The team has developed ASTs to support developers that are tackling the challenges with this demanding application.
- Strengths include fundamental work in catalyst development and electrode design.

Project weaknesses:

- While these are not necessarily weaknesses of the project as a whole, some minor comments are below.
  - It was noted that while the AST is being developed at ~100 hours, it actually takes ~350 hours to proceed through it. The team should specify what is being done to actively reduce that timeline to as close to the 100 hours as possible.
  - It is not clear what difficulties have been identified thus far in scaling the most promising catalysts to the 10 g scale or what difficulties are predicted moving forward to the eventual kilo scale.
  - Slide 27 showed that annealing at 800°C prevented large particle growth after the catalyst AST. It is unclear what optimizations are actively being carried out on annealing temperature.
  - There was mention of sonication as a current method of dispersion. It is unclear whether other high-shear processes that may have to be implemented at larger volumes have been considered.
  - FER of the NC700 membrane increases over the first 300 hours and then begins to decline. Perhaps this is simply because all easily removable F is removed during that time. It is unclear what changes to the fluorine chemistry would help mitigate early lifetime loss of F.
  - Regarding alcohol vs. water-rich durability, it seems there may be a fear that everything would revert to a water-rich environment during operation and water generation.
- The biggest perceived weakness of this project is that it appears to be moving slowly and/or behind schedule. With the amount of funding being allocated, the consortium needs to move more quickly with solidifying ASTs.
- As noted in previous years, this is a huge project, and it could be difficult to keep track of everything.
- Weaknesses include modeling and scale-up at this stage, although that work is planned.

Recommendations for additions/deletions to project scope:

- It would be interesting to explore the durability of catalyst materials during representative drive cycles for HD and MD vehicles. The MD use case involves much more transient and idle operation, and it would be interesting to see how these new intermetallic PtCo catalysts respond to the different frequency of stressors introduced by alternative use cases.
- The project is very well outlined and progressing extraordinarily well.
- It is not clear that there will be enough time to hold a new discretionary project call and have it generate impactful results. The team should address what the purpose of the project call is. Slide 15 has a couple of typos that need correcting (the “a” in “Criteria” and an additional “0” added to “25,00”).
- Additional work on the anonymized average status of OEM technology would be of keen interest moving forward. Additionally, the consortium needs to find a way to correlate the AST to on-road stack test results.

Project #FC-344: Low-Cost Corrosion-Resistant Coated Aluminum Bipolar Plates by Elevated Temperature Formation and Diffusion Bonding

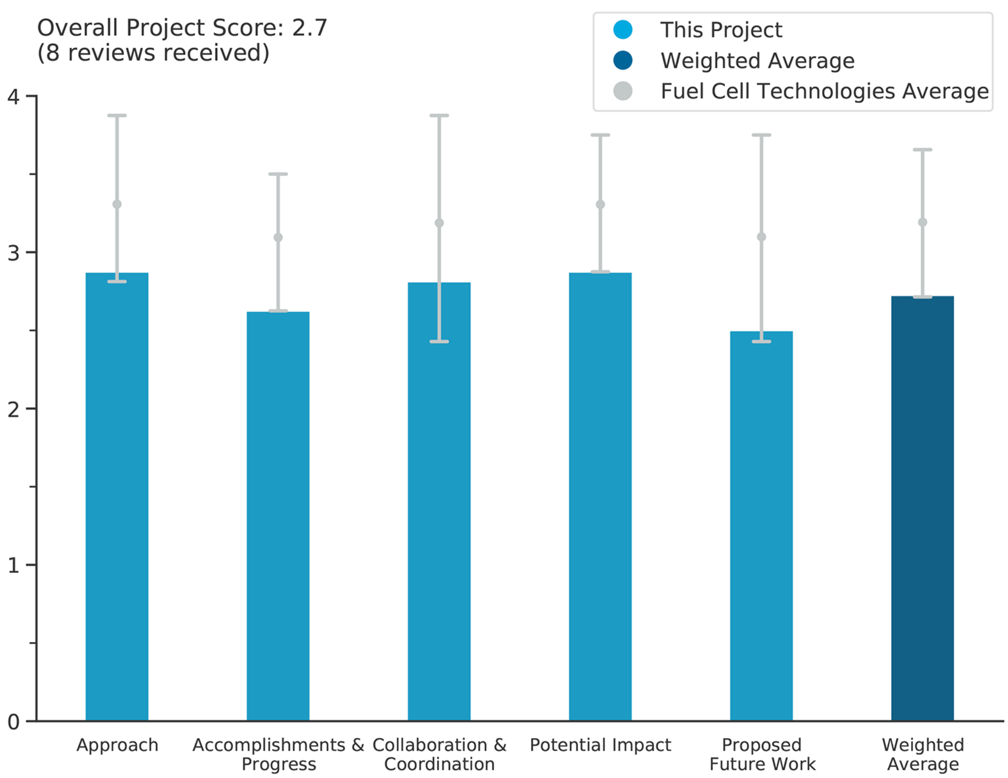
Tianli Zhu, Raytheon Technologies Research Center

DOE Contract #	DE-EE0009612
Start and End Dates	12/1/2021–11/30/2024
Partners/Collaborators	Pacific Northwest National Laboratory, TreadStone Technologies, Inc.
Barriers Addressed	• Targeted bipolar cost of $5/kW

Project Goal and Brief Summary

The project focuses on developing a defect-free coating process to fabricate low-cost corrosion-resistant coated aluminum bipolar plates (BPPs) for proton exchange membrane (PEM) fuel cells. BPPs are crucial in PEM fuel cell stacks, contributing to their weight, volume, and costs. The project utilizes elevated temperature forming (ETF) and diffusion bonding (DB) and is developing a defect-free corrosion-resistant titanium coating, optimizing TreadStone Technologies' (Treadstone's) DOTS technology using carbon particles or gold to meet performance targets.

Project Scoring



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

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Low-cost Al protected by Ti foil has good potential to bring cost down, and such a strategy has been successfully used in other types of fuel cell BPPs. Simultaneous use of ETF plus DB is innovative, with good potential for cost reduction. Carbon plus Ti composite coating may increase cost but will have performance and durability advantages.
- Usage of aluminum is a unique idea, and it might be a weight-reduction enabler. However, in the project, the application/design requirement for the BPP material development is not clarified. Also, technical targets of major attributes, e.g., weight (substrate thickness), formability, and yield rate (manufacturing process) are not mentioned in the project. Use of aluminum as a plate substrate may be applied to the area that requires significant weight reduction. Probably the weight target is higher than the DOE guideline. Substrate thickness, formability, and yield rate are highly related. Proper targets for major attributes are necessary. The current approach of using thick aluminum substrate and a time-consuming heated stamp does not seem to be appropriate. Leaching out of aluminum ions is harmful to the PEM. It is necessary to set an Al elution target.
- A thin Ti layer (0.007 mm) sandwiching an Al layer has the potential for lower cost and lower weight than utilizing a single metal (e.g., Ti or stainless steel [SS]). Carbon deposited on a Ti surface is a proven technology (e.g., Toyota Mirai), and the gold DOTS are also proven, although maybe not quite as commercialized. The project is currently unable to perform DB and form in one step, which is an obvious path.
- The proposed approach seems sufficient to assess technical feasibility. The amount of iteration and optimization that can be performed is unclear. However, these iterations will be critical to minimizing cycle time while maintaining system performance. It appears that demonstrating feasibility will be an important first milestone, but optimization will be critical to determining commercial viability.
- The proposed approach is aligned with the scope and objective of the project.
- It is not clear whether other approaches to bond Ti to Al have been investigated. The thickness window target for this approach is not defined. Without a target thickness window, there will be many trials before an optimum coating can be designed. The scalability of the process is not clear. To minimize time to increase the technology readiness level, the process scalability/feasibility needs to be considered before further trials.
- It would be good if some of the advantages over SS were made more apparent to justify the increased process complexity. Only the go/no-go milestone was listed. The team should include all milestones to better show project objectives.
- ETF and thermal DB are very slow processes. This approach of individually bonding the Ti protective layer is a non-starter for reaching reasonable production rate targets set by DOE and fuel cell original equipment manufacturers (OEMs).

Question 2: Accomplishments and progress

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

- The project has made good progress, including the development and testing of a simultaneous forming and defect-free coating process to fabricate low-cost, corrosion-resistant coated aluminum for use as BPPs for PEM fuel cells.
    - Good connection is made between cost and performance, and cost drivers are addressed well. This project addresses fuel cell cost and durability by developing low-cost, corrosion-resistant coated aluminum BPPs and fabrication techniques. It is quite challenging to achieve $5/kW, including processing cost.
    - Proof of concept is encouraging, with the goal being to develop Al-based, corrosion-resistant (using Ti coating) BPPs through ETF-DB and DuraC technologies that aim to meet the Hydrogen and Fuel Cell Technologies Office (HFTO) 2030 technical and cost targets for BPPs.

  - The project completed subscale die design, and fabrication is in process. The team developed secondary forming capability to carry out a forming trial while critical equipment is being repaired.
  - The project completed preliminary DuraC coating on a Ti sheet, with single-step coating and bonding in development. Cost analysis identified potential paths to meet the DOE BPP cost target of $5/kW.
- Good progress has been made toward the coating technology targeted. However, it is not clear if sufficient effort has been dedicated to understanding the fundamentals in the process. It seems the effect of heat cycles to cure carbon coating has not been studied. In slide 11, it is not clear whether there is a formation of a TiC layer. It is also unclear whether the carbon coating (1) is achieved via chemical vapor deposition or a similar coating from a carbonaceous precursor or (2) is a direct carbon coating via physical vapor deposition In the cost analysis on slides 12 and 13, capital cost to scale the process needs to be included. Sheet dimensions, BPP process (batch or roll-to-roll), and material usage efficiency have not been considered in the cost modeling.
- The presented accomplishments are correct, but there are remaining critical open issues:
  - Whether the proposed process is compatible with high-volume production rates (millions of pieces).
  - How this double-coating BPP will become cost-competitive.
  - The welding of such BPPs, although Al/Al is not easy to master.
  - How the stamped edges will avoid galvanic corrosion, an uncertainty that was already raised at the last Annual Merit Review (AMR) but has not been addressed.
  - How lowering the Al thickness will affect hydrogen permeation.
  - Long-term evaluations (>1,000 hours) in short stacks are highly expected.
- Having the primary piece of equipment required for fabrication break is a huge blow to the project. The work with the subscale die is a clever way of moving things forward; however, there will still be shortcomings in terms of ability to effectively optimize. The success of this project relies on the ability to successfully form the BPP within a duty cycle that makes the cost attractive. Without that level of investigation, it will not be possible to understand success.
- The material tests conducted show no new information on the capability of using cladding, which was demonstrated almost a decade ago through a DOE-funded project by Ford. That project used different metals, yet the concept is similar. The approach by Ford used a roll-to-roll cladding process, and this project has not made much improvement since that work. https://www.energy.gov/sites/default/files/2017/05/f34/fcto_biploar_plates_wkshp_hirano.pdf. The stamping coupon results have not been published, but the model shows promise. However, there is some concern that the differential elongation between Al and Ti will result in pinholes for the Ti layer and thus be ineffective for corrosion protection. Corrosion results on stamped coupons without any coating should be added as go/no-go criteria.
- Results to date look minimal. It is unclear if the project has yet to diffusion bond a Ti sheet with Al. Neither coating method has been used yet. (The presentation says "corrosion-resistant coating process identified"—that was surely in the original proposal.) The primary result is the technology to market (T2M) analysis. The materials that have been bonded do not seem to have been tested for adhesion or post-forming.
- There are concerns about whether this process can be translated to scale, due to the 12-minute cycle time for DB. It was stated in the question-and-answer session that this process could be parallelized to larger presses. It would be good to know whether those presses would have the necessary uniformity of temperature and pressure. It is concerning that no data on corrosion currents were presented in either the 2023 or 2024 presentation.
- The heated stamp seems to be effective in forming a BPP flow field, but the substrate thickness of 250 cm^2 and the 12-minute cycle time are highly questionable for weight reduction and volume production.

Question 3: Collaboration and coordination

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

- It is good to see the collaboration with Pacific Northwest National Laboratory (PNNL) and Treadstone leveraging their complementary strengths.
- Treadstone has extensive experience in this area. PNNL engagement for ETF and DB and testing is valuable.
- As it is early in the project and the different collaborators are working on different areas of the project, their efforts seem separate. It does not appear to be an issue at this point and should evolve as the project progresses.
- It is good to involve national labs for formability and material evaluation. It would be good to include the fuel cell stack OEMs or experts who know BPP design requirements to set proper technical targets and design evaluation tests in the subscale stack.
- Collaboration between partners seems to be sufficiently effective. However, project delays due to equipment failure suggest that alternate approaches or partners were not considered. There are still sufficient funds available to have explored alternate facilities to help meet milestones.
- Collaboration appears correct.
- While the team seems to have the right pairing of complementary strengths, it would be good to see more experimental results from RTX.
- The project has three formal project partners: RTX, PNNL, and Treadstone. However, Treadstone and the gold DOTS process do not seem to be the technology with which the project is moving forward.

Question 4: Potential impact

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

- Lower-cost BPPs and their durability are critical to meeting DOE goals. This work addresses both issues. The project is directly in line with HFTO 2030 targets.
- Low-cost, lightweight BPPs are a need for fuel cell electric vehicles. Few projects have utilized Al as a base metal.
- BPPs are a significant contributor to the cost of electrolyzers. This method, if successful, could help to reduce this cost and improve the rate of adoption of hydrogen electrolyzers.
- Achieving low-cost and durable BPPs will contribute to lowering the costs of stacks.
- Lightweight BPPs may have an impact on weight-sensitive applications such as aviation.
- The project goals align well with DOE targets for BPPs. A path to <$3/kW is promising. However, the cost to scale (capital expenditure investment) needs to be amortized, as well as the material usage efficiency.
- The project seems aligned with HFTO objectives to reduce costs of BPPs. It could be improved if data were provided regarding prospects for manufacturing at HFTO target rates. Also, it is hard to tell if performance of these materials will meet HFTO targets.
- The project objectives are aligned with DOE goals. However, it is not expected that this project will contribute to any significant improvement toward the goals for BPPs compared to carbon-coated 316L grade SS.

Question 5: Proposed future work

This project was rated **2.5** for effective and logical planning.

- The critical flaw in the approach is the 12-minute cycle time to bond and form the plate. Typical progressive die stamping is less than 2 seconds per plate. There is no way that this project is going to close the >100× gap in cycle time. Also, stamping will lead to cracks/gaps in the Ti–Al interface; therefore, Al will not be protected. The project leaders either do not know these critical flaws or are choosing to ignore the input from their peers. Therefore, the proposed future work needs to include a go/no-go review with (1) post-forming corrosion of coupons and (2) process analysis for forming and bonding with a cycle time of ~10 seconds.

- Budget period (BP) 2 is built on the success of BP 1 (completed). Characterization for durability testing is needed, along with completed initial corrosion testing of DB-treated subscale validation die coupons fabricated using ETF. Functional requirements must be met, including flexural strength >40 MPa and forming elongation of >40%. The cost of two layers and application process is very important. There should be a techno-economic analysis pathway to <$5/kW. Use of DOE design of experiments for the ETF+DB process is a good strategy for minimizing risks.
- It is necessary to set proper targets for major attributes based on the design requirement. The targets of weight, formability, and yield rate (manufacturing process) are imperative, and technical approaches need to be clarified.
- It is unclear if there are any limitations in flow field geometries that cannot be achieved. If there are foreseeable hurdles to molding/machining or defect formation during the process, those need to be addressed with sufficient mitigation.
- The project depends on the ability to demonstrate feasibility from the secondary forming capability and/or repair of the primary system. These challenges may limit the project's ability to demonstrate a feasible process. Detailed process optimization work appears critical.
- A life cycle analysis (LCA) should be carried out to ensure also the sustainability of the proposed solution.
- It is hard to understand what the proposed design of experiments entails. Not much detail is given related to future work.
- It would be good to see more emphasis on corrosion testing of these parts.

Project strengths:

- The project principal investigator has extensive experience with designing robust carbon-based BPPs. However, in this case, the attempt is to create a Ti-coated Al or carbon-coated BPP. The approach to BPP development follows an old-school traditional development process. To achieve ambitious DOE cost targets, development projects need to take some risks while also following some traditional paths.
- The project includes an interesting technology proposal and impact to a factor that drives significant cost of electrolyzers, resulting in large potential for impact. Early data suggests feasibility.
- ETF+DB is highly promising. Adding carbon coating for conductivity benefits is a good idea with additional risk.
- The approach is one of few that utilizes Al as a substrate material, which can potentially reduce cost and weight.
- Finite element analysis and model-based formability simulation are strengths.
- The project relies on an experienced team of experts.
- The project has great goals.

Project weaknesses:

- A cycle time of 12 minutes to conduct DB seems excessively long by about two orders of magnitude. The T2M calls for a stack of 4, but a simple calculation says that for a stack of 200 cells, with 2 plates needed per cell with cooling in between, 20 hours are required for enough plates to make a stack. A bigger stack can probably be used, but it is unclear how big—not to mention the starting point of 20 hours per stack is exceedingly large. The project has not made significant progress to date. The primary accomplishment is T2M analysis. It is unclear whether this process will be cost-competitive with a simpler approach of using a single thin Ti sheet. The coating processes seem to be simply using existing processes, so it is a bit unclear what the purpose is of duplicating known processes (e.g., Toyota Mirai carbon coating on Ti and Treadstone Au DOTS).
- The largest concern is that, in the past two years, no data on corrosion resistance or other electrochemical properties have been presented. Because of the lack of testing data, it is not clear whether the team will be

able to meet the go/no-go points. The forming process seems too slow relative to the DOE heavy-duty vehicle 20,000 stack/year target. The project team should consider pathways to manufacturing.

- The project follows limited processes for Ti coating on Al. It is not clear why alternate routes were not considered when the project encountered delays due to equipment failure. There seems to be sufficient DOE funding available to explore new methods rather than waiting for equipment to be fixed.
- Ti DB plus carbon coating may increase cost and interfacial resistance, and gold particles may increase cost. Keeping composite structure mass-producible is very important.
- Critical issues raised (especially the impact of the cutting edges) during the last AMR have not been addressed. If no correct mitigations are found, there will be no viable industrial solution proposed. LCA and recycling are not considered.
- The project relies on a terrible approach, and finding fatal flaws early suggests a lack of vision.
- Understanding of BPP design is a requirement.
- There is a lack of primary forming capability.

Recommendations for additions/deletions to project scope:

- The researchers need to experimentally prove they can diffusion bond a thin layer of Ti to Al and then form without invalidating the Ti layer. The project should include DB and form in the same step, as likely would be done in manufacturing. In terms of the DB process, it is much simpler to make small coupons for an ~250 cm^2 active area plate, especially when stacking is required. This issue should be addressed.
- It would be good to see some novel/innovative approaches to creating new robust coatings for BPP. It would also be good to see the large-scale manufacturing capacity of Treadstone, and the path to achieving <$3/kW is not clear.
- It is necessary to clarify the application area and design requirements of this BPP. Also, the design and material verification method should be properly defined. It is recommended that the project add members who provide the project with understanding of BPP design requirements and methods of design verification (test protocols).
- Go/no-go review should include (1) post-forming corrosion of coupons and (2) process analysis for forming and bonding with cycle time ~10 seconds.
- A detailed process optimization plan would be helpful. BP 2 go/no-go does not contain metrics that would effectively judge the technical success of ETF related to the physical form of BPPs formed.
- Because of project delays, it could be worth considering only DOTS or DuraC coating. This is not required but might help make up for delays.
- Comparative evaluation of costs and benefits of different configurations on performance and durability will provide valuable guidance.
- LCA and recycling should be added to the project scope to ensure its sustainability.

Project #FC-345: Development and Manufacturing for Precious-Metal-Free Metal Bipolar Plate Coatings for Proton Exchange Membrane Fuel Cells

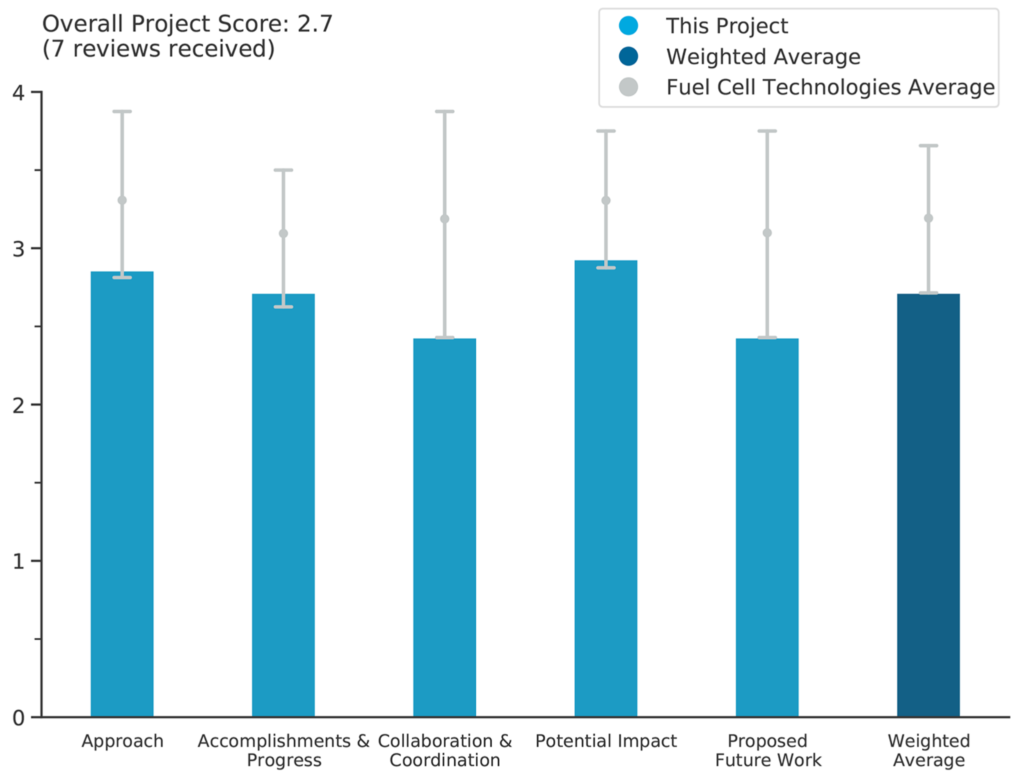
CH Wang, Treadstone Technologies, Inc.

DOE Contract #	DE-EE0009613
Start and End Dates	9/17/2021–3/31/2024
Partners/Collaborators	Los Alamos National Laboratory, Pacific Northwest National Laboratory, University of Tennessee, Knoxville, Austin Power
Barriers Addressed	Bipolar plate durability and cost: • Cost: <$5/kW (2025) • Resistivity <10 mΩ.cm^2 • Corrosion <1 x 10-6 A/cm^2

Project Goal and Brief Summary

The project focuses on developing a cost-effective fabrication process for precious-metal-free doped titanium oxide (TiO_x) coatings on low-cost metal substrates (low-grade stainless steel [SS] and aluminum) for heavy-duty applications in proton exchange membrane fuel cells (PEMFCs) suitable for roll-to-roll manufacturing processes. Bipolar plates (BPPs) are the second-most expensive component in PEMFC stacks. The goals include reducing the manufacturing cost of metal BPPs to meet a cost target of approximately $5/kW, developing an accelerated stress test (AST) protocol for rapid evaluation of BPPs, and investigating the conductance mechanism of the TiO_x coating. Activities include demonstrating viability of diffusion-bonded titanium to aluminum, improving diffusion bonding cycle time, optimizing the TiO_x formation process on the Ti-Nb particle surface, demonstrating the TiO_x-coated BPPs in PEMFC single-cell evaluation (including operation under AST conditions), and investigating performance degradation mechanisms of the TiO_x coating under PEMFC application conditions.

Project Scoring



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

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is very good, focusing on tangible processes and materials focusing on low-cost BPP and coatings development. Aluminum BPP is likely a little far out in terms of application, but low-grade SS is more relevant.
- The approach is good; performance and cost are addressed separately by using low-cost metal supports with surface functionalizations that require no precious metals. The safety plan is reasonable for the scope of work, and an outside firm is being hired/consulted to develop the safety plan. The relationship to other relevant efforts could be communicated more clearly.
- Project goals seem reasonable. Including a goal of developing a scalable process is a good idea. It would also be good to understand the degradation mechanism.
- The work is well-focused and very applicable to industry needs. However, while the barriers of resistivity and corrosion are very well-addressed and supported with clear evidence, the cost barrier is not addressed. The $5/kW cost barrier is identified, but no evidence was presented on the cost of the coating process or whether it could be scaled up to a high-volume roll-to-roll process.
- The limitations to alloying elements and their content in creating various BPPs should be clearly stated. The variability in surface roughness of the BPP coating is not clear, and the performance as a function of surface roughness is not clear either. On slide 5, bonding Ti alloy particles on a metal substrate surface to obtain the desired topographic structure and composition seems to be a key objective. However, there are no fundamental studies to identify the desired topographic structure that results in the most robust corrosion-free surface for high BPP performance.
- The project approach is to reduce interfacial contact resistance (ICR) using textured coatings. This approach is not going to improve the ICR compared to physical vapor deposition (PVD) carbon coating.

The authors are using baseline-corrected ICR and reporting values lower than DOE targets. However, the targets table references the non-baseline-corrected ICR. The project has not shown any approach to reducing the processing cost of applying the coating to BPPs. A significant portion of the BPP cost, per the Strategic Analysis, Inc., analysis, is for the processing, not materials.

- The project is focused on low-grade SS and platinum-group-metal-free coating to meet the <$5 kW target. TiOx-Nb and SS seem to be the primary materials being examined. When comparing the approach slides to the slides related to technical accomplishments, this approach seems scattered. It is unclear whether the approach entails a coating on SS, AST development, or diffusion bonding of materials.

Question 2: Accomplishments and progress

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

- Outstanding progress was made on two of the three project objectives. The project shows clear ex situ evidence, suggesting the DOE targets for resistivity (<10 milliOhms cm^2) and corrosion (<1 $microA/cm^2$) can be met at end of life.
- The electrochemical corrosion potential (Ecorr) and corrosion current (Icorr) are presented for titanium-coated 316 SS for 10,000 cycles for the AST at Los Alamos National Laboratory (LANL). Other corrosion and resistance data are provided for the Nb-TiOx-coated 409 SS. It will be helpful to see the AST repeated for the lower-cost 400 series support metal BPPs.
- TiOx does not meet ICR targets. In addition, it seems that this coating is not pore-free, so use with a low-grade SS would seem problematic regarding Fe cation release. The AST in use is a fast 1.0 to 1.5 V triangle sweep, in H_2SO_4. This aqueous phase version of the DOE Carbon Support AST is meant for use in examining the stability of the carbon for shut-down/start-up cycles. While this version is clearly "accelerated," it is not obvious that this AST would not induce additional degradation mechanisms regarding material oxidation and corrosion. The logic for this AST is unclear. The effluent measurement by inductively coupled plasma mass spectrometry (ICP-MS) is an important step to understanding what (e.g., how many Fe cations) is released. It seems a target is needed for the Fe release rate with respect to membrane durability. The potential of the free corrosion current (open-circuit voltage) is decreasing during the AST, which is described as decay. However, it is unclear if this result is bad, good, or irrelevant. It is also unclear whether the decay is due to the SS or Ti. Measurement was performed on 316L SS, which is not a low-grade SS, with Ti, which seems to be a different coating material that the team was evaluating for ICR (TiOx-Nb). The Pacific Northwest National Laboratory (PNNL) work on diffusion bonding of Ti/Al is curious because it did not seem to be the approach of this project and is instead the approach of the Raytheon project.
- On slide 8, it is not clear what the Ti/Nb ratio is. The cost impact of adding more expensive material such as Nb to the process is not clear. Slide 10 seems to suggest corrosion after 1,000 cycles. It is unclear what this correlates to as a function of the 25,000-hour heavy-duty fuel cell electric vehicle durability requirement. In other words, the Icorr and Ecorr of a BPP at end of life should be explained. Without establishing those, the metrics of Icorr and Ecorr as functions of cycles will not provide any indicators regarding fuel cell lifetime requirements of 25,000 hours. The surface morphology after corrosion and the bonding at the interlayer of Ti/SS are unclear as well.
- The fundamental reason for the dependence of the coating texture on the ICR is not clear. Clarification on this front may help to enable the development of better coatings. The challenge with the low-grade SS is the elution of iron from the plate. An iron elution test to quantify the amount dissolved would be useful. Not much progress has been made on the aluminum plate this year. More work is needed, and not much data have been shared this year.
- There has been no big change in ICR, corrosion resistance, or cost since the previous funded projects circa 2014 and very little technical progress since the FC-105 project: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review14/fc105_wang_2014_p.pdf. New materials are being tried; however, there is little to no impact on key metrics such as ICR or corrosion resistance. Project cost progress is quite minimal as well.

- The understanding of why texture shape impacts ICR is not clear; based on images, it seems like it could be change in surface area. It is not clear how pressure data on slide 8 relate to pressures and resistances inside the fuel cell.

Question 3: Collaboration and coordination

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

- Good collaboration with LANL and PNNL was presented. The AST development and potentiostatic testing results from PNNL were crucial to demonstrating two of the project objectives. No results from collaboration with Austin Power or UTK were presented.
- The LANL, PNNL, UTK, and Austin Power collaborations supplement Treadstone's expertise in BPP fabrication, characterization, and cost modeling.
- The project has a good team with specialized capabilities.
- Collaborations with UTK and Austin Power are not clear. Future single-cell tests on BPPs under fuel cell operating conditions are planned. However, it is not sufficient if the test is conducted in a single cell; rather, multiple sets at the same conditions need to be tested for reliability and repeatability of the process.
- The project has multiple partners: Treadstone plus LANL, PNNL, University of Tennessee, Knoxville (UTK), and Austin Power. However, all the partners seem to be doing unrelated activities without coordination. Two of the partners (Austin Power and UTK) showed no results and did not seem to be mentioned.
- It feels like LANL and UTK are just repeating tests or running protocol development to verify what has been accepted as baseline standards since 2014. There is no value in developing a new AST. Austin Power is supposed to do manufacturing cost analysis, yet there are no data and no update from that partner.
- It is not clear what PNNL and UTK have contributed to the project. A clearer explanation would be useful.

Question 4: Potential impact

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

- The support material is 70% of the cost of a BPP, even in the precious-metal-containing BPPs. This project is addressing the BPP cost by using lower-cost alloys for the support materials, then coating them to add functionality. This methodology is a logical way to address the required cost metrics.
- A high-volume BPP coating process that meets or exceeds the resistivity and corrosion performance of conventional Ti/C coatings but at a lower cost would significantly advance the Hydrogen Program goals. Strong evidence was presented supporting the first two goals; however, no supporting data was presented on the cost target.
- The project seems appropriately aligned with Hydrogen and Fuel Cell Technologies Office (HFTO) goals. Though probably not part of the goals of the funding opportunity announcement that awarded this project, it would be good to know if there is a pathway to reaching HFTO fuel cell manufacturing targets.
- Meeting fuel cell cost targets requires low-cost BPPs. Using low-cost base materials is a good approach.
- The project is in alignment with DOE goals for low-cost BPPs. However, the project is aiming to scale a single process. There needs to be some budget allocated toward investigating alternate materials and processing. Some risks need to be taken to investigate novel methods/materials to achieve the ambitious cost targets set by DOE. High-risk, high-reward approaches should be pursued when the target is almost unachievable.
- The project is excellently aligned with DOE goals yet has no potential to impact the cost metric since there is no work on process optimization of the coating.
- The project is very likely to have direct impact on the cost of fuel cells developed, but more work is needed from the team.

Question 5: Proposed future work

This project was rated **2.4** for effective and logical planning.

- The plan to test the coating in a proton exchange membrane single cell under AST conditions is a natural progression of the testing and should provide significant evidence of the coating's durability. While investigation of the degradation mechanisms in the single cell is very worthwhile, it is not clear how these studies will be performed, so it is hard to judge how they will contribute to the project. Although investigation of the manufacturing costs is not discussed in the future plans, these studies would be critical to project success and should be included.
- It is good that the team has included studies in single-cell fuel cell tests. It would be good to see more specifics about what degradation mechanism studies the team plans to carry out. The project has a stated goal of translating to a roll-to-roll process but no mention of work toward this goal.
- The single-cell and AST tests will reveal pertinent information about the lower-cost steel-supported BPPs. The expected cost savings can be realized only if adequate durability is also demonstrated.
- Demonstrating a new material for a coating on a machined single cell, while interesting, does almost nothing to prove the technical merit of the coating. The project leader claims that the project does not have the budget for a stamped plate. Small coupons (~3 cm x 3 cm) can be made within $10,000. It is suggested that the project leaders use their connections to find vendors to do small coupons to evaluate ICR and corrosion of stamped coupons/plates.
- The materials presented seem relatively unrelated (TiOx-Nb coating on low-grade SS, 316L with a Ti PVD coating, and then diffusion bonding of Ti on Al). It is unclear where this project is heading. Future work says the TiOx coating will be a focus, but the coating did not meet the ICR target; so perhaps the focus might instead be the TiOx-Nb, but it is unclear.
- The investigation of performance degradation mechanisms of the TiOx coating under PEMFC application conditions needs to be defined better since operating conditions vary from light-duty cycles to heavy-duty truck conditions.
- More work is needed to look at the coating defects, contamination, and contact resistance dependence on microstructure. Not much has been shared here.

Project strengths:

- The support material is 70% of the cost of a BPP, even in the precious-metal-containing BPPs. This project is addressing the BPP cost by using lower-cost alloys for the support materials, then coating them to add functionality. This methodology is logical for addressing the required cost metrics.
- Project strengths include (1) the simple composition of the coating (deposition of particles instead of complete layers should, theoretically, allow for a faster coating process and lower cost) and (2) good ex situ testing and AST development.
- The team seems strong, and results are promising. Materials have met many of the technical targets.
- Measurement of Fe cations during the corrosion testing is crucial for a porous coating on a low-grade SS.
- The project has a good team and approach relevant to the application and cost reduction targets.
- The project includes innovative material choices and surface textures.
- The principal investigator has extensive experience in industrializing BPP coatings. However, the approach is too conservative and lacks exploring novel methods to achieve cost targets.

Project weaknesses:

- There is a lack of any cost analysis. No direct comparisons of the performance metrics were made between coated 409 SS and 316 SS. For example, data were presented only on IRC AST with 409 SS; Ecorr and Icorr vs. cycle count was presented only for 316 SS. Total ion leach rate was presented only for 409 SS. Testing was performed on 409 SS when no cost analysis was presented demonstrating a significant cost saving vs. 316 SS. No data were presented showing the effect of Ti leaching on fuel cell durability.

- The cost impact of forming processes needs to be considered, in addition to the cost of base materials. Forming costs or production rates can be more challenging for 400 series steels than 300 series, and both are significantly more difficult to form than aluminum.
- Not much work has been done. It is not clear how much time is dedicated to the project. This concept is interesting, but more focus on deliverables is needed. Simple fabrication of few coatings and basic electrochemical measurements do not warrant so much money from DOE.
- The project appears uncoordinated between the partners, with each partner working independently on different materials. It is not clear if the Treadstone base material (low-cost SS) will meet corrosion targets with a non-contiguous coating. This material should be corrosion-tested as soon as possible.
- Presented results of degradation mechanism studies are lacking. It is not clear what PNNL's role in the project is and how it is different from work in FC-344.
- The approach is too conservative. High-risk, high-reward approaches need to be pursued.
- Focus is lacking on processing cost and corresponding optimization.

Recommendations for additions/deletions to project scope:

- This project needs to coordinate its partners so they are all working in the same direction. For example, the corrosion testing should be conducted on the materials being developed by Treadstone. This project needs to narrow down what the material and approach are and then develop the material and measure the performance. The results/materials are scattered. The Treadstone base material (low-cost SS) with the TiOx-Nb should be corrosion-tested as soon as possible. The team needs to present some information regarding whether these materials and processes will meet the cost targets. The AST should be validated to understand if the high potentials being used simulate in-cell corrosion or if they potentially add in surface oxidation, which is never reduced. The team should explore a reduction step going down to normal fuel cell operating conditions (e.g., 0.6 V) to reduce the surface oxides. Understanding the BPP degradation mechanism and whether the corrosion AST matches it should be accomplished.
- A cost and manufacturing analysis will be critical for the success of this project. Analysis of the trade-offs vs. cost with 409 SS vs. 316 SS is needed. It is unclear what the expected reduction in durability is (increase in Fe leach rate and change in ICR) when using 409 SS vs. 316 SS. The team should increase the AST cycle count to >30,000 to be in line with membrane electrode assembly ASTs and Million Mile Fuel Cell Truck (M2FCT) targets. Including fluorine in the electrolyte might be worthwhile. Measurement of the fluorine release rate in the single-cell effluent would be useful, as well as measurement of the Fe and Ti concentration in the single-cell effluent.
- The team should consider the cost impacts of the forming steps required, in addition to the raw materials costs, when selecting a 400 series steel over a 300 series steel.
- The project should switch to stamped coupon studies and conduct a thorough process analysis.
- UTK's contributions are insufficient and perhaps can be dropped going forward.

Project #FC-346: Fully Unitized Fuel Cell Manufactured by a Continuous Process

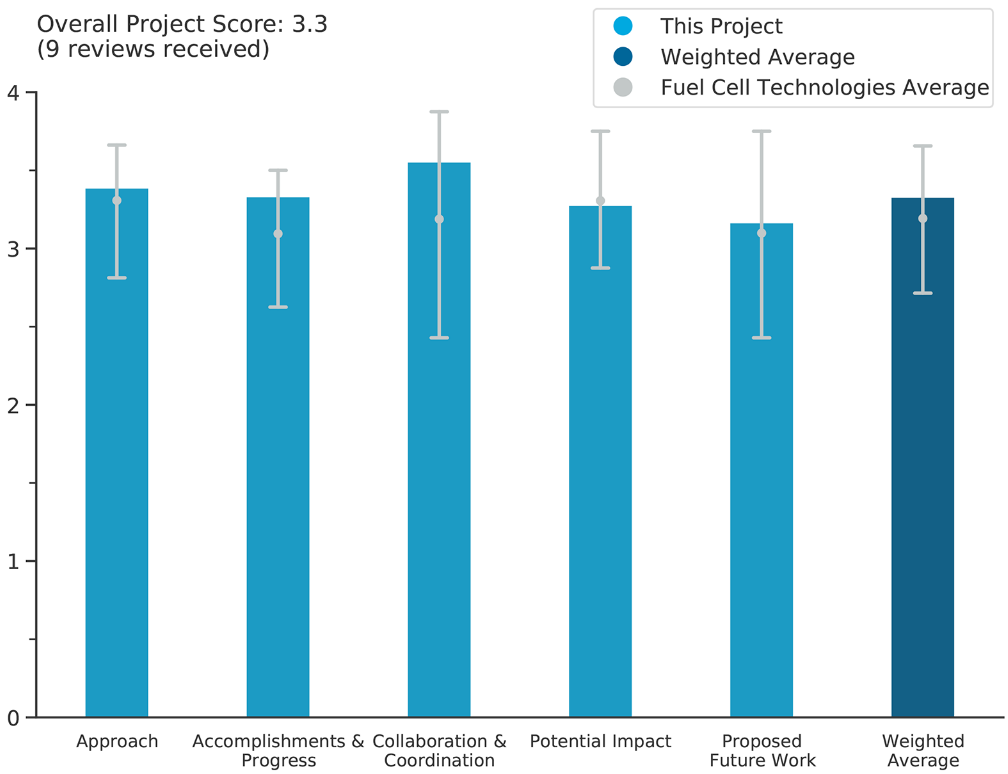
Jon Owejan, Plug Power Inc.

DOE Contract #	DE-EE0009614
Start and End Dates	2/1/2022–1/31/2025
Partners/Collaborators	University of Tennessee, Oak Ridge National Laboratory
Barriers Addressed	• Bipolar plate cost

Project Goal and Brief Summary

The project aims to develop a fuel cell architecture for heavy-duty applications, specifically a proton exchange membrane fuel cell (PEMFC) bipolar plate (BPP) utilizing flat foil metal separators with gas flow distribution through diffusion substrates' grooves, manufactured through continuous roll-to-roll (R2R) processing. Key outcomes include reducing BPP manufacturing cycle time fivefold, simplifying stack assembly, and reducing mass transport resistance. The research encompasses corrosion-resistant coatings, multiphase transport, modeling, validation, and new manufacturing methods. The projected targets involve a cost of <$4/kW, a plate mass of <0.15 kg/kW, and durability of at least 25,000 hours.

Project Scoring



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

Question 1: Approach to performing the work

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

- The project's workplan looks sound. The overview of the timeline (slide 7) is excellent; it is logical, easy to understand, and clear on who is doing what.
- It is nice to see the project team brought in an engineering consulting group to support the techno-economic analysis (TEA). The goals are clearly stated.
- The project team has a unique approach with an alternate design for unitized fuel cell manufacturing. It is good to see that Plug Power is able to promote such work.
- The project concept is innovative in that it is a significant departure from current practices. This approach or something similar has likely been envisaged many times throughout the years, but as materials and manufacturing methods improve, the feasibility of the approach needs to be reassessed. Therefore, the project is a meaningful contribution to the advancement of the technology. The project has many areas of risk. The team has addressed only some of these, which is appropriate, as not all risks can be addressed at once. The team has a reasonable plan that includes prototype development, ex situ studies, cell/stack design, performance evaluation, R2R manufacturing assessment, modeling, materials development, and cost studies. The approach is logically stepped from small-scale through full-scale single cell and short stack, with a final durability test. If the approach is successful, the team will need to undertake further work to fully evaluate durability, cost, and manufacturability. Much of the team's work can be considered advanced proof-of-concept only. The durability of the design is perhaps the largest question if performance is achieved. Areas of concern include the following: increased interfaces and more parts (more resistance, manufacturing tolerances), durability (e.g., gas diffusion layer [GDL] structure, membrane–GDL interface, metal coatings, material contaminants, coolant structure), and manufacturing (more parts, new approaches, cycle times). The following bullets provide further details on the areas of concern:
    - The wireless cell voltage monitor (CVM) is a concept that is worth evaluation. Questions remain as to the effectiveness and reliability of measurement. The team did not provide a clear cost or reliability comparison to more conventional approaches.
    - The GDL is a large gap, as the team is currently using older Toray Carbon Paper (TGP)-style GDLs and does not appear to have a significant collaboration with a GDL supplier or a clear path forward on a manufacturing method that does not affect GDL roughness. There was no mention of potential GDL compression set issues, which would be a concern and could result in significant pressure drop changes during the stack lifetime. Additionally, ripping of the GDL materials can have serious consequences on the following fronts: (1) roughening of the surface resulting in higher-pressure drops, (2) reduction in GDL support for the membrane and a risk of creating voids in the tops of the channels in the GDL through pulling of the fibers (these voids can lead to membrane cracking), and (3) reduction in mechanical stability of the GDL.
    - While the performance results appear promising, the advantage is still a question, as high pressure drops were observed. On the positive side, the design does not appear to introduce additional electrical resistance.
    - The TEA looks promising, but it depends on a one-second cycle time. It is unclear clear how realistic this cycle time is.
    - The researchers indicate that they plan to use a membrane electrode assembly (MEA) chemical stability accelerated stress test (AST) to address material concerns due to oxidation; however, a mechanical durability test is also required and must be combined with the chemical test to understand impacts on the membrane.
- Plug Power's project for a fully unitized fuel cell manufactured by a continuous process is a high-risk, high-reward project that, if successful, could significantly reduce the manufacturing costs of a fuel cell stack. There are many novel components to this approach, most of which need to integrate seamlessly for the concept to work. Certain aspects could be developed independently, such as the plate coatings and the wireless CVM. There are several concerns with the wet coating approach, including (1) how the team plans to remove the passive layer from the plate surface before coating and prevent oxidation during open-air wet coating, and (2) how the team plans to coat both plate surfaces.

- The project objectives are well-outlined and appropriately focused on meeting the DOE BPP targets, reducing manufacturing time, simplifying stack assembly, and reducing mass transport resistance. The manufacturing target could be more clearly presented; from the cost analysis, the target appears to be 10 million cells/year at 1 cell/second. The goal of reduced mass transport resistance is not clearly articulated. While the project is overly ambitious, the proof-of-concepts and knowledge generated will have a significant impact on the industry.
- This unique concept of BPP flow field shows better performance, particularly the high-current-density region, than conventional stamped metallic BPPs. The project BPP seems to be thicker because of the dedicated coolant flow field. Thus, it is necessary to show the significant benefit of this unique BPP concept over compromised thickness (i.e., stack volume).
- The project team has a logical approach, good project timeline, and clear go/no-go points along the way. There are some side projects/distractions (e.g., CVM) that will not help with BPP goals but are fun to do anyway.
- The approach and relevance of the project are well-aligned with the overall objective of the DOE 2030 goals for BPPs. However, some fundamental parameters are missing. For example, on slide 4, it is unclear what the thickness is, in comparison to the foil separator, the GDL, and the coolant mesh corrosion resistance. The project team needs to provide these baseline properties.

Question 2: Accomplishments and progress

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

- The team is making good progress, and the project appears to be on schedule. The inclusion of the wireless voltage monitoring is great.
- The project has demonstrated progress on many fronts—not just on the plate but on most parts of the repeating cell—to test the new concept.
- Data of corrosion current and interface electrical resistance meet DOE guidelines. Higher fuel cell performance is shown, particularly a high-current-density region, with dry and wet conditions in the subscale (i.e., 60 cm^2) single-cell test. The actual size of the cell (400 cm^2) and short stack data are expected for flow distribution in-plate and plate-to-plate. The effectiveness of the mesh coolant layer is unknown at this time.
- The team has made significant progress, demonstrating improved fuel cell performance with a grooved GDL, although pressure drops are still too high. The team benchmarked against a straight channel conventional flow field, whereas most original equipment manufacturers (OEMs) use wavy or other patterned/constricted channels to improve oxygen transport under the lands. The wet coatings have poor adhesions and do not meet the corrosion requirements with Al 1100. The team has proposed a design for a unitized cell with feed channels for hydrogen, air, and coolant introduced into separate plastic frames. There are seven discreet parts in the cell assembly, whereas a conventional process has two to three. This complexity raises concerns about significant assembly tolerance, and it is hard to see how the assembly cost will be less expensive. Aligning the ports in the hydrogen and air frames with the GDL ports will be a particularly big challenge. The wireless CVM was able to generate a signal, but the CVM requires too much parasitic current and cannot measure below 400 mV, meaning it cannot be used to control cell reversal. Other concerns about the CVM include whether it can measure high-frequency resistance (HFR), what the individual cell sampling frequency and resolution are, whether 1 Hz is fast enough to catch damaging events, and how reliable it is (a faulty CVM is a major issue). The team has demonstrated a method to cut grooves in the GDL, which is not scalable. TEA was completed on the full stack assembly, but the assumptions as to which materials and processes were included in the TEA were not shared (aluminum or stainless steel plates, coating method, coolant mesh material, coating, etc.).
- The project team has made significant progress toward demonstrating the project goals. Evidence was presented that the DOE BPP targets for corrosion current and interfacial contact resistance have been met. The projected BPP cost is well below the DOE target. The goal of simplified stack assembly was demonstrated; however, handling of the stamp frames (which have a multitude of loose strands that form the channels) will present an issue that was not addressed. The goal of reduced mass transport resistance

was not addressed. The measurement of mass transport resistance requires electrochemical impedance spectroscopy (EIS) measurements, which were not performed.

- The team has made good progress in Budget Period 1. All of the relevant technology hurdles are being addressed at the design and single-cell levels. There are some additional questions to be asked. (1) On slide 8, it is unclear what titanium–carbon ratio and thickness were investigated. (2) The project is studying viable wet coatings to understand potential manufacturing and cost impacts. On slide 9, it is unclear whether the project has a curing process and what the impact of post-processing is on the flatness of the BPP. (3) On slide 12, it is unclear what total plate thickness was achieved compared to the target. (4) On slide 12, it is unclear what the GDL structural strength is after forming the groove against requirements.
- The project team has made great progress since last year. Slide 12 includes an impressive stoic sensitivity plot. However, it is unclear whether the GDL fibers from the grooving process affect gas transport or cause any pressure drop. The HFR of the two-layer MGL280 case is reasonably higher than the others on slide 13.
- The project team has made significant progress, and the project is still only ~40% complete. Barriers to be addressed that require additional clarity on the approach include GDL roughness and mechanical strength, additional process steps, and composition of final mesh materials.
- Wet coating of TiN is an interesting approach, but there is concern that porosity or boundaries between particles and binder would lead to poor protection against corrosion if used with aluminum. It is unclear why the wireless cell voltage monitoring work is included in this project, as it does not seem directly related to the project goals. It would be beneficial for the project team to include more explanation of why this work is needed in this project. The inclusion of TEA was nice.

Question 3: Collaboration and coordination

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

- The project has good collaboration between project partners. Plug Power is effectively engaging project sub-principal investigators to make technical progress in the project. The use of Smith Engineering to do manufacturing feasibility analysis and TEA is the right use of external resources.
- The project had close collaborations with a number of funded and non-funded partners. The collaboration has been well-coordinated, productive, and in many cases critical to the success of the project. Even though some of the collaborators’ work is still at early-stage development and may not make it into the final product, this proof-of-concept work is still valuable.
- The project includes various institutions with complementary strengths, and the principal investigator has pulled in non-funded partners as well to make progress toward the project goals.
- The project has multiple collaborators that all have well-defined roles. The team appears to be working well together, and the inclusion of non-funded partners is great.
- This is a good specialized team that is capable of supporting the project.
- The project team has appropriate industry and academia collaboration.
- All partners have made significant contributions. Oak Ridge National Laboratory (ORNL) has done the joining and coating work, the University of Tennessee has done the cell modelling, Smith Engineering has done the process design and TEA, and Limitless Design has led the wireless CVM work. It would be good to see more engagement with GDL suppliers in providing affordable GDL with channels.
- The project’s collaboration looks reasonably good, but it appears to suffer from limited collaboration with a GDL manufacturer.
- The team at ORNL may be doing work outside the project scope. It would be good to make sure ORNL stays focused on the project objectives.

Question 4: Potential impact

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

- This high-risk approach is very appropriate for DOE funding, since it is unlikely that industry would undertake this effort without the government funding. If successful, the project may have a major impact on stack costs.
- If successful, the project will have a significant impact on the design of thin BPPs and reduce the cost of manufacturing significantly.
- While this high-risk project has significant technical challenges, many aspects of this work should lead to potential cost reductions. As the current DOE cost projections are still far from the target, this project is well-aligned with Hydrogen Program goals and objectives.
- This project aligns strongly with Hydrogen Program goals. It is critical to demonstrate and explore R2R stack manufacturing techniques to meet the DOE stack cost targets.
- This project has a low technology readiness level (TRL) but includes out-of-the-box thinking. It is unlikely to impact any production processes in the near future, but it is a good design to improve upon in the future.
- The project aligns well with the DOE goals. However, it is concerning that the BPP has increased from three layers (two halves plus seal) to nearly six layers (three frames and three separators). This complexity could translate to an assembly nightmare and low yield. Any gain on savings from eliminating stamping could be lost from trying to assemble these layers without yield loss.
- The project is aimed at improving cost, weight, and manufacturability of BPPs, and the results are promising so far that these goals can be achieved; however, there is limited indication of whether the durability targets can be achieved with this approach.
- It is necessary for the project team to clarify the total benefits of this unique BPP flow field concept.

Question 5: Proposed future work

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

- The project has proposed several interesting concepts and plans to be tested at full active-area level. The reviewer sends best wishes to the principal investigator and his team.
- The project team included a high-level overview of the future work on slide 7, and the plan appears to be good. It would be nice if the team had clearly defined beginning-of-life performance targets. In short, it is unclear what level of performance is required to make this approach comparable to (or better than) a more conventional PEMFC stack with respect to cost and weight.
- The team at Plug Power is addressing all the relevant technology barriers and challenges associated with this BPP concept. The risks to the manufacturing process should be sufficiently addressed early in the project. A design for manufacturability and risk analysis need to be conducted after scaling to large-platform single cells prior to short-stack or full-stack implementation. GDL structural strength, groove design parameters, and processing need to be sufficiently addressed prior to scale-up.
- The topics for future work are reasonable, but more details would be appreciated.
- The future work is well outlined by the project team. There are several questions to be addressed, and while the plans indicate the team will be addressing most of these, the GDL structural integrity and overall durability remain concerns, and the approaches to address these have not been mentioned.
- The future work will occur according to a systems engineering process.
- The future work is vaguely described. It is unclear what testing will be done, how the scaleable manufacturing will be demonstrated (i.e., at what scale and speed), what the durability plan will be, and what the impact of potential loose fibers from GDL groove forming will be. It is also unclear if the frames for reactant and coolant delivery will be built and tested within this project, which is a very important part of this project and must be demonstrated, but it is not explicitly listed in the future work. The team should measure resistance of the full plate, including both foils and the coolant mesh after welding/adhesion. It is unclear how the modeling work (marked as complete) is driving the design.

- While the proposed future work is well-thought-out and builds on past work, it is very ambitious. With less than 12 months left in the project, it seems very optimistic that a full-scale active area short stack can be designed, built, and fully tested. It would be preferable to see the 50 cm^2 cell scaled up to multiple cells before scaling up the active area. Many issues, such as compression uniformity and sealing, are not readily apparent in single cells and only surface in stacks.
- Based on slide 22, it is not clear what the future prospects are for the project.

Project strengths:

- The project strengths are that it (1) addresses R2R manufacturing of BPPs from a ground-up perspective, rather than trying to shoehorn existing designs into an R2R process., (2) has focused on minimizing component count and high-volume manufacturing processes, and (3) uses an innovative approach with stamped or formed GDL channels.
- Innovative cell design is assessing a possible step-change in design approach to meet targets. This comprehensive approach combines experimental methods and predictive modeling with increasing device scales. Several collaborators are involved in the project.
- This very creative project has an out-of-the-box approach. The team is working on many concepts with a relatively small budget, making this project a good value for the money. The team is strong, with clear contributions from all partners.
- The project team is pursuing an outside-the-box approach that has the potential to enable substantially lower costs and weight.
- The team at Plug Power has significant expertise in BPP and fuel cell stack design. However, the team seems to be pushing the boundaries regarding plate thickness and GDL design. A continuous collaboration with GDL experts and manufacturing is crucial to the success of this project. The University of Tennessee's performance modeling is the right approach to designing new GDLs with grooves.
- The project has a good team capable of alternative design thinking.
- Strengths include the system engineering process at a fuel cell stack OEM and the modeling capability of flow field design effect.
- The project has a very creative principal investigator and an excellent team with a significant skillset.
- Overall, this is a strong project. The approach is very good.

Project weaknesses:

- The reviewer did not see any significant weakness.
- A single-layer GDL with the selected 1.0 x 0.22 mm configuration was not demonstrated. The high performance of the single-layer experiment is likely due to the very high back pressure of the cell, which does not give an accurate indication of the performance expected with a single-layer GDL. It is not clear that a channel depth of 0.22 mm can be achieved with a single-layer GDL. The team did not complete measurements of mass transport resistance or EIS, which would give some good insights into what is happening within the GDL channels and how they could be optimized. The team also did not complete durability testing with single cells. The forming of the channels could potentially weaken the GDL, damage the underlying microporous layer, or create loose fibers. If the team completed humidity cycling AST, it could show whether the support of the membrane has been compromised. The effects of channel geometry on anode and cathode performance were not separately investigated. Finally, no stack data were presented, as all the data shown was from single cells.
- Wireless CVM scope seems to be nice to have rather than a critical path to success of this project. The CVM development is negatively impacting the project progress to meet the BPP go/no-go decision criteria and milestones.
- The project team is missing pieces of the puzzle regarding how to assemble these various layers into an approximately 300-cell stack with tight tolerances.
- The project's cell unitization is very complicated, with more parts and assembly steps than conventional cell designs.

- The project's GDL grooves manufacturing method may not work and is central to the project approach. The team showed a lack of attention to the potential durability issues.
- There are so many different aspects of this project, and it is unclear that there are enough resources to effectively complete all the work and integrate all of the subcomponents. There is no GDL supplier on the project committed to providing grooved material in roll form.
- This work is at a low TRL with less impact on high-volume production requirements.

Recommendations for additions/deletions to project scope:

- The team should emphasize that this technology can potentially address far more than just BPP barriers (slide 3). If successful, this project can enable substantially reduced stack assembly costs with the proposed R2R approach.
- The project team should perform single-cell membrane relative humidity cycling AST to demonstrate the membrane support has not been compromised (either through a damage/cracked microporous layer or weakened mechanical support). The team should also perform EIS on single cells to better understand the true ohmic and mass transfer resistance of each GDL configuration. These results would allow better verification of the flow modeling.
- The team should eliminate work on aluminum plates, which is extremely challenging. This project is ambitious enough as it is and would be a success if the team got it to work with stainless steel plates. There should be a go/no-go decision point for the wireless CVM. The team should measure iron elution during the corrosion tests on coated stainless steel and test for corrosion resistance after welding (i.e., whether the welding location of coated foils is more susceptible to corrosion).
- The wireless CVM scope seems irrelevant to the success of this project. It seems to be nice to have rather than a critical path to success of this project. The recommendation is to de-scope the wireless CVM efforts and focus on the grooved GDL and coolant mesh coating aspects of the project, which are critical to achieving the performance and cost targets of the project.
- This project already has too many items. The team should just focus on the CVM connection at the plate level and eliminate the electronics/data acquisition portion of the CVM.
- The team should complete combined mechanical–chemical testing of the membrane in the MEA as a function of GDL structure and plate properties.
- It is recommended that the project team clarify potential benefits of this unique BPP concept.

Project #FC-347: Development of Low-Cost, Thin Flexible Graphite Bipolar Plates for Heavy-Duty Fuel Cell Applications

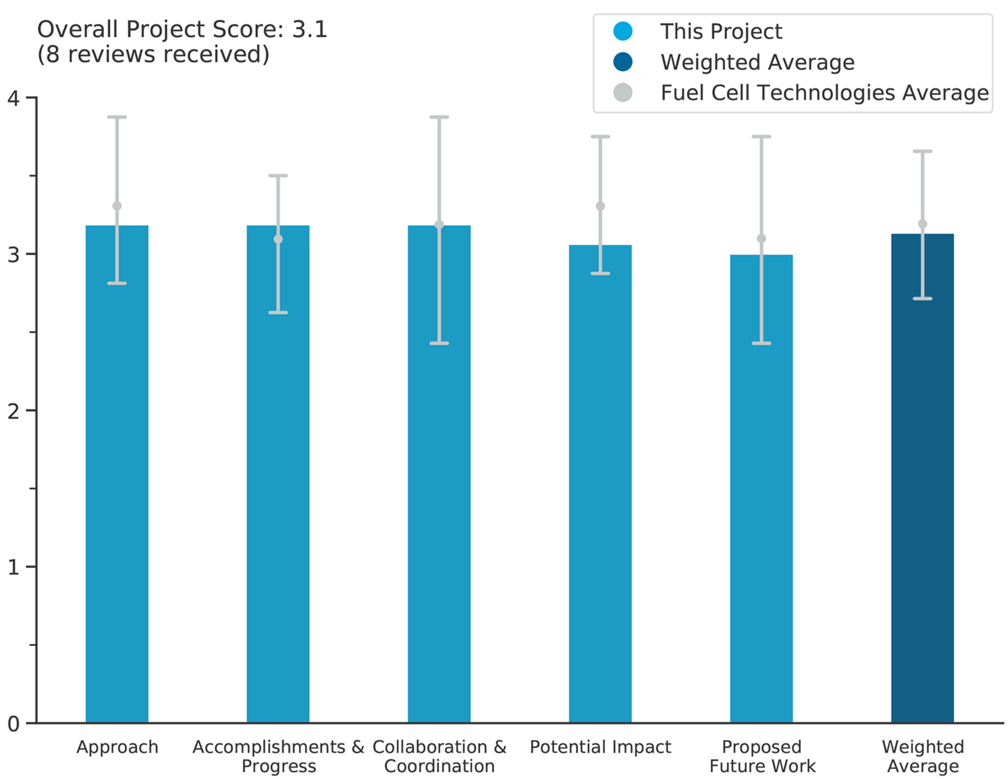
David Chadderdon, NeoGraf Solutions, LLC

DOE Contract #	DE-EE0009615
Start and End Dates	5/1/2022–5/31/2025
Partners/Collaborators	Ballard Power Systems, Strategic Analysis, Inc., Norley Carbon & Graphite Consultants, LLC
Barriers Addressed	• Bipolar plate assembly cost

Project Goal and Brief Summary

The project aims to reduce the cost of bipolar plate assembly (BPA) graphite by approximately 90% to enable a BPA cost of $5/kW for next-generation heavy-duty fuel cell applications. The project addresses the technical barrier of leak failure due to inclusions in the graphite and proposes various approaches to eliminate the impurities and evaluate their impact on BPA performance. The cost reduction will be achieved through the development of thin (from approximately 1.7 mm to 1.4 mm) and durable, flexible graphite plate assemblies with low graphite basis weight (from approximately 600 g/m^2 to 340 g/m^2) and minimal leak-causing impurities (from approximately 17% to <5% leak failure rate due to inclusions in thin plates). Reducing the BPA thickness and impurity content will contribute to higher volumetric cell and stack power densities. Milestones include producing flexible graphite from alternative feedstocks, implementing an ash separation process, and evaluating the effectiveness of a clean furnace sealing material. Future work includes testing alternative graphite feedstocks, optimizing the graphite expansion process, and conducting short stack testing to demonstrate BPA performance.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach is to reduce BPA thickness. A <5% impurities, nine-task approach with a go/no-go milestone is a good progress marker. Impurities in graphite are a good opportunity for improvement. Ash analysis is a good starting point. There is a good understanding of the graphite manufacturing process and sources of impurities. Ash particles cause defects, and at lower thickness, they become more important. The graphite cost is 36%. Thinner BPA saves money, and the strategy for this is well-described.
- NeoGraf Solutions' (NeoGraf's) approach to developing a BPA is focused on overcoming barriers to cost. The approach is focused on removing impurities from the graphite manufacturing process to reduce the number of rejections to less than 5%. This should allow the project to meet the DOE target of ≤$5/kW_{net}$. This project required a safety plan, which NeoGraf has provided and placed into action. The project is well-defined, and the team has made an effort to apprise the Million Mile Fuel Cell Truck (M2FCT) consortium or project progress.
- The approach is sound. It is very good to see the project has tolerance specification for ash content.
- The project is focused on reducing the leak rate of graphitic bipolar plates. The main activity is around decreasing the amount of ash and impurities in the starting materials. NeoGraf takes a very straightforward approach and is looking to quantify new vendors of graphite with low ash content and eliminate ash during the heating process. The project also found that iron impurities are an issue and has developed a method to take out magnetic particles. The team has also carried out techno-economic analysis, as well as making plates and testing their leak rates. While the approach is very direct toward eliminating the impurities, it seems that NeoGraf could be more creative in their ways to eliminate ash. It would have also been helpful to see a full energy dispersive spectroscopy (EDS) spectrum of different batches of graphitic carbon. There seems to be quite a body of literature on the impurities of graphitic carbon and methods to purify. NeoGraf did not comment on how much it would cost to implement the use of a magnetic bed to remove iron impurities. The work could have been better satisfied if NeoGraf were to ask a clearer research question, instead of the project goal of "Achieve a leak failure rate due to inclusions of <5% in thin plates" and an emphasis on 200-micron particles. A more interesting question might be, "What is the maximum amount of ash that can be in graphitic carbon that can be used to make plates with a 99% success rate?" to include particle size, etc., of the ash. Perhaps this has already been done, but more understanding of project metrics (e.g., 200-micron particles) would be interesting.
- The approach to reduce cost by reducing flexible graphite plate thickness addresses barriers of bipolar plate cost and addresses power density, specific power, and durability. Graphitic bipolar plates have demonstrated over 25,000-hour durability in bus applications, suggesting they have the durability required for heavy-duty vehicle applications. The approach is looking at reducing inclusions by looking for sources of graphite with lower levels of large inclusions, looking at a method to remove iron-rich inclusions, and looking for ways to reduce/eliminate impurities from the processing equipment. Some of the larger impurities were identified as being iron-rich inclusions. A process to remove these impurities was implemented. The project does not seem to have a plan to test for leaching iron, which has a large impact on membrane durability. It is not clear what the state-of-the-art stack power density is with the current plate thickness and how much it would increase with the proposed thinner plates. It would help to show the proposed thinner plates are likely to meet DOE target power densities.
- The project is working to develop natural graphite into carbon composite bipolar plates for heavy-duty vehicle fuel cells. A key objective is <5% leak failure rate; this target (< 5%) seems too high; it seems like the leak rate target should be substantially reduced down to <<1% and <<0.01% for mass manufacturing, at which point they can start thinking about the point in time where not every plate has to be leak-checked, which is an expensive portion of the plate process. The current approach is to remove ash particles >200 microns. This seems like a near-term target, but the target should eventually be reduced to much smaller inclusions. Besides the size of the particles, it is also important to understand what the particles are made of in terms of contamination of other fuel cell parts, e.g., iron will reduce the membrane life, and chloride would poison the catalysts.

- The project statement of work is one of bipolar plate material supply. It does not cover the bipolar plate manufacturing process. Therefore, technical barriers and defined metrics are not adequately addressed in the project, so the relationship between material quality and bipolar plate metrics is unclear. It was not clarified how a supply material target of "<2 ppm [parts per million] of ash contain" is related to <5% leak failure rate for the bipolar plate process. This target rate is questionable, and it seems too high, because this failure rate still requires 100% inspection. As mentioned in the project, these materials have been used as a fuel cell bipolar plate since the late 1990s. Metrics of the bipolar plate with this material include not only leak failure rate but gas permeation and formability, if the project can meet the design requirement of the bipolar plate flow field. However, those are missed in this project.
- Eliminating inclusions and reducing leak rates will help with overall cost reduction. However, the project is not developing approaches that are broadly applicable to the rest of stakeholders. The work proposed here will help NeoGraf and have very little impact to other flexible graphite producers.

Question 2: Accomplishments and progress

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

- NeoGraf was able to identify several material suppliers that could supply graphite flake that meets the metric for ash particles >200 microns and is working with the suppliers to ensure they can provide that material in ton-scale orders. NeoGraf has identified and implemented a magnetic process to remove iron-rich particles >200 microns from graphite flake and implemented improvements in process equipment to reduce impurities added during processing. NeoGraf completed an upgrade of the exfoliation furnace, replacing old refractory bricks with abrasion-resistant refractories with fewer mortar joints. NeoGraf was able to produce an initial batch of bipolar plates from graphite flake with 30 ppm of ash particles with a size >200 microns. This resulted in 256 leak-tight BPAs and 5 plates with leaks, reaching a leak failure rate of 1.9%, exceeding the go/no-go target failure rate. The project experienced setbacks in timing due to inability of initial graphite flake suppliers to supply flake at ton-scale with the same quality/inclusion content as material they supplied at small scale.
- Preliminary cost analysis by Strategic Analysis, Inc. (SA) found that the thin BPAs developed in this project can meet the DOE BPA cost target of ≤$5/kW for heavy-duty applications. Good progress was made in identifying high-purity graphite flake feedstocks and eliminating potential sources of process contaminations. It is very likely that the go/no-go decision point will be met by demonstrating <5% rate of BPA leak failure due to inclusions. Supply chain needs include securing a consistent, production-scale source of graphite flake with less than 20 ppm of ash particles >200 µm and replacing silica with zirconia for better impurity detection and minimized impurity levels. Cost impacts should also be considered; ash collection improvement is low-cost and effective.
- NeoGraf has made good progress toward meeting the project goals. The researchers have assessed various sources of graphite, updated equipment for manufacturing flexible graphite, and performed preliminary tests. The project is at less than 2.5% rejection in small runs (~250 plates). Thus, the project has demonstrated good progress toward addressing DOE cost goals.
- There is good progress on selecting materials and making sheets.
- It is good that NeoGraf is working with a variety of samples to derisk supply. It seems there may be concerns that new materials, when delivered in ton-quantities, will be able to meet specifications. There is good progress on removal of iron contamination with magnetic separators. It is unclear what the limitation is to removing more than 75% of iron particles. The process modifications to address silica and ash collection in ducts are good. The new furnace design is smart. It will be nice to see results in the future. Performance data from bipolar plates made with different graphite supplies would be appreciated.
- The progress was good, albeit toward a narrow work scope of lowering ash content. The scope of the project is very narrow. It is not clear whether the inclusion rate of <5% is relevant or whether a particle size metric is needed. Preliminary results show 256 leak-tight BPAs were produced and 5 BPAs failed leak testing because of possible or confirmed inclusions. This is a failure rate of 2%. It is not clear how that affects the techno-economic analysis. It is also not clear whether plates that pass the leak test at beginning of life fail prematurely if they have a high ash content. Other questions include what is needed for a failure rate of <0.1%, whether that is important, and whether the process to test leak rates is expensive.

- Magnetic separation of iron-rich particles seems like a good step, although removal of only 75% seems like it could be improved. The presentation did not comment on the cost of this step. Progress has been made in refining the production steps, including removal of process contaminants. Bipolar plates have been made, analyzed, and tested. Out of 256 plates, 5 failed leak testing, which is a ~2% failure rate, so this meets the project target—but also confirms that each individual plate will have to be tested.
- The data shows that ash contain meets the target, but this metric is not enough to prove the concept.

Question 3: Collaboration and coordination

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

- Ballard has extensive experience in this area and provides valuable perspective from customer experience. The supply chain for graphite is well-utilized, and Norley Carbon has good experience. SA provides cost analysis.
- NeoGraf has strong collaborations with Ballard and has also initiated interactions with the M2FCT consortium. Ballard is a great technology partner to increase the likelihood of NeoGraf meeting the project goals. Ballard is also the perfect consumer of the low-cost plates being developed.
- There appears to be good collaboration within the project between NeoGraf and Ballard. The collaboration with M2FCT has not really begun yet but is scheduled for the next phase of the project.
- The project partners seem to be completing work in their task areas.
- The partners in the project seem appropriate to achieve initial manufacturing. SA and M2FCT could be used more. A process company that can purify the graphite down to much lower inclusion rates could be added.
- NeoGraf had excellent collaboration with Ballard, who is a major buyer for their project. More collaboration with M2FCT, particularly around physicochemical analysis, would have been more helpful.
- It is good to include a bipolar plate and stack manufacturer in the project, but the statement of work of bipolar plate manufacture is not enough, and other metrics are not defined to prove this material for the bipolar plate.
- This feels more like supply contracts rather than collaboration.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has high potential impact. Graphitic plates have shown good durability and are likely to meet heavy-duty vehicle durability targets. The success here will reduce the cost of graphitic bipolar plates and increase power density by reducing repeat distance of the cell.
- The project is strongly aligned with the Hydrogen Program's goals of addressing fuel cell system cost. NeoGraf is hitting its performance targets of reducing rejection rates for the bipolar plate assemblies. The results shown speak to the advances made and the impact they may have on Hydrogen Program objectives.
- Ballard has shown carbon plates can meet commercial cost goals. Fully implementing these improvements can help meet DOE goals.
- Slide 4 presents the cost (from SA) of the graphite BPAs; however, notable in the pie chart is the cost of leak testing every individual plate, up to 5% scrap, and the graphite purification process. It seems like NeoGraf/Ballard or SA needs to consider the costs that SA did not include in its study. Done "appropriately," graphite bipolar plates should enable fuel cell heavy-duty vehicle manufacturing and not have corrosion issues that metal plates can have.
- When successful, the graphite with low inclusions can lead to high-quality, lower-thickness plates.
- Targeting thinner bipolar plates is a good idea and should reduce stack size and material costs.

- These materials have been used for the bipolar plate since the 1990s. Leak failure rate improvement is not enough for potential impact. The target thickness of the bipolar plate (1.4 mm) is still too thick for heavy-duty application. It should be close to the thickness of the metallic bipolar plate.
- The impact of this project is only satisfactory because it seems that NeoGraf is developing bespoke processes with their vendors. NeoGraf is not providing insight into when the project materials will overtake metal bipolar plates and other choices. It is not clear how much the additional purification processes will cost.

Question 5: Proposed future work

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

- The proposed future work by NeoGraf is a logical next step in the work that has been completed. The focus is on cost by reducing scrap. This, along with benchmarking, is the focus of the future work proposed. Testing in future work is crucial for benchmarking the cost of fuel cell plate manufacturing with project technology.
- The list of improvements by task is well-laid-out. The manufacturing runs and tests identified are logical. Out-of-cell tests followed by stack tests will provide useful information to validate achieving DOE goals.
- Plans for future work will address statistics. The team will make more plates to validate failure rate results from the relatively low number of plates so far, make plates from alternative graphite flake sources with low inclusion content, scale up the optimized plate manufacturing, and begin short-stack testing. It is not clear if there are plans for other ex situ durability testing, such as plans for determining iron leach rates, and what the plans are for interactions with M2FCT or for having M2FCT test the plates.
- The proposed future work is reasonable. It would be good to see more data on interface contact resistance, corrosion current, and single-cell fuel cell results. It would also be good to include some information on whether the production methods used here are capable of meeting the 20,000 stacks/year target.
- Most of the future work is addressing the production process. It seems like the biggest issues in getting this to mass manufacturing are the graphite impurities, purification, understanding what the impurities are, the impurities' effects on other components, and getting rid of the inclusions.
- It looks like NeoGraf will continue to scale the processes to remove ash and magnetic impurities. The scope of the Phase 2 budget is fairly narrow. It would be good for NeoGraf to describe more of the considerations for the techno-economic analysis. The durability testing will also be interesting.
- It is recommended that the project evaluate this material with other bipolar plate metrics—for example, hydrogen permeation, plate thickness, and formability—before going to full-size fabrication and testing.
- The project feels more like supplier screening and process control. However, the work proposed and conducted within this project does not have broader impact.

Project strengths:

- The project strengths are in teaming with Ballard, a fuel cell company that is focused on using the technology being developed. Another project strength is developing a technology that has already met many of the DOE targets for durability.
- Lower-cost improvements are identified to make graphite plates more reproducible and durable and to improve their performance. The project partners are very complementary.
- The project team of Ballard and NeoGraf is strong. The project appears to have found some suppliers that can supply graphite flake of acceptable quality.
- Metrics and goals are very straightforward. Progress is steady, and the project is likely to be successful within the metrics of the DOE Hydrogen Program.
- The graphite composite plates have the potential to meet cost and weight targets for fuel cell heavy-duty vehicles.
- There is a long history of material supply to bipolar plate production.
- There is a long history on flexible graphite and plate-making.
- This is a strong project.

Project weaknesses:

- There are no project weaknesses in this reporting period.
- The team needs to understand the impurities, how much these impurities will vary from carbon source to carbon source, what exactly can/will leach out of the plates, and what performance/durability impact those impurities have. The <5% leak rate might be acceptable for near-term early commercialization but does not seem close to what is needed for mass manufacturing at a 500,000-stack level. To get the cost down, testing of individual plates probably needs to be removed. The team needs to incorporate the graphite purification step and the leak-testing step into the cost modeling. It is unclear whether the project is considering effects of impurities other than iron and inclusions that cause leaks.
- This project does not define proper metrics from the bipolar plate design requirement. A leak failure rate of <5% is still too high for bipolar plate manufacturing. The leak failure rate still requires 100% inspection. Other metrics of hydrogen permeation, plate thickness (1.4 mm target is still too thick), and the formability/forming process need to be addressed.
- The scope of the project is very narrow. Outside the scope of the project that was awarded by DOE, it would be helpful to understand the origin of the team's metrics and to understand whether there are still unknowns for which the team is not testing.
- The plans for durability testing are not clear. Details are lacking on cost modeling and modeling of power density expected with final plates.
- There is a lack of vision to help solve the broader issue of incoming quality and process control of graphite materials and making sheets.
- Connecting processing parameters with durability parameters is needed. Also, carbon particle orientation may provide a key to improving conductivity and durability.
- It would be good to see more data on performance of these materials in corrosion tests or operated in a fuel cell.

Recommendations for additions/deletions to project scope:

- The work as planned is very well-organized. The measurements of in-plane vs. through-plane conductivity will provide better guidance in evaluating different options.
- Targets for this project are set for an initial production of prototypes or limited production (e.g. the <5% leak rate). That is a starting point, but the project should also consider the targets for commercialization, when production is 500,000 stacks, and how to reduce the overall cost. To set targets for mass manufacturing, the project should conduct a simple statistical analysis regarding the leak rate and determine what reliability is required to get rid of the individual plate testing to reduce cost. The team needs to incorporate the graphite purification step and the leak testing step into the cost modeling.
- It is recommended that the project redefine metrics of this material for bipolar plate use. A leak failure rate of <5% is still too high for bipolar plate manufacturing. The leak failure rate still requires 100% inspection. Other metrics of hydrogen permeation, plate thickness (1.4 mm target is still too thick), and the formability/forming process need to be addressed.
- NeoGraf should work with M2FCT for more detailed characterization of the graphite, both before and after processing, and correlate to the leak failure rate.
- The project should develop inline process control and defect monitoring of graphite sheets to eliminate plate inspection.
- More collaboration with M2FCT would be beneficial.
- There are no recommendations for additions/deletions to the project scope this reporting period.

Project #FC-348: Fuel Cell Bipolar Plate Technology Development for Heavy-Duty Applications

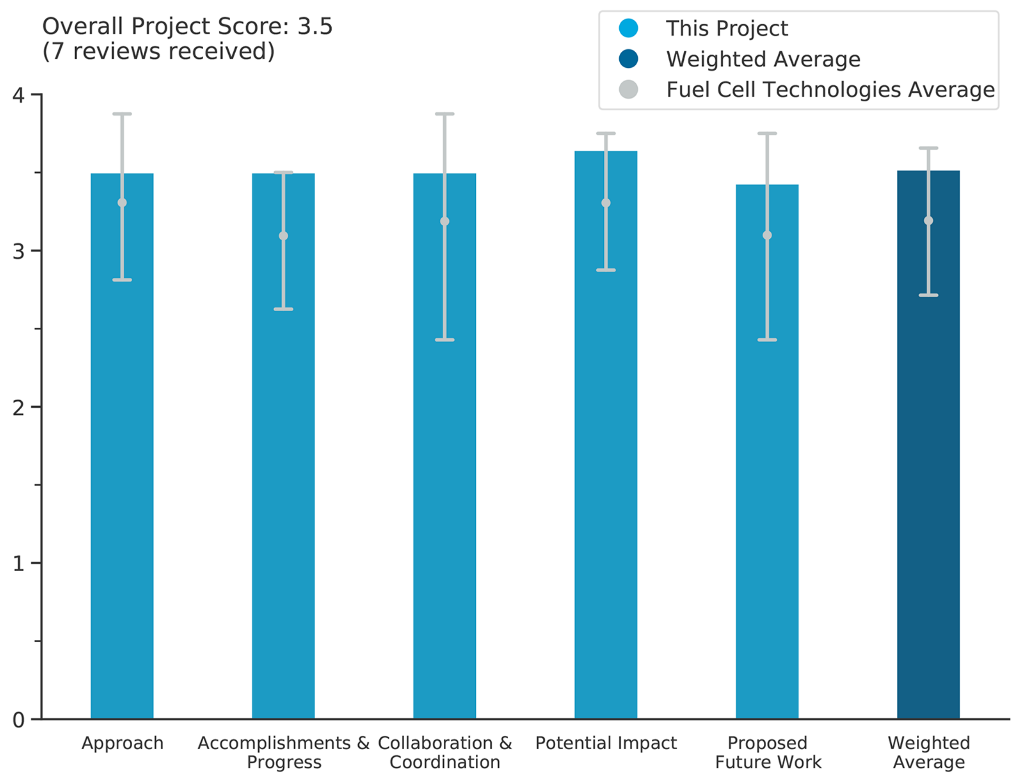
Siguang Xu, General Motors LLC

DOE Contract #	DE-EE0009616
Start and End Dates	1/1/2022–6/30/2025
Partners/Collaborators	The Pennsylvania State University, Northern Illinois University
Barriers Addressed	• >40% equivalent elongation for ferritic stainless steel • Low-cost and durable coating • Fast laser welding (90 m/min)

Project Goal and Brief Summary

The goal of the project is to develop a bipolar plate (BPP) manufacturing solution that achieves a BPP durability of 25,000 hours and a weight of 0.18 kg/kW for 100,000 units per year. In the fundamental technology development phase, the project is developing thin coil stamping technology (to achieve >40% equivalent elongation), low-cost post-stamping coating technology (to meet 25,000-hour durability and high conductivity), and fast BPP laser welding technology (to meet 100,000 units per year throughput with a less than 2% scrap rate). The next phase involves integrating the developed technologies into the design, manufacturing, and testing process of a small BPP (50 cm^2 active area) for feasibility and scalability studies.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach to the work is excellent. Siguang Xu presented a systematic study addressing key issues related to using lower-cost metals for BPPs, including stamping, joining, and corrosion coating of low-cost ferritic stainless steel (FSS) formability. The presentation was very clear, with relevant details clearly published. The results of the study are also relevant to stainless steel (316L).
- General Motor's (GM's) approach to developing a low-cost BPP is focused on overcoming critical barriers to meeting DOE goals. The critical barriers were identified, and significant progress was completed against the goals. The project was required to submit a safety plan. The safety plan has been sufficiently addressed in the presentation. This project is well-designed; it focuses on plate stamping, then welding and coating. The project is well-designed, feasible, and integrates well into GM's efforts. If successful, the approach can be used by others manufacturing BPPs.
- The project adequately covers considered metrics of the BPP, including iron elution and formability. Iron elution, in particular, is an important factor in the use of stainless steel for the BPP. Iron elution evaluation after stamping is necessary (it is planned for the next budget period) to prove pre-coating capability. Pre-coating capability is imperative to enabling the roll-to-roll process. Detailed formability metrics are defined.
- Assumptions reflect goals very well: 25,000-hour durability, $5/kW using low-cost coatings. Physical vapor deposition (PVD) and atomic layer deposition (ALD) coatings have good potential; tools for characterization are adequate. GM's approach has logically organized steps to ensure BPP process development success.
- The approach is to target coatings, materials selection, forming, and laser welding—a solid approach focusing on basics and a mix of simulation and experimental demonstration. The use of lower-cost FSS is central to cost reduction.
- The approach to BPP manufacturing addresses key components to BPP cost, base metal material cost, and joining/welding speed, as well as the durability barrier by addressing coatings. Addressing manufacturing speed is important, as to hit target production volumes, one needs to produce ~4,000 BPPs per hour.
- The approach section could use more detail. More details about how the approaches investigated are expected to improve BPPs and reduce costs would be helpful. Since the go/no-go milestone was accomplished within the period covered in this presentation, it would be good to see those results.

Question 2: Accomplishments and progress

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

- Three-stage (3hit) forming is introduced to improve both FSS formability and BPP geometry. Good progress has been made. Good cost savings have been achieved: less than $0.04/BPP cost impact versus more than $2.00 materials cost savings (316L). The PVD coating meets the Budget Period (BP) 1 target and is more robust than ALD coating. Laser welding quality at 90 m/min has been improved significantly—the humping index concept is quite interesting and useful. Peeling strength is greater than 25 N/mm, with much smaller humps. The project has good understanding of failure modes and a strategy to mitigate them. The relationship between flat land and vertical land for forming BPP is well-explained; thinning is a serious concern for durability. Forming targets have been met. The high-speed humping issue has been modeled and validated in the lab, with good use of x-ray and computational fluid dynamics modeling tools.
- GM has made outstanding progress toward achieving the overall project goals. The goals for BP 2 have been met. BPP cost is still estimated at <$5/kW$_{net}$, with accomplishments in forming a low-cost steel being attributed to much of the savings. Thus, GM's results have led directly to overcoming critical barriers.
- GM has shown improved formability using a 3hit stamping process. GM can reduce thinning, increase equivalent elongation, exceed 40% elongation, and essentially match the thinning and elongation of 316 stainless steel in traditional stamping with cheaper steels such as 439L, 444, and CRS22. The project has

made good progress on high-speed laser welding. GM has developed a model for humping and, based on feedback from high-speed imaging and the model, has developed a mixed-mode laser welding technology that significantly improves laser quality at 90 m/min, providing high-peel strength welds with reduced humping. The project has developed an ALD coating that meets DOE corrosion resistance and interfacial contact resistance targets. The project was not able to measure strain rate during the forming process, as proposed. The project has changed to using a plate design more representative of current designs used for vehicle applications.

- Siguang Xu and team made excellent progress toward developing BPPs with steel (non-316L), particularly toward stamping features and welding/joining time. A gap, as admitted in the research, was studying the processes with coated plates.
- The 3hit forming process has been successful in meeting the objectives. The team has successfully identified causes of humping in laser welding. Process windows for laser welding are nice predictive output, and it is good to see how these were validated experimentally. However, the model is missing some details, which is a concern. It seems like at lower laser powers, one would have to slow down to get enough welding, and eventually it would be too low to get any welding; therefore, these plots should have a boundary at some low power where the process is no longer possible. Otherwise, the implication is that one can run faster by turning off the laser.
- The 3hit forming of plates is a solid advancement. The welding characterization achievements are a significant advancement.
- Promising data are shown. The process time of each coating process (PVD and ALD) is necessary for manufacturability assessment.

Question 3: Collaboration and coordination

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

- GM's leadership in fuel cell development is key on this task. There is appropriate collaboration with universities and national labs for analysis. The success of this project may be focused primarily on GM's work, which may be appropriate for this effort. Collaboration with the Million Mile Fuel Cell Truck (M2FCT) Consortium is highlighted.
- GM team has extensive background in BPP manufacturing and robustness improvements. The Pennsylvania State University (Penn State) high-speed laser is an important need, along with Argonne National Laboratory's (ANL's) capability for in situ x-ray. Northern Illinois University (NIU) has complementary BPP capability.
- The combination of team members brings solid experience and capabilities in each area.
- It is good to leverage academia in the project.
- All partners are contributing to the project.
- The accomplishments were shared for Penn State's work on laser welding theory, but no research was shared for work by NIU on FSS formability. The team was working well with M2FCT and Los Alamos National Laboratory.
- Collaborations with Penn State and ANL on laser welding have resulted in good advancements in that area. Collaborations with M2FCT on corrosion testing were mentioned, but it is not clear if work for this project has been done by M2FCT or collaboration is in the area of developing BPP durability test protocols. There does not appear to be any collaboration with a BPP supplier or manufacturer. Future collaboration with the new Roll-to-Roll Consortium could be useful.

Question 4: Potential impact

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

- Relevance and impact are clearly stated. A waterfall chart is a great tool to show the pathway to the $5/kW BPP assembly target. Reduction in the cost of the plates is a key aspect of achieving the overall DOE stack and system cost targets. Thus, the project's focused approach on cost reduction of the plate material, forming, welding, and coating is directly on target.

- A successful BPP using the GM improvements is very impactful in meeting DOE goals. The high-speed laser welding process, going from 30 to 60 m/min, is quite impressive for cost reduction and robustness. The domestic fuel cell manufacturing plant at GM will benefit from this BPP development.
- The project is very systematic. If the project is successful, it will show a path to using lower-cost steel materials, lowering the cost of fuel cell stacks, moving toward DOE goals and greater adoption. The research on the FSS is generally relevant to 316L. The project is also contributing to the education of students at Penn State and NIU.
- The project has high relevance. It addresses manufacturing speed, cost, and durability of BPPs, one of the higher-cost components of the fuel cell stack.
- The project is highly aligned with the Hydrogen Program goals. This project has already resulted in advanced fuel cell BPP design and cost and has shown pathways to meeting durability targets.
- This concept of stainless steel substrate and low-cost pre-coating capability is a high-impact enabler of BPPs for heavy-duty fuel cell applications.

Question 5: Proposed future work

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

- The proposed future work is focused on manufacturing and benchmarking. This work is clearly driven by past progress. The project is logically planned; the future work is appropriate.
- Future work is adequately defined. Assessment of the pre-coating capability should be ensured.
- Each of the main tasks includes a good, clear list of future work.
- Future work to test coatings is logical. Plans for integrating the forming, coating, and sealing technologies are logical. It is not clear what additional steps are proposed to improve weld quality at high speed (90 m/min). Future work indicates the team will use a high-strain-rate tensile test (with Hopkinson bars) for experiments to determine the strain rate effect on formability. The partners have been unable to measure strain signal properly with Hopkinson bars to date. It is not clear what future improvements are planned that will allow the team to properly perform the high-strain-rate tensile tests with Hopkinson bars. Other techniques may be needed.
- The team raises the concern that BP 2 may be delayed because of the long lead times for stamping plates. Although the team laments the lack of U.S. vendors, the long lead times are realistically just the long time needed to develop new tooling, particularly for a new process (3hit). The team could be more creative in avoiding likely delays in the BP 2 schedule by using additive manufacturing for tooling and smaller stamping houses, some of which are located in Michigan.
- Future work is aligned with the lessons learned. Material loss during deposition needs to be addressed. Batch versus continuous process evaluation will be helpful.

Project strengths:

- The technology is being tested on modern and representative plate design, which is very good. The project has a good listing of barriers and a good statement of numerical targets for each. Use of lower-cost FSS is central to cost reduction. The waterfall chart showing the cost benefit of each factor is very good.
- BPP development is led by large-scale manufacturers with many years of experience in fuel cell technologies.
- The laser welding work is a strength. A strong team has been assembled.
- The work is very systematic. The presentation clearly shows the relevant research.
- The manufacturing process is based on the GM platform for stamping for high-speed manufacturing. GM capabilities in prototyping are used to fast-track the development cycle.
- The team has adequate understanding of BPP design requirements.

Project weaknesses:

- No specific project weaknesses were observed in this reporting period.
- The active area is modest/low at 66 cm^2. Coating materials and thicknesses were stated in the question-and-answer period but should have appeared on the slides. For the welding, little is stated about the impact of plate thickness, which is an important parameter; optimal welding parameters should be explored as a function of sheet thickness. A waterfall chart is presented, but there is not a tight coupling between the individual targets and their cost impacts. For instance, the welding speed may fall short of the 90 m/min target, but the sensitivity to cost is unclear. The presentation should show quantification of performance gain of rounded versus flat lands, as well as added cost of three-stage (3hit) versus one-stage (1hit) forming.
- Comparative evaluation of PVD and ALD processes should be performed for key parameters: performance – conductivity, strength, material yields – losses in manufacturing, manufacturing speed of deposits, etc.
- The present path of using a standard BPP stamping vendor will likely cause project delays. The team should look for creative solutions to expedite the project research.
- Collaboration with BPP suppliers and manufacturers is lacking.

Recommendations for additions/deletions to project scope:

- It is unclear whether the tests cited (interfacial contact resistance, iron elution) are adequate to capture all forms for corrosion and/or degradation. This testing should be reconsidered and expanded as needed. Optimal welding parameters should be explored as a function of sheet thickness. Expanded techno-economic analysis should be conducted to explore the sensitivity to each of the targeted parameters. For instance, if the goal welding speed is not achieved, what the cost impact is and whether the lower speed can be offset by multiple simultaneous laser beams need to be elucidated.
- Future interactions with the Roll-to-Roll Consortium could be beneficial.
- Assessment of pre-coating capability, such as iron elusion after stamping, should be ensured. The iron elusion target should be validated with fuel cell durability testing.
- Out-of-cell tests and in-cell stack test results will be useful in judging relative merits.
- It would be helpful to include results from 316L for comparison, where relevant, particularly for corrosion.
- There are no recommendations for additions or deletion in project scope this reporting period.

Project #FC-349: Foil-Bearing-Supported Compressor–Expander

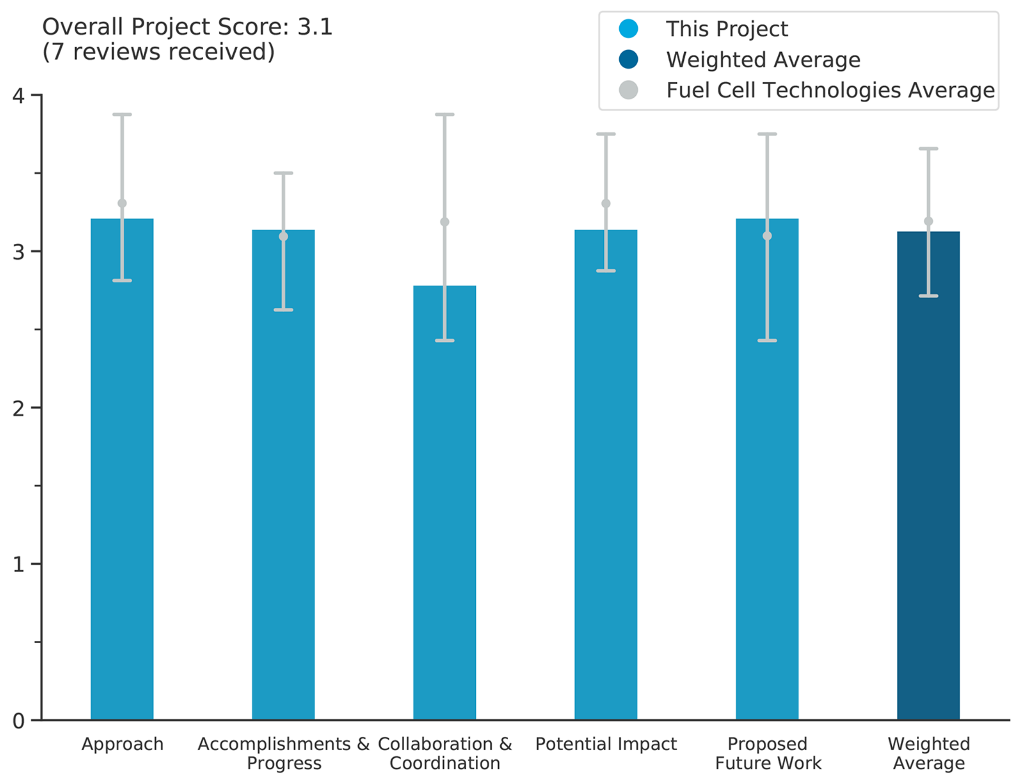
Giri Agrawal, R&D Dynamics Corporation

DOE Contract #	DE-EE0009617
Start and End Dates	5/1/2022–11/1/2024
Partners/Collaborators	Loop Energy, University of Texas at Dallas
Barriers Addressed	• Meeting the efficiency for the compressor–expander at the required pressure ratio

Project Goal and Brief Summary

The project focuses on developing a fuel cell system compressor–expander (CE) for heavy-duty (HD) vehicle applications. The approach involves the development of a high-speed centrifugal CE supported on oil-free foil air–gas bearings, incorporating surge bypass, variable turbine nozzles, a permanent magnet motor, and a motor drive with SiC switches.

Project Scoring



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

Question 1: Approach to performing the work

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

- The use of air foil technology for a fuel cell electric vehicle air compressor concept is reasonable, and this approach has the potential to enable a component that is attractive. It is not clear whether the project includes any fuel cell system modeling, which can help ensure that the project actually delivers useful advancements in this key balance-of-plant component. The principal investigator should present the key benefits of the compressor technology in a table that compares the different technologies (gas foil bearings, lubricated bearings, etc.) and the key metrics (lifetime, energy efficiency, size/weight, start/stop cycles, noise, cost, etc.).

- Target metrics are clear and precise.
- The approach to developing a high-speed CE supported on oil-free bearings is very relevant to the overall goals of the Hydrogen and Fuel Cell Technologies Office (HFTO). The requirement for the CE is to operate up to 80,000 repetitions per minute (rpm) with 25,000-hour durability. It is not clear from the approach if the technologies outlined in slide 5 can meet those requirements. Bearing durability at that velocity is still unclear because the bearings have been operated to a max of only 65,000 rpm so far. It would be better if the project outlined the technology improvements or changes that will help achieve the project targets. It is unclear what the basis is for the durability protocol used, 10,000 start/stops, 500 cycles between 25% and 100% speed, and 1,000 on/off cycles. The basis behind these protocols and how it correlates to 25,000 hours need to be established.
- Project objectives are clearly defined, along with potential impacts. The deliverable is a CE with high reliability (25,000 hours), lower cost (<$3,000), and high efficiency (>77%) for HD fuel cell applications in the range of 200–250 kW. Features of this CE include air bearings, surge bypass and variable turbine nozzles for efficiency, a permanent magnet motor, and use of SiC in the motor inverter. The project is divided into roughly three tasks, defined as design, fabrication, and test/evaluation, which is typical of component development. R&D Dynamics Corporation (R&D Dynamics) is responsible for the CE design and testing. The company is partnered with the University of Texas at Dallas (UT Dallas) (motor inverter) and Loop Energy (specifications and bench testing). Specifications and requirements should be better defined, and the compressor usage profile for an assumed 25,000 operating hours should be clarified. Also, the durability protocol and requirements need better vetting to ensure the targets and test method are reasonable. A protocol of 10,000 start/stops and 1,000 on/off cycles is too low for vehicle applications. Also, for the expander, water erosion must be included as part of durability considerations.
- R&D Dynamics presented a clear approach to meeting the project objectives. However, it is not certain the project will meet the efficiency or cost targets sought by DOE. It is also not clear whether the project will be completed on time, as discussion of a no-cost extension may or may not have already been accounted for in the project. Cost is highlighted as a barrier but could be better understood at this point in the project.
- The approach lacks details, but it is within mainstream technology of (oil-free) air foil bearings, with expander, drive, and SiC switches. The pressure ratio target of 2.5 seems low for the maximum flow of 285 g/s; typical values are expected to be 2.8–3.0. The minimum speed requirement is not defined.

Question 2: Accomplishments and progress

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

- R&D Dynamics has shown good progress toward meeting some project objectives. The project formally ends November 1, 2024; it is not certain that the work will be completed by this date. Perhaps a no-cost extension has been requested. Results have led to a good understanding of the performance of the proposed fuel cell air delivery system. Durability of the compressor has yet to be addressed. If durability targets are met, the fuel cell air delivery system may have advantages in fuel cell durability over competitive designs.
- Relative to design build and testing, the project has accomplished many of the goals. A compressor has been built and tested to 65,000 rpm. The project formally ends November 2024, which leaves little time to complete performance and durability testing. The team is asked to provide a project timeline showing task and planned completion dates to better allow assessment of progress relative to targets.
- The project has done very well in regard to the technical targets. However, the ultimate metric is cost, which does not seem to have been addressed in much detail. It would be good to understand what manufacturing strategy needs to be implemented to achieve cost targets.
- The project appears to be on the proposed schedule. The results to date suggest that the critical barriers may be overcome.

- CE testing has been performed up to only 65,000 rpm. Based on the data, the coefficient of performance seems to have plateaued at 65,000 rpm at 0.78 at ~250 g/s flow at a compressor isentropic efficiency of 60%. It is not clear what the path is to achieving 80,000 rpm and 75% efficiency at 285 g/s. It is also unclear why there are 10,000 start/stop cycles for the compressor but only 1,000 on/off power cycles, whereas in real operations, every on/off would result in a start/stop for the compressor.
- R&D Dynamics has designed and built the CE assembly. The team has been able to test it only up to moderate speeds (65,000 rpm) because of an algorithm issue. The results up to 65,000 rpm align with the expected map and approach but do not yet meet efficiency targets. The pressure ratio of 2.5 seems low for the max flow 285g/s; typical values are expected to be 2.8–3.0. There is also no mention of turbine expansion pressure ratio.

Question 3: Collaboration and coordination

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

- R&D Dynamics has good engagement with project partners. The presentation highlighted discussions with Loop Energy and UT Dallas, showing specific accomplishments for each collaborator. Discussion between R&D Dynamics and Loop Energy resulting from a potential change in ownership could be discussed at the next Annual Merit Review.
- The team has a relatively immature fuel cell system developer (Loop Energy), and Loop Energy's role appears to be limited to testing (no system modeling). UT Dallas' role is clear, and some results were presented.
- It will be great to see Loop Energy test the unit with a fuel cell system.
- R&D Dynamics is the project lead. To date, R&D Dynamics has completed most of the work: design, build, and testing. UT Dallas is providing an alternative motor drive, but it is not clear what is unique about the drive—for example, whether it contains SiC switches and how it differs from the drive R&D Dynamics uses. Eventually, Loop Energy will test the compressor in a fuel cell field bench. It would be helpful to know the test objective (if it can be shared), i.e., whether the test will assess the compressor performance and dynamics for a representative HD truck power cycle.
- The collaboration with Loop Energy and UT Dallas, although sufficiently satisfactory, does not seem to be enough. As the project is developing a component that has significant impact on fuel cell performance and efficiency for HD truck applications, the target performance metrics and durability should have been defined with the help of original equipment manufacturers (OEMs) at the beginning of the project. Loop Energy is not an established OEM in the automotive space and might not be the right partner in this project.
- Loop Energy assisted with specifications and is expected to test the CE at the end of the project. Loop Energy's commitment to this task is unclear, owing to the company's recent acquisition. UT Dallas developed an alternate motor drive for testing with the CE.
- Although the presenter stated that Loop Energy is expected to complete assigned tests, concerns remain about Loop Energy's future. UT Dallas was tasked with developing an alternate motor drive, which was delivered. However, differences with the R&D Dynamics design are unclear, negatively affecting the perceived value of the UT Dallas design.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aligns well with HFTO goals and objectives and has the potential to advance progress toward performance targets, especially with respect to improving fuel cell system energy efficiency (reducing parasitic loads), decreasing system capital costs, and improving system reliability (reducing downtime). Additionally, since fuel cell vehicles are currently very niche products, DOE support for air compressors, which are optimized for fuel cell applications, is very beneficial in motivating suppliers to invest in developing advanced products.

- The CE is obviously an important subsystem of the fuel cell system and thus is extremely relevant to the development of the technology. However, because cost is somewhat vague, it is hard to know whether this will become an enabling product.
- For fuel cell applications, there are currently air bearing centrifugal/CEs in production, e.g., Bosch. This project should clearly state how this compressor differs from those, for example, whether the difference is mainly higher flow capacity relevant to HD fuel cell systems. Relative to DOE targets, the project looks in line to succeed.
- The project's impact on DOE goals for fuel cell air delivery systems may be limited by cost. R&D Dynamics' approach should meet DOE performance metrics, including fuel cell durability targets.
- The project has the potential to advance fuel cell system efficiency, if fully realized. However, it seems that the CE can meet the efficiency target at the required pressure ratio only at the max flow rate. At a 50% flow rate, efficiency has been de-emphasized. In addition, the project is already behind schedule. Obtaining the data at 80,000 rpm and meeting the durability target must be made critical paths prior to fabricating final demonstration units.
- This project aligns well with the HD fuel cell system targets, although a pressure ratio of 2.5 seems low for the max flow of 285 g/s.
- Disadvantages of the selected technologies should be given equal time. A clear assessment cannot be formulated without this additional information.

Question 5: Proposed future work

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

- The proposed future work is appropriate.
- Work required to complete this project includes performance testing, durability testing, bench testing, and cost estimation. The durability criteria are low for on/off and start/stop cycles and also miss evaluation of erosion from humid air on the turbine. Compressor performance testing on the bench and in a fuel cell system will likely provide the most useful information. Performance results should obviously include efficiency but also dynamic response. The final report should provide usage profiles to clarify how the compressor was evaluated. Also, perhaps it is possible to include an accelerated life durability test to assess bearing durability—unless the expectation is that start/stop testing covers that.
- Durability and cost estimates are the focus of R&D Dynamics' future work. Both durability and cost estimates will address critical barriers to meeting the DOE goals for fuel cell air delivery systems. The impact of alternate pathways, should durability and cost estimates not meet DOE goals, could not be assessed.
- The future work makes sense, but the Loop Energy integrated testing does not seem to be listed.
- Correlation of the test protocol outlined in slide 15 with the actual durability requirement (25,000 hours) is critical to future development of a durable CE. Fabrication of final demo units should be done after the durability demonstration.
- R&D Dynamics has plans to optimize the test set-up and control scheme to better meet performance requirements, but details of the plan were not shared. R&D Dynamics has a detailed durability test plan, but it did not explicitly include liquid water tolerance or freeze testing, nor did it include shock and vibration testing. The team plans to conduct a cost estimate and production plan.

Project strengths:

- This project technology of a centrifugal CE for HD application, using air foil bearings, has potential to meet DOE compressor efficiency requirements.
- The project has an interesting overall approach that is likely to yield an advanced air delivery system for HD fuel cell electric vehicles.
- The principal investigator and team seem to have strong expertise in the area of CEs. The project targets high-efficiency, durable oil-free CEs, and the project team seems to understand the barriers and the challenges in designing and prototyping.

- R&D Dynamics has technical knowledge of turbo machinery and has executed on a good approach to improving fuel cell durability in high-power (>100 kW) fuel cell systems.
- The project is developing a high-efficiency durable compressor 200+ kW fuel cell system.
- Technical performance from the CE is impressive.
- The approach, progress, and proposed future work are good.

Project weaknesses:

- Durability evaluation is not in line with demonstrating a reliable compressor design for fuel cell vehicle applications. R&D Dynamics should seek the input of potential customers to ensure the durability targets are reasonable. It is expected that more development and durability testing will be required before this technology is ready for commercialization.
- There is a lack of details about how the team plans to address issues to achieve high speeds and hit maximum air flow requirements. A pressure ratio of 2.5 seems low for the max flow of 285 g/s; typical values are expected to be 2.8–3.0.
- Loop Energy does not seem to the right partner to provide requirements for CEs for HD truck applications. Loop Energy's participation within this project is unclear and needs to be terminated. The involvement and project scope for UT Dallas is very vague and does not clearly outline the university's tasks. UT Dallas is mentioned as developing alternate motor drive partners; however, there are no data on the alternate drive developed by UT Dallas.
- Either the work related to partner institutions is risky, or the benefits are unclear. The justification of the potential impact could be improved.
- Turbo compressor durability remains a project weakness at this point of execution. Cost and project completion could also be an issue.
- No fuel cell system modeling is included.
- The cost plan is weak.

Recommendations for additions/deletions to project scope:

- The project should consider adding fuel cell system modeling and collaborating with the Million Mile Fuel Cell Truck (M2FCT) consortium for this purpose.
- The unit should be tested at Loop Energy as soon as possible to learn whether there are any integration issues.
- Loop Energy can be removed from the project and another truck OEM added, which would be more valuable for this project.
- The team might consider adding, on a best effort basis, the following tasks to the proposed future work: effects of freezing, vibration, and high altitude on CE performance.
- The project should include liquid water tolerance or freeze testing, as well as shock and vibration testing.
- Durability targets should be reevaluated, and the team should seek input on developing the durability test.
- The reviewer has no additions or deletion to the current project scope.

Project #FC-350: High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cells

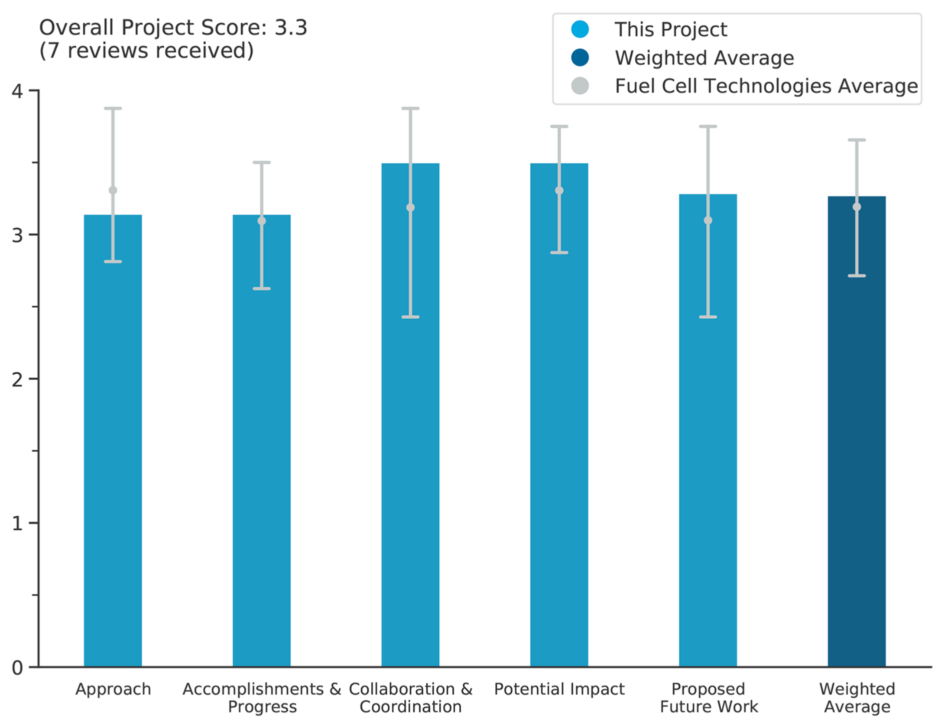
Doug Hughes, Eaton Corporation

DOE Contract #	DE-EE0009618
Start and End Dates	9/1/2022–11/30/2024
Partners/Collaborators	Ballard Power Systems, National Renewable Energy Laboratory
Barriers Addressed	• Air system power consumption targets: ○ 27.9 kW at 100% flow ○ 10.8 kW at 50% flow ○ 0.32 kW at idle • Response time target: 2 seconds • Turndown ratio target: 20

Project Goal and Brief Summary

The project goal is to develop a highly efficient and responsive air system for on-highway commercial vehicle fuel cells by using positive-displacement Roots® machines, maximizing waste energy recovery, and managing water to enhance performance. The project aims to achieve ~50% improvement in air system power consumption, leading to improved reliability, durability, and affordability. Existing fuel cell air systems are a significant source of parasitic power loss and limit system durability and reliability. The proposed system innovation can potentially reduce power consumption by 50%, equivalent to a 9% improvement in fuel cell output. The project's approach involves optimizing the proposed system through modeling and simulation, designing and building a subscale test system, and conducting design studies to establish component specifications.

Project Scoring



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

Question 1: Approach to performing the work

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

- Project approach and timeline seem well-reasoned. Analysis and design studies have been completed, showing the potential of a Roots compressor–expander, along with other system components, to meet DOE targets such as efficiency and cost. These studies have justified moving forward with the design–build, build, and performance assessment of the defined components and system. This work is to be completed within the remaining year of the project, which seems possible with Eaton Corporation's (Eaton's) capability and work in progress. It is recommended that the project scope be better clarified as to what will be validated and delivered and what will not. Clearly, durability, reliability of oil seals to prevent contamination, compressor corrosion due to water dosing, and freeze robustness are outside the scope of this work but have been considered.
- The use of positive-displacement Roots technology for a fuel cell electric vehicle (FCEV) air compressor concept is unique and has the potential to enable a component that is attractive. The project includes fuel cell system modeling, which should help ensure that the project delivers useful advancements in these balance-of-plant (BOP) components. It is recommended that the principal investigator present the key benefits of the compressor technology in a table that compares the different technologies (Roots, gas foil bearings, etc.) and the key metrics (lifetime, energy efficiency, size/weight, start/stop cycles, noise, cost, etc.).
- Eaton has a clear understanding of the critical barriers to meet the DOE targets for fuel cell air management systems. Eaton has developed a project to meet these barriers by adapting positive-displacement Roots technology to fuel cell applications. Durability testing is one metric that seems lacking, but it may be out of scope for the proposed effort. The presenter stated that Eaton has completed analytical projections that show life to 25,000 hours. Given the number of questions for reviewers last period, some level of projection validation through testing could be helpful to secure a follow-on award.
- The approach is sound.
- Overall, the project approach is good. Slide 6 does not provide a reason for the six-month gap between the budget period (BP) 1 go/no-go and the BP 2 build plan. Regarding slide 7, it is unclear whether the system response time is desired at all operating points. The status of 0.4 sec response time is from simulated values. Project goals are based on current supercharger products that are designed for diesel internal combustion engines (ICEs) and not for FCEVs. The project goals should be based on FCEV design requirements, which are not outlined on slide 7. Finally, it is not clear whether the cost of the component would change if the response time requirements changed.
- This project is working on a very complex system (Roots compressor, gear box/oil lubrication, water dosing, recuperator). The system uses an older technology Roots (positive-displacement) compressor. Roots compressors are not designed for high compression ratios. The compressors are more suitable for applications that require a constant volume of air or gas at relatively low to moderate pressures. Roots compressors can also be less efficient at low speeds. Roots compressors can experience backflow or blowback of compressed air or gas from the outlet to the inlet. Backflow or blowback can occur if there is a sudden pressure difference or if the discharge pressure exceeds the system pressure. Backflow can affect the compressor's performance and may require additional measures, such as check valves, to prevent it. Using a gear box and oil pump will add system complexity and introduces the possibility of oil contamination.
- The system electrical power consumption target at the 50% load point (10.8 kW) is not met (14.5 kW is anticipated). It is stated that the importance of this specific load point was de-emphasized, that the duty cycle would reduce the 50% load point impact, and that the performance of the next-generation design is expected to improve. It would be beneficial to give a reason or explanation for the low performance at the 50% load point. The noise level goal at the idle load point (between 63.6 and 67.2 dB-A at 1 m) is expected to be met (65 dB-A at 1 m) without noise abatement. It should be indicated which methods of noise abatement could be used, as well as their approximate impact on the noise level.

Question 2: Accomplishments and progress

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

- Project targets for go/no-go were defined primarily in terms of air system efficiency, transient response, and noise. A power reduction walk quantified the benefits of adding an expander, a water dosing humidifier, improved electrical efficiency, and a recuperator. Design studies and system analysis were completed to show that the proposed air system architecture has the potential to achieve stated targets, and the analysis justified protype build and testing. In addition, the facility and component design are completed. The project team is achieving objectives and should be on track to finish the project on time.
- The project appears to be on the proposed schedule. It is not clear whether the “oil control features” are effective or if water dosing and a recuperator should be used. However, the results to date suggest that the critical barriers may potentially be overcome.
- The benefits of performance of a system with a Roots compressor and a water dosing system have been quantified using a static model. The gearbox design is complete. Eaton claims the projected system will exceed 25,000-hour durability, but the methodology was not disclosed.
- The project is only at the design stage, but it seems to meet DOE objectives at 100% operating point.
- Eaton is on track to meet the majority of the project objectives. Air efficiency at 50% operating point and fuel cell air delivery durability may not be proven by the end of the project.
- National Renewable Energy Laboratory (NREL) has impressive accomplishments on simulated iterations and ranking by duty cycle weighted net electrical power consumption. Results based on various selections should be published for the benefit of the larger technical community. Slide 13 identified a number of risks regarding liquid water in freezing conditions and maintaining humidity under all fuel cell operating conditions. However, there are no mitigation strategies or plans to address those risks.
- Slide 9 indicates that the R1188HPR compressor and V550 expander were selected. Presumably, key metrics for these components are given in slide 38, because slides 11 and 26 provide performance maps for the next-generation compressor (1175HPR) and expander (R525), and they do not match reported values. Performance maps for the selected components, the R1188HPR compressor and V550 expander, should be provided. The maps would also provide a context to explain the 50% load point power consumption, which does not meet the target. Many of the slide 38 key metrics (system response time, durability, cost, etc.) are not supported by data.

Question 3: Collaboration and coordination

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

- The team has a well-established fuel cell system developer (Ballard), and Ballard’s advisory role is appropriate. NREL’s role is clear, and some results are presented here. It is great to see the team is working with Million Mile Fuel Cell Truck (M2FCT) on duty cycles. The team should also review the system model with M2FCT’s model (i.e., the Argonne National Laboratory [ANL] model) to ensure agreement and potentially identify improvement opportunities (e.g., in the models or in metrics/targets for air compressors in heavy-duty [HD] applications).
- Eaton has a high degree of collaboration with the partners. Both Ballard and NREL are engaged and helping improve the likelihood for both project success and impact to large-scale (>100 kW) fuel cell systems.
- Collaboration between project partners is excellent. Collaboration with Purdue University (Purdue) for recuperator design is a good use of academic resources/expertise.
- This project has demonstrated strong collaboration. NREL has conducted system modeling. Ballard has provided system requirements and highlighted risks.
- Eaton worked with NREL and Ballard to successfully complete the evaluation of the proposed air system architecture.

- Collaboration with Ballard is helpful for determining the suitability of water dosing.
- Purdue is mentioned in slide 14 but does not appear in the collaboration and coordination on slide 16.

Question 4: Potential impact

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

- The project aligns well with the Hydrogen and Fuel Cell Technologies Office's (HFTO's) goals and objectives and has the potential to advance progress toward performance targets, especially with respect to improving fuel cell system energy efficiency (reducing parasitic loads), decreasing system capital costs, and improving system reliability (reducing downtime). Additionally, since fuel cell vehicles are currently very niche products, DOE support for air compressors, which are optimized for fuel cell applications, is very beneficial in motivating suppliers to invest in developing advanced products.
- Fuel cell system efficiency is dependent on BOP efficiencies, and the fuel cell air system contributes the majority of the parasitic power loss. Hence, this project has a significant impact toward the overall efficiency targets of the HFTO.
- This project is high-risk, but high-reward. If Eaton and the project team can address the many technical challenges of the air subsystem, the project has the potential to significantly improve the efficiency of HD fuel cell applications.
- Developing a compressor that can operate for over 25,000 hours is a challenge and is critical for delivering fuel cell systems that have equivalent life to today's ICE vehicles. Many vehicle fuel cell systems currently use centrifugal compressors with air bearings that, at this point, are questionable in their ability to reach the 25,000-hour life target. However, Roots-type air machines have demonstrated long life in various applications. Therefore, the main impact of this project would be delivering a long-life compressor that is competitive in cost, efficiency, and packaging. Replacement of the membrane humidifier with a water doser/recuperator may offer better reliability but creates challenges, some of which have been mentioned by previous reviewers (e.g., corrosion, freeze, dosing design, system complexity). If there is not a clear cost benefit, this task will have little impact or be of little interest.
- Eaton's work is relevant to meeting the DOE objectives for fuel cell air delivery systems.
- The reviewer is unable to judge the cost impact of such technology.

Question 5: Proposed future work

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

- The remainder of the project involves system build and testing. The major milestones and timing of this work have been clearly defined and are expected to be completed early next year. Designing a gear box to couple the motor, compressor, and expander to achieve target efficiency will be a challenge.
- The balance of Eaton's work will focus on building and testing the next-generation compressor. This work is logically and effectively planned. A better understanding of durability may be needed for/in future projects.
- Future challenges and risks are clearly identified, with some mitigation planned. It would be good to see some performance data as they relate to these risks by the next Annual Merit Review, with additional data after mitigation.
- The proposed future work is appropriate.
- Plans include component procurement and system testing. Analysis of the overall system cost and volume should be included. There is no clear plan for durability/corrosion resistance testing.
- The presentation provided a list of dates from a basic timeline. A more descriptive proposal would be preferred.

Project strengths:

- From the work presented, the project has completed a significant amount of design and a number of design studies toward the build of a Roots compressor–expander. Eaton has the experience and capability to successfully build and test this compressor. The reviewer is looking forward to the performance assessment next year.
- The project has a good overall approach that is likely to yield an advanced air delivery system for HD FCEVs. The team is collaborating with M2FCT.
- Modeling of the proposed technology is excellent. It will be interesting to see the prototype data in the next phase of the project.
- The project's strengths are leadership: an industry leader in vehicle air machinery and a world leader in fuel cell system design and manufacturing.
- This concept, if the team can address all the technical challenges, has the potential to significantly improve efficiency over the operating space.
- The principal investigator's experience with air systems for automotive applications is a strength. Compressor–expander efficiency is still far from 2030 targets. It is not clear whether the targeted efficiency is achievable using the technologies outlined in this project.
- Strengths include the potential impact/relevance and proposed future work.

Project weaknesses:

- Below are comments on items to address:
    - Regarding operation consideration, the project title reads, "High-Efficiency and Transient Air Systems for Affordable Load-Following Heavy-Duty Truck Fuel Cells." However, little mention is made of considerations for integration in a truck—especially for packaging, as well as whether the Roots compressor can be compact. Also, the usage/power profile for assessment of 25,000 hours/1.2 million miles should be stated. The compressor seems to be sized for about a 250 kW system. Perhaps life estimate is based on max flow—it is not clear.
    - Regarding efficiency, peak efficiency appears to be below what centrifugal compressors can achieve today. The graph for 1175HPR shows a peak of 73%; centrifugal compressors can be higher (77%) without an expander. It would be helpful to know the best efficiency that can be expected with the Roots compressor–expander, as well as any projections on the efficiency loss of the gearbox.
    - Regarding cost, it would be helpful to have an estimated cost comparison to clarify how this system would be more affordable.
- This very complex system adds several components (an oil pump, recuperator, and water dosing pump) not included in typical fuel cell systems. The impact on overall system cost and packaging is not included. Roots compressors are not designed for high compression ratios. It is unclear how system durability is being assessed.
- Eaton has presented current estimates on fuel cell air delivery system power consumption, which are on track to meet the project objectives. However, the risk for water dosing is very high. Although a go/no-go decision was passed based on simulation results, the risk to success is very high, and no component-level water dosing tests are planned before the entire system is built in October 2024.
- The description of a few approach elements could be improved (50% load point energy consumption and noise level abatement). Supporting data are missing for several elements (compression–expander performance, system response time, durability, cost, etc.). Purdue's role is not defined.
- Eaton did a good job addressing reviewers' comments from last year. Durability will remain a project weakness.
- There was no reference to cost in the presentation. It would be helpful to see a chart on costs–benefits vs. those of traditional compressors.
- It is not clear whether the team understands the potential failure mechanisms for the compressor. It is hard to develop valid accelerated test protocols without this fundamental understanding.

Recommendations for additions/deletions to project scope:

- Understanding the impact of water injection into the fuel cell air delivery system is critical. Component-level durability and reliability testing needs to be performed with water dosing tests prior to building the entire system.
- Analysis of the overall system cost and volume should be included. Dynamic and freeze testing of the full system, including the stack, should be included. Ballard should have the capability to do that.
- It is recommended that the project provide a cost–benefit chart or table, including an estimated manufacturing cost, so that reviewers can fully assess the technology impact compared to traditional compressors.
- The team’s system model should be reviewed next to M2FCT’s model (i.e., the ANL model) to ensure there is agreement and potentially identify improvement opportunities.
- The project priority should be focused on compressor development and testing. Evaluating water dosing and a recuperator should be deleted if cost and time become an issue.
- Durability testing would be one suggestion for an addition to project scope.

Project #FC-351: Durable and Efficient Centrifugal Compressor-Based Filtered Air Management System and Optimized Balance of Plant

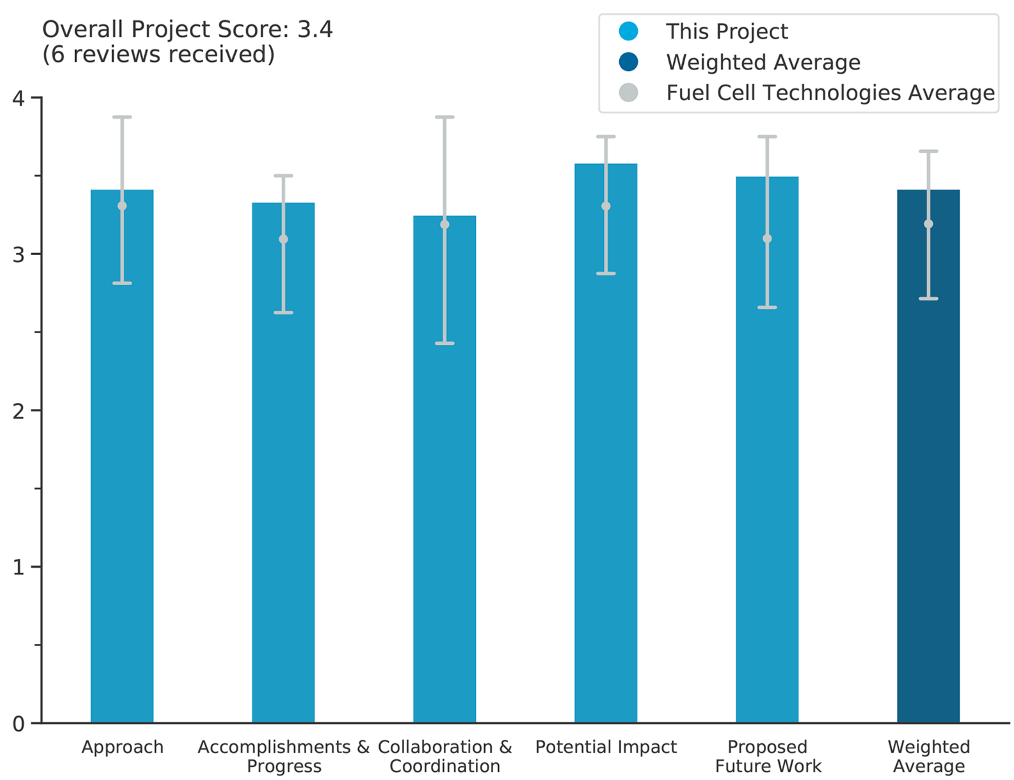
Mike Bunce, MAHLE Powertrain, LLC

DOE Contract #	DE-EE0009619
Start and End Dates	10/1/2022–1/1/2025
Partners/Collaborators	BMTS Technology, MAHLE Filter Systems, Oak Ridge National Laboratory, General Motors Global Propulsion Systems
Barriers Addressed	• Durability of air management system • High parasitic losses leading to increased fuel use

Project Goal and Brief Summary

The project's goal is to develop a low-cost ($12/kW), high-reliability (25,000-hour) air management system for heavy-duty (HD) fuel cell vehicles. The approach involves optimizing compressor and expander designs, utilizing novel compressor bearings for increased durability and reliability, and implementing primary and catalytic air filters to enhance the durability of the fuel cell stack. The project uses a quasi-empirical one-dimensional fuel cell system model for optimization, right-sizing, and interface control, along with prototyping controllers and hardware-in-the-loop test benches.

Project Scoring



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

Question 1: Approach to performing the work

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

- AHLE Powertrain (MAHLE) has a clear approach to completing the work proposed. The project objectives of developing a low-cost and high-reliability air management system are clearly highlighted throughout the presentation. Critical barriers have been addressed; the project focus is now on demonstration. Concerns regarding glycol leakage through the compressor bearing may still be relevant; however, MAHLE presented testing that shows concerns may have been addressed. MAHLE's work on air filtration might be key to improving fuel cell system life. A safety plan was not required; however, MAHLE did address its approach to safety and best practices. Improving this project significantly would be difficult.
- The project includes a comprehensive approach to the air system. A new water-lubricated compressor bearing and chemical filtration are very interesting technologies that have the potential to extend lifetimes.
- The general air compressor concept is good, and it is nice that the project also includes filtration and chemical traps, since these are also key components of the air delivery subsystem. The project includes fuel cell system modeling, which should help ensure that the project delivers useful advancements in these balance-of-plant components. It is recommended that the principal investigator present the key benefits of the compressor technology in a table that compares the different technologies ("3D bearing," gas-foil bearings, etc.) and the key metrics (lifetime, energy efficiency, size/weight, start/stop cycles, noise, cost, etc.).
- The funding opportunity announcement (FOA) cost targets are for a 300 kW fuel cell system. However, the predicted status in slide 8 is for a 200 kW fuel cell system. The cost projection for 300 kW should be recorded, or the gaps to meet the FOA targets must be documented. Efficiency targets are also for a 300 kW system, but the efficiency table is for a 200 kW system. The path to achieving final efficiency targets is unclear.
- The project consists of two elements. The first is development of a compressor–expander with a water-lubricated bearing, which is expected to have higher durability than air foil bearings. The second is an improved filtration chemical adsorption concept to increase fuel cell stack life. The project mainly centers around the design build and testing of a compressor–expander, air filter, and chemical trap. The main concern for a water/glycol-lubricated bearing is stack catalyst contamination, so a reliable leak-free design must be demonstrated. Also, there are concerns about turbine erosion with the flow of high-humidity exhaust gas.

Question 2: Accomplishments and progress

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

- MAHLE has demonstrated outstanding progress toward project objectives. The team is on track to meet or exceed the DOE goals for fuel cell air management systems in terms of cost, volume, and weight. MAHLE has also made good progress demonstrating durability with the studies on glycol leakage through the compressor bearing.
- Progress has been made on all components, and the project is on track. The compressor (as designed to mitigate leaks) was tested, and a turbine design with erosion-protective coating was selected. An air filter has been designed and is undergoing testing. Also, materials that can trap catalyst poison have been evaluated.
- The project appears to be on the proposed schedule. The leak trap results are promising. The results to date suggest that the critical barriers will potentially be overcome.
- The team has made excellent progress on the technical front. Cost was mentioned as meeting targets, but the presentation included little explanation regarding how the measurement against targets was assessed.
- Data supporting predicted metrics for the compressor and expander are not provided. It is expected that components exposed to the glycol coolant will require corrosion protection. However, this aspect is not addressed. The combination of materials 1 and 2 for the chemical trap (secondary filter) is estimated to be

effective for 300 to 500 h, implying 50 to 83 filter replacements or regenerations. This situation represents a significant risk.

- Slide 9 showed a seal that was designed to mitigate ethylene glycol leaks. The seal was tested, but the results were not presented with any quantitative values. It is unclear what the glycol flow rate is in the system.

Question 3: Collaboration and coordination

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

- MAHLE has properly highlighted its partners, as well as defined their roles and responsibilities. Interactions with ORNL, as well as GM, Hyzon, and Ballard, were mentioned during the discussion. MAHLE has done an excellent job coordinating with partners to increase the success of this project.
- Based on the progress stated, all four partners (MAHLE Powertrain, MAHLE Filter Systems, BMTS Technology, and ORNL) are working together to achieve the project goal on time.
- Collaboration seems to be excellent between partners, given the technical accomplishments to date.
- The team has a well-established fuel cell system developer (General Motors [GM]), and its advisory role is appropriate. MAHLE appears to be closely aligned with the compressor developer, BMTS Technology. Oak Ridge National Laboratory's (ORNL's) proposed role is clear, but it is not clear what ORNL has actually done. It would be nice to see the team review its system model with the Million Mile Fuel Cell Truck (M2FCT) model (i.e., Argonne National Laboratory [ANL]) to ensure agreement and potentially identify improvement opportunities (e.g., in the models or in metrics/targets for air compressors in HD applications).
- It is unclear why collaboration with ORNL is limited to the secondary chemical trap and testing. The team could have used ORNL to quantify the leak rate of glycol, if any. It is unclear whether, as part of the collaboration with ORNL or GM, an accelerated stress test will be developed to obtain compressor–expander durability projected to 25,000-hour fuel cell durability.

Question 4: Potential impact

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

- The project aligns well with the Hydrogen and Fuel Cell Technologies Office (HFTO) goals and objectives and has the potential to advance progress toward its performance targets, especially with respect to (1) improving fuel cell system energy efficiency (reducing parasitic loads), (2) decreasing system capital costs, and (3) improving system reliability (reducing downtime). Additionally, since fuel cell vehicles are currently very niche products, DOE support for air compressors, which are optimized for fuel cell applications, is very beneficial in motivating suppliers to invest in developing advanced products.
- The team will assess the impact of each of the following components:
    - Filters such as the air filter with adsorbent are already in use on fuel cells, so this technology is not novel. If the team has developed something distinct/unique, it should be stated.
    - The chemical trap can address common contaminants that degrade the stack electrode. A practical design will be needed, especially to accommodate adsorbent regeneration. Then a tradeoff should be completed comparing the value of improved stack life vs. component cost, which will be useful.
    - The compressor will have a benefit if a reliable lubrication seal can be demonstrated. It will be valuable to have the seal durability test vetted.
- The project is strongly aligned with the Hydrogen Program's goals. The progress MAHLE has demonstrated indicates high probability of meeting project objectives.
- If the cost targets are indeed feasible, then this project has a very direct impact on the state of the art.
- Project goals are aligned with the HFTO 2030 targets. However, the FOA targets are for a 300 kW system, and this project is targeting a 200 kW system. If the cost, volume, and weight linearly scale with system sizing, it is unclear whether the project will still achieve the same $/kW.

Question 5: Proposed future work

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

- MAHLE has transitioned this project to the demonstration phase. The remaining challenges and barriers will be focused on understanding fuel cell stack degradation trends, measuring filter performance, and turbine durability. The remaining challenges and barriers will be addressed through durability testing. The project has logically and effectively planned the demonstration phase. Mitigation for glycol leakage through the compressor bearing may still need to be addressed once durability testing is complete.
- The remaining tasks to be completed are well-defined. The tests for compressor durability are critical to demonstrate success.
- The proposed future work is appropriate.
- Testing is planned, along with total cost of ownership (TCO) and evaluation of commercialization potential.
- There is a good approach to future work, where component-level performance and durability will be tested prior to system integration and testing. Lifetime performance prediction and TCO modeling will need accelerated testing or a trend in the degradation rates, which are not available in the industry today for HD fuel cell electric vehicle (FCEV) applications. It is unclear what the vision is to model TCO and lifetime performance without this data/model currently.

Project strengths:

- This excellent project is tackling a large part of the air subsystem with innovative technology. The planned commercialization evaluation is especially impressive.
- The project features a good overall approach that is likely to yield an advanced air delivery system for HD FCEVs. The inclusion of an air filtration system is a significant strength.
- Partnerships have been shown to be the project's greatest strength. The MAHLE team has met or exceeded the DOE goals for fuel cell air management systems in terms of cost, volume, and weight.
- Strengths include the approach, collaboration and coordination, potential impact/relevance, and proposed future work.
- The project approach is well-defined; the work is well-coordinated, with the team working to deliver designs and complete validation that addresses performance and durability.
- The principal investigator's expertise in air systems is a strength. The potential risk for ethylene glycol leaks through the compressor–expander is unclear.

Project weaknesses:

- There are no glaring weaknesses in the execution of this project as presently reviewed.
- The basis for the compressor and expander predicted metrics (efficiency, cost, weight, volume) is missing key components such as efficiency maps. The corrosion of parts exposed to the glycol coolant is not addressed. There is a significant risk that both filters will need regular replacements or regenerations.
- It is not clear whether the team understands the potential failure mechanisms for the compressor. It is hard to develop valid accelerated test protocols without this fundamental understanding.
- The use of the catalytic filter for trapping contaminants to meet fuel cell stack inlet concentration requirements will only increase costs. A path to reduce that cost must be investigated.
- It will be difficult to define how much improved chemical filtration will improve life, but this filtration is obviously needed to justify added cost.
- More discussion is needed around how the predicted cost was evaluated.

Recommendations for additions/deletions to project scope:

- No changes are recommended, as this project is very comprehensive.
- The reviewer has no additions or deletions to the current project scope.

- The team should review its system model with the M2FCT model (i.e., the ANL model) to ensure agreement and potentially identify improvement opportunities.
- Baseline measurements should be performed for ethylene glycol leak rates at beginning-of-life and predicted end-of-life conditions for verification.
- Components of the compressor–expander in contact with the coolant should be protected against corrosion.
- It is recommended that the team gather the input of some outside companies on the planned compressor durability testing. There should be some vetting to better ensure acceptance of results.

Project #FC-352: Leveraging Internal Combustion Engine Air System Technology for Fuel Cell System Cost Reduction

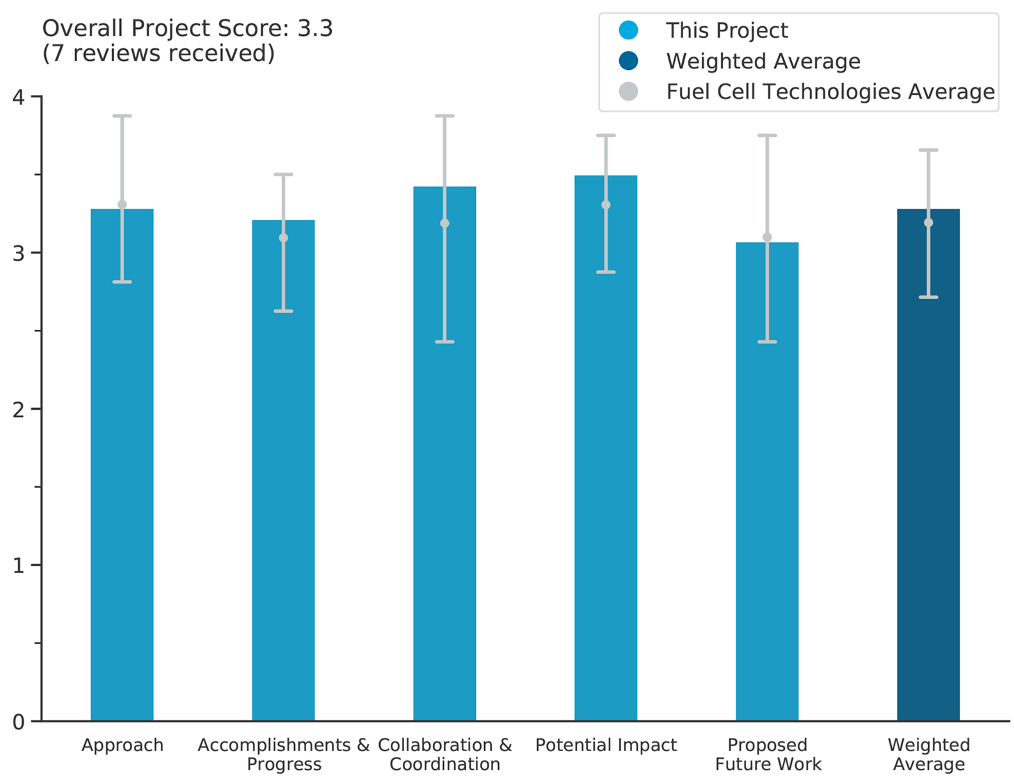
Paul Wang, Caterpillar, Inc.

DOE Contract #	DE-EE0009620
Start and End Dates	8/1/2022–7/31/2025
Partners/Collaborators	BorgWarner Emissions, Ballard Power Systems
Barriers Addressed	• Zero-leak seal validation for oil-lubricated bearings • Turbine wheel optimization and validation for low-temperature/high-humidity conditions

Project Goal and Brief Summary

The project aims to research, develop, and demonstrate a high-efficiency air boosting system for proton exchange membrane fuel cells (PEMFCs) in heavy-duty (HD) applications, including enabling a lower-cost PEMFC system. The project utilizes Pugh analysis, simulation studies, and component design to assess various air system architectures and technologies, leading to an informed down-selection. The balance-of-plant (BOP) components, especially air system components, have a significant impact on the performance and reliability of fuel cell systems. The project addresses this barrier by developing an air system that consumes a lower percentage of fuel cell power output, reduces system cost, and minimizes system downtime. The project's approach includes system simulation, component development, adaption of proven technologies, and extensive bench testing to validate the developed air system.

Project Scoring



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

Question 1: Approach to performing the work

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

- The general concept of "leveraging engine air system technology" is good since these types of air compressors have been developed for vehicle applications and, therefore, inherently have attractive attributes, such as low cost, long life, and vibration tolerance. The team appears to be aware of the major differences, as evidenced by the key barriers/challenges, namely zero leak of lubricants into the air stream and a turbine that is optimized for the fuel cell exhaust stream. rolling element bearings (REBs) are a worthwhile technology to pursue for this application, as indicated on slide 8. The principal investigator (PI) should present the key benefits of REB in a table that compares the different air compressor technologies (REBs, gas foil bearings, etc.) and the key metrics (lifetime, energy efficiency, size/weight, start/stop cycles, noise, cost, etc.). The project schedule has an excessive amount of time for the design work (30 months) and relatively little time for building, testing, and validation work (12 months). Hopefully, the team can stay on schedule during the final and most critical phase of the project. A minor detail is that the approach shown on slide 5 is complex and confusing. This confusion appears to be primarily because the chart is essentially a Gantt-type chart, but the horizontal axis is not time, so everything appears to be occurring in parallel, which is clearly not the case.
- Caterpillar has a good approach to overcoming the critical barriers proposed by DOE for developing a fuel cell air delivery system. The critical barriers have been identified, and Caterpillar has adequately provided a status of performance against the critical barriers. The project is meeting or exceeding the majority of the barriers and will now focus on addressing durability.
- Caterpillar is focused on assessing a compressor–expander using "standard bearings" for fuel cell systems with capacities ranging from 350 to 1,000 kW. Caterpillar is working with BorgWarner Emissions (BorgWarner) to develop and assess a design capable of achieving DOE targets. The greatest technical challenge is demonstrating that oil-lubricated REBs in centrifugal compressors can meet life targets. A design that prevents lubrication oil from leaking into and contaminating the fuel cell system is also critical. Demonstrating that the turbo expander will be durable with high humidity exhaust is also recognized. The project started in 2022 and is divided into five logical development tasks. The project includes system analysis, compressor/motor design, controls, testing, and analysis. Testing will validate performance, and an accelerated durability test will be conducted.
- This project focuses on a centrifugal compressor–expander with REBs with oil lubrication. This off-the-shelf component should lead to reduced cost. It should be noted that the Toyota Mirai uses a similar approach in its fuel cell electric vehicle (FCEV) at a smaller scale. It would be easier to evaluate the approach if all targets, such as maximum flow and pressure ratio, were clearly defined.
- The project approach is sound.
- Leveraging current air system technology for fuel cell systems seems like a good overall approach; however, the project does not identify specific requirements for the fuel cell system that have to be met by the air system, especially since the fuel cell system has strict requirements regarding air purity and durability. Caterpillar has Ballard Power Systems (Ballard) as a partner to provide requirements and specifications, but this information has not been communicated to the public/audience. Since this work is a development project with 80% funding from DOE, the PI should share the critical requirements toward which the project team is working. It is unacceptable that these requirements are not communicated. Development projects within DOE not only help specific organizations with technology/product development but also help the larger community to understand new technologies and adapt them to their applications. In this regard, the PI should share the air purity or contaminant limits acceptable for fuel cell application as defined by Ballard. Task 5 (test and validation) should also address this via monitoring oil or contaminant concentrations in the air system exit to the fuel cells.

Question 2: Accomplishments and progress

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

- Caterpillar has shown outstanding progress toward meeting its project objectives. The project is currently meeting or exceeding the following DOE goals: motor and controller efficiencies, compressor and turbine efficiencies, reliability, noise, packaging, and cost. Bearing selection is the major progress in this reporting period. Preliminary testing has identified three bearing configurations that result in no detectable lubrication leakage. The balance of the work will be in manufacturing and testing the proposed fuel cell air delivery system.
- The project appears to be on schedule, as the schedule has been designed. The results suggest that the project will potentially overcome the critical barriers. Hopefully, during the final year of the project, the team will be able to demonstrate the "projected outcomes" shown on slide 19.
- The presentation does not clearly state which tasks (1–5) or subtasks the project team has completed or to what extent they are completed relative to the timeline. Based on the milestones listed on slide 7, Task 1 (Concepts & Simulation) and Task 2 (System Design & Design Support) appear to be completed. Currently, Task 3 (Compressor Development), which entails compressor and turbine design and matching; motor design; bearing life assessment; and development of an oil seal detection method, has been mostly completed. The overall project appears to have reached objectives and is on track to build, test, and evaluate a compressor in 2025.
- Project progress is good and seems to be on track.
- First, the project PI has made good progress toward the project goals; however, sufficient information has not been shared regarding the compressor maps (slide 12). For a fuel cell system of 350–1,000 kW, the desired air flow rates would span a wide range and, hence, the range of the compressor would be essential to assessing the overall performance and efficiency. Second, on slide 15, the hydrogen flame ionization test does not show leakage via carbon face seals; however, it is not clear whether this test was a beginning-of-life (BOL) test or if an end-of-life (EOL) test was also performed.
- The project team has defined the system and developed a transient model. The models show improved efficiency at high loads, but the concept would be disadvantageous at low power. A new design with a low specific speed wheel is required to meet flow and pressure requirements. Thus, an off-the-shelf device may not be feasible. REBs have been shown to have low friction and are projected to meet life requirements. It is unclear how those projections were completed and if there will be oil leakage into the air at EOL. The carbon face seal meets sealing requirements at BOL.
- The project team completed leak detection tests at a relatively low temperature of 50°C. From that standpoint, the leakage risk at higher temperatures corresponding to the maximum fuel cell load remains undefined. The summary includes projected values for several key metrics; however, several of these estimates (motor and controller efficiency, compressor and turbine efficiency, booster size, weight, and cost) are not supported by data.

Question 3: Collaboration and coordination

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

- Caterpillar is working closely with BorgWarner to deliver a compressor–expander that meets performance and durability targets. Project performance will exceed DOE targets, which will be validated through testing. It is expected that Ballard will help to define the conditions and requirements to develop compressor durability tests.
- Caterpillar has a strong team for addressing fuel cell air delivery systems. Coordination between the team members is appropriate to improve the likelihood of the project's success.
- The project team has a well-established fuel cell system developer, Ballard, and its role is appropriate. Caterpillar appears to be closely aligned with its other sub-contractor, BorgWarner. It would be nice to see the team review its system model with the Million Mile Fuel Cell Truck's (M2FCT's) model (Argonne

National Laboratory [ANL]) to ensure that there is agreement and potentially identify improvement opportunities (e.g., in the models or metrics/targets for air compressors in HD applications).

- Caterpillar has strong collaboration with BorgWarner, who is responsible for component design and testing. Ballard appears to be consulting mostly on requirements and providing general fuel cell expertise.
- Caterpillar appears to have effective collaboration with BorgWarner. It is unclear how much collaboration exists with Ballard.
- The project has good collaboration between partners regarding system requirements; however, it is not acceptable that those requirements are not shared in a public project funded by a DOE technology office.

Question 4: Potential impact

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

- Caterpillar has made significant advancements toward meeting the DOE goals for fuel cell air delivery systems. The projected cost of its fuel cell air delivery system is significantly lower than the DOE target and could be attributed to the team's industrial focus. This project completely advances progress toward the Hydrogen Program goals.
- The project aligns well with the Hydrogen and Fuel Cell Technologies Office's goals and objectives and has the potential to advance progress toward its performance targets, especially regarding the following: (1) improving fuel cell system energy efficiency (reducing parasitic loads), (2) decreasing system capital costs, and (3) improving system reliability (reducing downtime). Additionally, since fuel cell vehicles are currently very niche products, DOE support for air compressors, which are optimized for fuel cell applications, is very beneficial in motivating suppliers to invest in developing advanced products.
- Currently, there is a lack of available air compressors for large fuel cell systems. This compressor concept can be scaled to the airflow capacities required for those systems. The development of durable, leak-free roller oil bearings is critical to this success. If successful, this technology would provide a significant option for fuel cell systems.
- This project can positively and significantly impact the fuel cell system BOP cost.
- Effective air machinery is needed to decarbonize ultra-HD applications.
- This project has direct impact for large fuel cell engines (>200 kW).

Question 5: Proposed future work

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

- Caterpillar's proposed future work clearly builds on its past progress. Its focus will be on building and benchmarking the fuel cell air delivery system it has developed. This work is logically planned and will provide the data sought by DOE for future programs in high-power (>100 kW) fuel cell systems.
- The planned work for the remainder of 2024 and 2025 is listed. Compressor design and fuel cell system simulation will be completed in 2024, and component testing and assessment will be completed in 2025. It would be good to know what the actual performance and durability testing will entail and on what vehicle system requirements they are based.
- Future work includes finishing design, building equipment, and assembling and testing units for performance and leakage. The project team also plans to run accelerated stress tests, which are undefined at this point. The team should specify whether the rolling oil bearing system requires additional components, such as an oil pump, a filter, and oil plumbing. If so, those items should be included in the air machine system cost, weight, and volume projections.
- The proposed future work should include verification and validation tests to confirm the purity of air entering the fuel cell stack.
- The recuperator benefits were shown to be marginal at low and medium current densities. Therefore, this workstream should be eliminated, especially because project FC-350 also found this component to be of marginal benefit.

- The proposed future work is appropriate, but the Fiscal Year 2025 plan is aggressive. If any unexpected issues arise during the hardware build and test phase, it is unlikely that the team will be able to stay on schedule.
- The next phase involves testing prototype hardware and collecting performance data.

Project strengths:

- Project strengths include the approach, collaboration and coordination, potential, and relevance.
- Caterpillar's partnerships with BorgWarner and Ballard are the project's greatest strengths. Another project strength is keeping the fuel cell air delivery system as simple as possible.
- Caterpillar and BorgWarner are working closely together on this project and have the skills and capabilities to design, build, and test a concept compressor.
- The project has a good overall approach that is likely to yield an advanced air compressor for HD FCEVs.
- It is a good sign that this project has more discussion on cost than other projects in this area do.
- The equipment supplier (BorgWarner) and the system integrator (Caterpillar) have a strong collaboration. One strength is the approach to use off-the-shelf equipment to reduce cost, although results to date suggest that some modification of existing equipment will be required.
- The project PI is an expert in system BOP for HD truck and off-road applications. Ballard is a leading fuel cell stack and system developer; however, the purity requirements for the air system from Ballard were not made public.

Project weaknesses:

- The project has no glaring weaknesses in its execution as presently reviewed.
- The planned validation testing, both for performance and durability, is not well-defined. It seems that there is both component and system testing. The input of Ballard will be critical in developing the testing procedures. In next year's Annual Merit Review, some details on planned durability testing should be presented since this task is the main concern of the project.
- The concept would provide a benefit only in applications that operate primarily at high loads, as most Caterpillar applications are, but would have limited use for other applications. Selected REBs require proper lubrication and maintenance to ensure optimal performance and longevity without leaking into the air over their lifetimes.
- The value of leak detection tests is questionable. The estimates for key metrics are not supported by data. The recuperator work is not expected to provide significant benefits.
- The project requirements regarding purity, contaminant, tolerance, etc. need to be shared with reviewers and in the slides for the rest of the technology community.
- The project has an overly optimistic hardware build and test schedule.
- The project does not plan to test the technology in conjunction with an actual fuel cell system.

Recommendations for additions/deletions to project scope:

- The team uses models to predict life >25,000 hours for the critical elements, including the electric machine, aerodynamic components, and bearing system. It would be more valuable if the team could provide some specific examples of how the life predictions are made (e.g., what the modeling inputs/outputs are for bearing life prediction). It would be helpful to see liquid water and freeze tolerance testing.
- The team's system model should be reviewed against M2FCT's (ANL's) model to ensure that there is agreement and potentially to identify improvement opportunities.
- The recuperator should be removed from testing. It adds cost and takes up valuable packaging space. The analysis should be enough to assess its value.
- The recuperator work should be discontinued.
- The reviewer has no additions or deletions to the current project scope.

Project #FC-353: Fuel Cell Cost and Performance Analysis

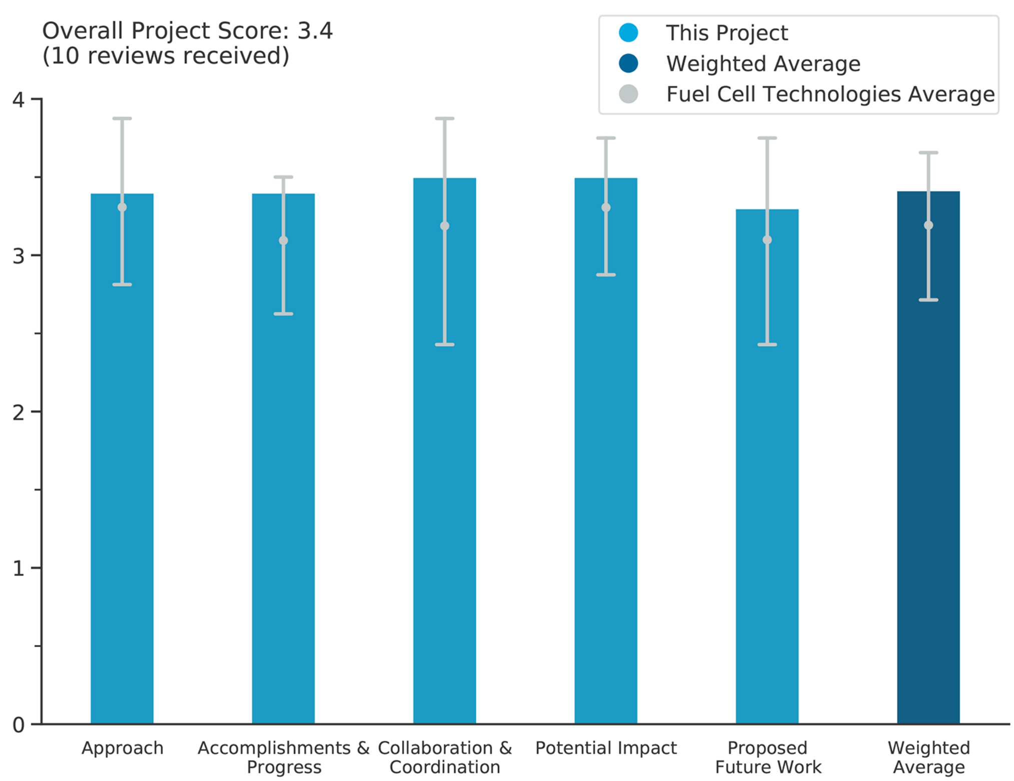
Brian James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0009628
Start and End Dates	10/1/2021–09/30/2025
Partners/Collaborators	National Renewable Energy Laboratory, Argonne National Laboratory
Barriers Addressed	• Need for realistic, process-based system costs, realistic values for current and future cost targets • Demonstration of impact of technical targets and barriers on system cost: Balance-of-plant components, materials of construction, system size and capacity (weight and volume)

Project Goal and Brief Summary

This project's primary goal is to develop fuel-cell-centric techno-economic analysis (TEA) models based on Design for Manufacture and Assembly (DFMA), an engineering methodology geared toward reducing time-to-market and production costs by simplifying manufacture and assembly in the early design phases of the product life cycle. This methodology will be employed in an effort to understand the state-of-the-art fuel cell technology for light-duty (LD), medium-duty (MD), heavy-duty (HD), and off-road mining (ORM) vehicles; project the cost of future fuel cell systems; and measure and track the cost impact of technological improvements in these systems. The project will highlight cost drivers to facilitate Hydrogen and Fuel Cell Technologies Office programmatic decisions. The information gained from these initiatives will be disseminated to the fuel cell industry through comprehensive reports.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach proposed is well-aligned with the scope of the project.
- The project generally has a good and effective approach to developing cost models that have significant strategic value for the DOE Hydrogen Program and the community. The project appears to use stakeholder input well, and results appear to be well-documented and communicated clearly. The side studies and investigations of niche applications in the project, such as ORM trucks, seem good, but it would be good to see clearer articulation of the strategy for selecting these topics.
- There is good comprehensive analysis leveraging the Argonne National Laboratory (ANL) system and vehicle analysis, covering a range of important applications. Each module includes a membrane humidifier and a hydrogen recirculation blower. Reputable fuel cell system manufacturers do not use both the humidifier and the blower; they commonly use only one of them. It is unclear why they are included—perhaps to save cost.
- Overall, the approach is good. The assumption of fuel cell system operation is simply carried over from that of an on-road HD fuel cell system, which is significantly focused on efficiency to show the total cost of ownership (TCO) benefit against advanced diesel engine HD trucks. Therefore, fuel cell system cost of the on-road HD long-haul truck is significantly higher because of the larger active area needed to meet the 0.7 V/cell operating point. It is necessary to evaluate whether this significant high efficiency is required for ORM haul trucks because baseline ORM haul trucks' usage profile is different from that of on-road HD long-haul trucks.
- There is no safety plan; diversity, equity, inclusion, and accessibility plan; or community benefits plan as part of this project. SA continues to work on the TEA of fuel cell systems based on a combination of factors, including fuel cell performance, materials, and manufacturing costs. The analysis is known to be reputable, and the recent DOE funding opportunity announcement 2922 is based largely on the premise that the cost of fuel cells will come down if gains can be made with volume/automated manufacturing. The only issue with the approach is that it is presently difficult to validate because no one is manufacturing at scale. SA updated its models based on 2020 costs, which is important. This year, SA also added a new study on ORM trucks. SA considered alternate materials to determine the impact on the long-term costs of fuel cells.
- The project goal is to develop a realistic economic analysis for manufacturing and assembling fuel cell hybrid systems with cooling for LD, MD, HD, and ORM vehicles. The project is divided into three main tasks: Manufacturing Process and Technology Review, System Definition and Bill of Materials, and TEA. The first task has been ongoing since the start of the project, and the later tasks started in 2024. The project analysis method requires defining manufacturing cost (material, method, rate, and amortization) for baseline system designs. Feedback from industry is used to develop cost models. It would be helpful if the team could provide further detail on what type of input industry has provided (for example, system cost per kilowatt or industry-provided guidance on manufacturing cost[s]). Also, it would be good to know what the manufacturing method includes (e.g., stack parts or stack assembly).
- It appears that one major output is how costs fall as a result of volume of manufacture. However, material costs from suppliers can dominate the costs, and it is difficult to understand if accurate material costs from material vendors are being supplied. For example, perfluorosulfonic acid (PFSA) at \$650/kg for 50,000 HD vehicles per year represents 50,000 kg and \$32/m^2 at 0.05 kg/m^2, 20 m^2 per HD vehicle, 275 kW at 14 kW/m^2. The key PFSA players may be giving those estimates for volume production costs, but it is unclear how real/committed suppliers will be able to supply at that price, given that 50,000 kg annual production is not that much more than current PFSA production. It would be good to see vendor material costs as a parameter on a graph to illustrate how material costs can dominate. The same question can be applied to catalyst suppliers to explain how close the analysis is to market price on precious metals. Manufacturing costs on catalysts may be trivial compared to material costs, but it is not clear how the model is addressing manufacturing cost. Furthermore, if Pt market demand increases, it could put upward pressure on Pt price and not downward pressure on the price as the model may be figuring.
- The work is well-structured and follows a sound engineering practice. There is opportunity to improve by being clear regarding what factors are within the scope and outside of the scope of cost (where the latter

will typically be factored into price). Specifically, when it comes to cost versus price, while the presentation does indicate that the focus is on cost and markups or margins are excluded, the additional technical material (slide 29) includes “markup factor.” Further, it is unclear if Strategic Analysis, Inc. (SA) considered any additional system safety devices aligned with International Organization for Standardization (ISO) 26262d. The assumptions on testing and certification costs are questionable, as these can be higher, especially for low-volume systems. Providing a clear delineation between the elements impacting cost and those influencing price will facilitate establishing clear reference points for those utilizing these results. It is also crucial to align this project with the DOE vision when articulating cost targets. In the process of validating the approach, it is equally crucial to highlight known real-world costs and prices, while distinguishing between the two. Given the sensitivity of some of these figures, anonymizing the data may be necessary, but having reference points that fall comfortably within the margin of error of the model would aid in anchoring future predictions. This approach should also introduce the concept of uncertainty assessment, which is not always evident in figures like those presented on slide 4. Since costing and pricing entail inherent uncertainties, establishing bounds of uncertainty and propagating these uncertainties is important. While the sensitivity analysis displayed in slide 37 is a step forward, it primarily identifies critical factors in the model. The reviewer’s concern lies in assessing the model’s accuracy with respect to real-world data, however sparse it may be.

- This bottom-up analysis is grounded in physical design and actual manufacturing steps. However, performance and durability stem from modeling. Conducting an anonymous survey of performance and durability among stack manufacturers would seemingly enhance the approach.
- The approach for the fuel cell power plant is sound. However, a total system cost, including hydrogen storage, tires, and a cooling system, should be considered.

Question 2: Accomplishments and progress

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

- The project had good accomplishments and progress for the year, including an updated HD vehicle system design and updated costs, as well as an ORM study considering how HD fuel cells can be adapted for niche applications. The presentation showed good analysis on the potential cost impacts of the advanced catalyst from the Million Mile Fuel Cell Truck (M2FCT), which helps show the impact of the DOE Hydrogen Program. The presenter showed a good start on the battery/fuel cell hybridization study, with results that can inform TCO analysis.
- SA presented progress on fuel cells using PtCo/C zeolitic imidazolate framework (ZIF)-8 cathode catalysts, updated values for HD vehicles using 2020 costs, balance-of-plant (BOP) components, battery hybridization, and ORM trucks. All of these studies are important variables for fuel cell vendors to consider in cost reduction/durability. Although the findings are only projections (and not decisive), the studies can provide important guidance.
- There has been impressive progress in incorporating ORM trucks alongside MD vehicles and HD vehicles. It is encouraging to see price adjustments being integrated based on industry feedback. The assumptions of scenarios outlined in slide 12 may require reconsideration for open-pit mine haul trucks. While the precise impact of extreme temperatures in mines is unclear, it is worth noting that, while typical air temperatures in those regions may reach around 45°C, the actual operating ambient temperatures could be significantly higher, possibly exceeding 55–60°C, because of solar irradiance, local emissivity, and lack of air circulation. These considerations underscore the importance of factoring in the operating profiles of power draw for accessories and other systems on the vehicle when considering the aging of the system, especially in the context of vehicle modeling support activities conducted by the national labs. Adjusting these assumptions to reflect the real-world harsh operating conditions in mines could lead to more accurate and relevant estimates on fuel cell use and aging, which may influence the cost projections. In addition, high ambient temperature will inhibit heat transfer, potentially requiring much larger radiators and even (under extreme conditions) necessitating chillers. It may be useful to check the costs to identify if there is point where the latter is more cost-effective than the former.
- The project has completed definition of baseline fuel cell systems for LD vehicles, HD vehicles, and ORM trucks. The team has also completed tradeoff analysis of battery capacity and fuel cell net power. Cost models have been developed for each system as a function of annual production volumes. Current cost

estimates are above DOE targets. Good progress has been made setting up models, and cost numbers are reasonable. Relative to ORM trucks, system configuration of 1.3 MW may be low for power requirements but will be dependent on usage profile and hybridization. For large ORM trucks, over 2 MW of total power could be needed.

- There are consistently good outcomes with the given assumptions. Required air filtration depends on the specific usage environment, particulate filtration, and chemical filtration. Particularly, the need for chemical filtration is due to airborne contamination, which cannot be mitigated with system control.
- The SA team has clearly done a thorough and refined analysis, with a strong focus on the trade-offs in battery hybridization. Over the years, SA analysis has become so fine-tuned that it can evaluate even seemingly minor changes to the stack and system. Given the precision of this analysis, it is crucial to incorporate recent price inflation, as it will likely have a more significant impact.
- Considering the importance of operational expenditures in HD applications, it would be good to see more TCO analysis. Comparison of capital and operational expenditures with those of other technologies (diesel, alternative clean tech, etc.) would be interesting. Some HD applications use liquid hydrogen for storage. It is unclear how hydrogen pressure was handled for the fuel cell module. Considering the large share of platinum group metal cost, it would be nice to account for recycling of critical materials. It is unclear why dollar cost was updated to 2020 and not 2023 when inflation is much higher.
- The project has a detailed model of the costs as a function of different inputs. However, there are many inter-related parameters. For example, if material costs are low, then production automation can dominate the costs. However, if material costs are high, then process automation is not that significant. Most important is efficient material utilization.
- Accomplishments correspond to the foreseen work plan. As mentioned in many studies, inflation has had significant negative impact on the cost of electrolyzers. It is unclear how this is not the case for the cost of fuel cells in the study. It also remains unclear what the impact would be of using non-PFSA membranes.
- Updating the cost analysis to mining trucks was very helpful.

Question 3: Collaboration and coordination

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

- The project clearly has very good coordination with the project subcontractors to leverage their technical expertise in supporting the development of system, manufacturing, and cost models. A wide variety of other stakeholders have also been involved to provide supporting information to the project.
- The National Renewable Energy Laboratory (NREL) and ANL collaborate well. NREL contributes to assessing manufacturing cost, and ANL contributes to assessing system configuration and performance. Industry collaborators are the Fuel Cell Joint Technical Team, MAHLE, CellCentric, Clenersys, and Mann+Hummel; these organizations have recently provided system input for operation and system design.
- SA collaborates broadly with industry to sharpen their cost analyses and has also incorporated feedback on practical BOP components.
- SA and ANL collaborate well. The team also appears to receive good feedback from industry in relevant areas.
- Collaboration between the national labs seems excellent.
- There has been good engagement with the analysis teams at NREL and ANL, and there is potential to leverage broader component expertise from other national labs as well. Consortium-level engagement appears to be on track, which is encouraging. However, it is recommended that engagement with original equipment manufacturers (OEMs) be strengthened across all three applications, not limiting interactions solely to component providers or other research institutions. These discussions are likely to yield more valuable insights in a one-on-one setting rather than in an open forum, as industry stakeholders often prefer detailed exchanges in such settings. Specifically, direct discussions with OEMs developing ORM and mining companies could provide valuable insights into both known and unknown factors in the analysis. Stress-testing the analysis directly with these individual enterprises could offer more informative feedback compared to broad consortium-level discussions, which may dilute the input.

- This project benefits from a highly qualified group of collaborators. For membrane electrode assembly (MEA) production, it is advisable for SA to engage with a commercial roll-to-roll enterprise to validate the feasibility of NREL quality control methodologies, ink formulations, line speed, and other relevant factors.
- The project partners are well-recognized experts in the field. Continuous close discussions with industrial users and suppliers are encouraged.
- An appropriate team is forming.
- It would be good to see better collaboration with material suppliers to get a better validation of the material prices at different volumes. There should be some kind of skin in the game from these suppliers to give a better assurance that their model inputs are accurate.

Question 4: Potential impact

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

- This work represents a pivotal aspect in shaping the value propositions for fuel cell electric vehicles (FCEVs), making the work inherently significant. Additionally, it has the potential to offer crucial insights into areas where further research may be necessary. Expanding the sensitivity analysis could unlock deeper exploration of potential pathways, identifying the most efficient routes toward achieving DOE cost targets. While this may extend beyond the current scope of the project, it could significantly influence the direction of future research and development (R&D) efforts needed to progress toward meeting the DOE cost targets.
- This project helps assess tradeoff in system design and manufacturing toward achieving cost targets for various vehicle applications, which have been more recently extended to ORM trucks. Challenges in reaching DOE cost targets have been identified. The project will help drive focus on work required to close/minimize the gaps.
- The effort should result in feedback to DOE as to where the major development efforts are needed to reach the cost targets. If the model suggests that everything is on track and that all that is needed to reach targets is to increase the volume to 50,000 vehicles per year, and industry does not react, that means that something else is preventing commercialization.
- The project has a very clear positive potential impact and relevance for the DOE Hydrogen Program and the community, helping to benchmark the technology status against DOE targets and providing strategic direction.
- This project presents the most comprehensive publicly available fuel cell cost modeling effort. Numerous organizations refer to this work and its associated assumptions when making decisions regarding hydrogen-related R&D. While this reviewer acknowledges the DOE focus on ORM trucks, it is suggested that the fuel cell development community might benefit more from additional tradeoff studies related to Class 8 trucks.
- The outcomes of this project and the corresponding TCOs of the different vehicles will impact the investment decisions of new adopters for hydrogen mobility.
- Historically, this effort has been productive and helps clarify issues and gives development direction.
- Cost is extremely relevant to the adoption of this technology.
- Cost analysis is valuable.
- The impact of the SA analysis is very important because it sets the metrics for DOE, and typically the world, for fuel cell targets. However, SA is only making projections, and none of the projections have been validated, as people are not manufacturing at scale yet. Also, the materials cost numbers are still outdated (not using 2024 values). The choice of studying the PtCo-ZIF material was also questionable, as the material is available only in gram quantities and has not been proven out.

Question 5: Proposed future work

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

- The future work outlined aligns well with the overarching goals of the project. Expanding on the baseline DFMA models seems appropriate and can enhance the project’s effectiveness. Incorporating real-world data to contextualize the results would be beneficial. Additionally, introducing uncertainty assessments of the results and exploring options such as variations in lifespan for costing, which can contribute to other TCO analyses, would add depth to the project analysis. It is also important to clarify what falls within the scope and what lies outside of it. Considering stack failure modes beyond the membrane–catalyst level, such as bipolar plates including metal with coatings versus graphite, can further enrich the analysis and provide a more comprehensive understanding of the system's dynamics.

- The proposed future activities are reasonable overall but may be too narrow in scope. It is unclear whether all the important topics for fuel cell cost analysis are being considered adequately. It is good that the ORM truck application has been investigated, but the need for continued focus on this application going forward is questionable. The project seems to have found that the ORM truck application could use HD stacks with a different system design. If this will be a continued focus, the project should clearly articulate what the unique value is from learning more on this topic. It may be of value to follow a "breadth-first" approach and identify more niche applications that can be combined to support scale. It may be valuable for the project to revisit recycling to support DOE's relevant recycling R&D efforts.
- The sensitivity analysis will be very interesting. It is recommended that the team include as much information about raw material and process costs as possible. Additionally, the team should consider the possibility that no fuel cell stack can last 25,000 hours and include stack replacement in the analysis.
- The proposed future work plans include the impact of several novel processes and BOP components. The team's final report is due for HD vehicles in September 2024. It seems that SA should try to reconcile the DOE goals of $80/kW for 100,000 systems/year by 2030 with its model. SA notes that performance increases are needed to reach these cost goals.
- The remaining project will refine cost models and system architecture. In addition, work will be conducted to assess reduction in stack cost through screen printing, coatings, and the electrode manufacturing process.
- The proposed future work is properly defined.
- The material cost quotes that suppliers are giving seem much too low, and therefore the model predicts manufacturing costs to be more heavily dominated by reducing labor by using high-volume equipment such as rotary screen printing and dry electrode and wet ink processing studies. However, if material costs are more representative of where we are today, then the study should emphasize how to use materials more efficiently, rather than emphasizing high-volume manufacturing to reduce labor.
- The plan is clear. However, it also illustrates the technical difficulties of achieving the DOE targets of $60/kW and $80/kW. There is no clear path.
- Future work appears correct. The evaluation of using non-PFSA membranes should be included.
- It would be worthwhile to see more work done on other relevant sub-systems required for the FCEVs.

Project strengths:

- The project presents a robust and detailed approach to cost analysis and prediction. Extensive effort has been dedicated to projecting costs and anticipating manufacturing technology advancements and potential. The project excels in dissecting the components of the fuel cell system, meticulously engaging stakeholders to comprehend the impact of scaling up production practices (this includes the stack/MEA and BOP components). By targeting critical applications in hard-to-electrify markets, such as MD/HD truck and mining applications, the project covers a diverse range of power node points. Additionally, its alignment with the objectives of the M2FCT consortium and its requirements enhances the project's relevance and potential impact.
- This cost analysis work has evolved significantly over the years, benefiting from extensive input from numerous stakeholders. The work has been thoroughly scrutinized and is widely cited.
- The analysis work is rigorous and well-communicated. SA made good progress for the year on high-impact areas for the Fuel Cell Technologies subprogram and good coordination with project partners and relevant stakeholders.
- This project is setting a baseline cost for fuel cell systems for various vehicle applications and defining areas of focus for cost reduction. Also, relevant industry collaborators have provided guidance and information for the analysis. System design selection is well-thought-out.

- Cost projections for the fuel cell stack and engine are excellent.
- The project includes a very detailed analysis model.
- The project includes a consistent zero-based cost analysis method.
- The history of TEA is used by the fuel cell industry for guidance.
- This project relies on many years of development and a well-recognized team of experts.
- The team has great collaboration and a strong relationship with stakeholders.

Project weaknesses:

- The project lacks clarity in distinguishing what falls within the scope versus what is out of scope. It is crucial to establish a clear boundary diagram to communicate and ensure the understanding of assumptions. Moreover, the work needs to be benchmarked against real-world costs and prices to depict the current state of the industry accurately. This benchmarking may require leveraging use cases with reasonable volume, such as forklifts or other applications. While not a direct replacement, Tier I's and OEMs are utilizing key learnings from these platforms to migrate toward various applications such as MD/HD trucks, making them valuable benchmarks. By incorporating these benchmarks, the project can better contextualize its findings and provide insights into industry standards and practices.
- No specific weakness is observed, except the evaluation of the numbers with real market prices.
- No significant weakness is observed.
- Obtaining accurate supplier cost estimates can be challenging. The analysis does not account for all durability challenges of components and the true cost of maintenance. While exploring niche applications is intriguing, prioritizing refinement and assessing the life cycle cost for Class 8 trucks might offer greater benefits to the broader industry.
- Many of the assumptions and details of the analysis are hidden in the written report, which will not be available until a much later date. One can only take the results at face value. No one can judge the correctness of the analysis.
- Assessments of manufacturing cost and component cost are difficult to obtain, and information shared by industry will be limited. Therefore, cost models are of limited accuracy.
- The practical cost of an FCEV includes many other factors (e.g., hydrogen storage, filling, tires, and cooling systems).
- None of the models are validated. The SA HD vehicle model deviates from the DOE goals.
- The future work scope may be too narrow and needs a clearer strategy for selection of focus areas.
- More realistic material model inputs should be included.

Recommendations for additions/deletions to project scope:

- While the primary focus of this project does not lie on TCO, it is imperative to enhance TCO analysis with diverse cost options. The project centers predominantly on specific assumptions concerning fuel cell power, lifespan, and composition, as indicated in slide 8. However, the potential ramifications of alternative options would be worth including. For instance, TCO analysis could delve into assessing the varied impacts of fuel cells with differing lifespan expectations. Currently, the researchers are introducing some variability of life in BOP components but are not regarding this variability as a controlling factor for other elements within the system, including the stack. Incorporating this variability or options assessment into the cost analysis would prove advantageous. This approach could shed light on the broader implications and potential cost efficiencies of alternative configurations or lifespans within the fuel cell system.
- This project should consider how it could provide information to support the Regional Clean Hydrogen Hubs and deployment activities, or hydrogen technology "liftoff" broadly. This information could include investigating cost levers that are important at a lower scale or identifying more niche applications that could improve fuel cell manufacturing scale with DOE support. It is recommended that the project revisit recycling in some way. SA has investigated recycling in the past, and it may not make sense to introduce the topic into the standard cost analysis. Nonetheless, it seems important to consider possible implications for cost and materials circularity. It could be a good opportunity to leverage the new recycling consortium.

It was good to investigate the ORM truck application, but the need for continued focus on this application going forward is questionable. The project should clarify if there is a strategic reason to focus on that topic further or possibly consider a broader range of similar niche applications.

- It is recommended that the team increase emphasis on warranty cost analysis, utilizing current life estimates of stack and system components for Class 8 trucks. This analysis should include scenario planning based on reported durability, rather than targets. Additionally, the team should consider investigating or validating TEAs from incoming manufacturing projects and existing projects that introduce novel materials and processes. For instance, the team could determine the price at which high oxygen permeability ionomer materials would need to be in order to offer a cost benefit.
- It is recommended that the project redefine the fuel cell system architecture (including fuel cell sizing) and operating conditions for ORM haul trucks based on their operating profile, which is different from that of on-road HD long-haul trucks. Particularly, a system-efficiency-focused operating point (0.7 V/cell) is simply carried over to mining haul trucks. It is highly impactful on the fuel cell system cost, and it should be reevaluated for mining haul trucks.
- It would be very helpful if SA could validate at least a piece of the project models somehow. SA should also update the cost values to 2024, as prices have gone up significantly. The new restrictions on fluorinated compounds are likely to drive prices higher. There needs to be reconciliation of the DOE and SA HD vehicle cost goals. It would be good to know if SA can be more transparent about how new work problems are accepted. Perhaps DOE could open a “question box” and then sort through what makes sense for SA to study in the next year’s work.
- It would be great to see a side-by-side cost comparison of a diesel truck vs. a fuel cell truck that accounts for all the sub-systems: fuel storage, tire costs, radiator costs, and servicing and replacement costs.
- Power electronics (boost converter) are both critical and expensive parts of the fuel cell system. They should be included in the fuel cell system design boundary.
- The cost of power electronics (such as a boost converter) is unclear. This cost should be incorporated into the cost assessment.
- An analysis with varying material costs could be included.
- It would be interesting to consider the impact of the recycling of materials on the overall costs.

Project #FC-354: L'Innovator Program

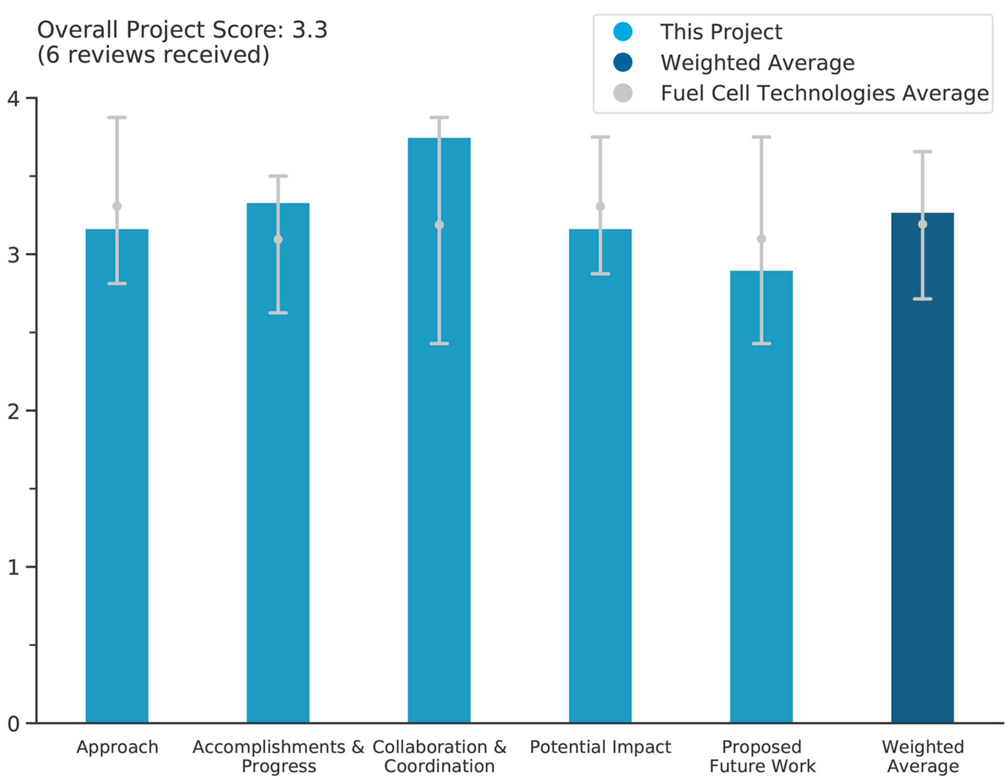
Emory De Castro, Advent Technologies

DOE Contract #	LA20C10799
Start and End Dates	4/1/2021–3/31/24
Partners/Collaborators	Los Alamos National Laboratory, Brookhaven National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	Heavy-duty Class 8 tractor–trailer • Peak power density at 2 atm 840 mW/cm^2 => 1,000 mW/cm^2 • Stack life 25,000–30,000 hours • Heat rejection <1.45 kW/°C

Project Goal and Brief Summary

The L'Innovator ("Lab Innovator") was developed to enable a robust domestic fuel cell industry by assembling bundles of unique, state-of-the-art national lab intellectual property and facilitating their development by a commercialization partner. This pilot project for L'Innovator, led by Advent Technologies (Advent), focuses on demonstrating a minimum viable product of high-temperature, proton exchange membrane electrode assemblies (MEAs), using Los Alamos National Laboratory's (LANL's) ion-pair coordinated membrane and MEA technology and Brookhaven National Laboratory's (BNL's) core catalyst technology. With the technology's viability confirmed, the project team will scale up these next-generation MEAs and demonstrate their benefits in stacks or systems. Anticipated outcomes include lower costs, better durability, higher efficiency, and higher power density.

Project Scoring



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

Question 1: Approach to performing the work

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

- Advent is transforming the field of high-temperature proton exchange membranes (HT-PEMs) for fuel cells used in long-haul trucking, power back-up, marine shipping, aviation, and squad-level military missions. Advent has successfully transferred intellectual property generated by LANL and BNL. The team continues to improve the technology via judicious design of the cell (e.g., gaskets and gas diffusion layers [GDLs]). Although the polarization curves are not competitive with state-of-the-art low-temperature PEM fuel cells (LT-PEMFCs), the gains made in heat rejection, heat management, and water management should translate to a smaller fuel cell plant in the vehicle. There is still ample opportunity to close the gap between LT-PEMFC and HT-PEMFC performance. Overall, the design of work, its execution, and accomplishments are excellent. Advent provided (and discussed) a slide about the company's safety culture and examples, which was appreciated. The team was not required to have a diversity, equity, inclusion and accessibility plan or community benefits plan as part of its project. However, Advent recruited students from Northeastern University as co-ops and is looking to work with community colleges to recruit additional workforce.
- The approach is well-defined and sound. It would be excellent if the performance and durability milestones were clearer. The goal seems to be to be better than polybenzimidazole (PBI)-based fuel cells, but it is not clear that that is really good enough since these devices have not had a significant impact to date.
- The project has demonstrated a good technical approach for improving the ion-pair HT-PEM technology and demonstrating scalability. The project lacks presentation of relevant applications and demonstration with appropriate duty cycles. This work seems to be happening in collaborative assessments with industrial partners but should be presented publicly to clarify the potential impact of the technology.
- Advent's approach to overcoming DOE critical barriers is to focus on heat rejection and durability. Advent's intermediate-temperature fuel cells directly address a fuel cell's thermal subsystem. High operating temperatures could result in a simpler thermal system, thus reducing cost and perhaps improving fuel cell durability. The project seems to be missing a task on durability. The pathway to assessing durability targets of 25 khr may not have been appropriately presented. The team does show decreases in cell degradation rates over a 1,500-hour test.
- The objectives and approach of the project are very relevant to the Hydrogen and Fuel Cell Technologies Office (HFTO) goals. However, it is not clear if new ion-pair technologies are being investigated to improve overall performance to meet high-power density targets. It is not clear if this technology is viable for heavy-duty (HD) truck mobility applications. The presentation focused more on land, air, and sea applications. Fuel cell MEA ability to cycle for HD truck applications is not clear. Heat rejection ($Q/\Delta T$) of 1.03 kW/°C was referenced on slide 4. It is unclear whether this calculation includes inefficiencies in the fuel cell performance, with heat adding to the coolant loop, especially during start-up and idle operation.
- Project goals indicate that the focus is given to PEM membranes. It is expected that the stack design would need modifications to operate at such high temperatures. It is unclear which design was used or what was done to complete this task. It is assumed that a previous Advent design was used to incorporate newly developed MEAs. The approach does not contain elements that are necessary to improve other key metrics such as performance, degradation, and cost, which is especially important because these metrics are not met (the total Pt loading and degradation rate are too high, and the performance is too low). In other words, too much emphasis is given to heat rejection at the expense of other metrics.

Question 2: Accomplishments and progress

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

- Advent has made excellent progress on the scale-up of the polymer for the membrane (~1 kg batches), binder (~50 g, with plans to go to larger batches), and membrane manufacturing (20 m^2/week). Advent has also developed a new, fluorine-free electrode binder. This is important, given the concerns around future perfluorosulfonic acid (PFAS) regulations and companies exiting the PFAS business because of liability concerns. The team has also developed a catalyzed-coated membrane (CCM). A peak power density with hydrogen–air has been achieved at 0.9 W/cm^2 if back pressure is applied. MEAs have been made at

600 cm^2. Overall, Advent has done an excellent job transferring the technology and scaling up materials for the manufacture of fuel cell stacks. The team continues to enhance HT-PEMFC technology, exceeding HT-PEMFC performance and durability benchmarks.

- The project has made good demonstrations of performance improvements over the project from alloy catalysts and cell integration with a CCM approach, as well as from catalyst development work. There is good preliminary system/stack demonstration and some preliminary durability results.
- Advent has shown improvement in cell current–voltage characteristics, as well as decreases in cell degradation rates using an optimized membrane over PBI. Cell degradation and cell durability may not be completely related. Progress toward some of the DOE goals is shown. Durability, however, may be the most critical barrier to address in meeting the DOE goals.
- A 120-cell stack of 600 cm^2 MEAs operating at 180°C and 1 A/cm^2 has achieved 0.5 V performance at ambient pressure. This achievement is significant for HT-PEMFCs. However, the load cycling ability of the MEA is not demonstrated for HD truck mobility applications. Start-up time and other operating conditions that are unique to the HT-PEM technology need to be highlighted because some of them will not meet HD truck mobility applications and might be a no-go. It is unclear whether the mass activity, electrochemical surface area, and specific activity data table on slide 8 is based on the rotating disk electrode (RDE) or MEA. Only MEA data should be considered for assessing technology readiness for mobility applications.
- The performance keeps improving, which can enable real improvements in the company's niche products. However, the decay rate still appears to be very high, and there does not seem to be any plan to address it.
- The best performance achieved at beginning of life is approximately 0.5 V at 1.07 A/cm^2, which is 200 mV lower than the DOE HD target (0.7 V at 1.07 A/cm^2 after end of life). Furthermore, this performance is achieved with relatively high stoichiometries (1.5 and 2.5 for hydrogen and air). Kinetics of both PtCoNiCr and baseline Pt catalysts obtained with an RDE are exactly the same in the kinetic regime. The claimed advantage of the alloy is unclear. RDE and cell data are different, with a significant difference of approximately 100 mV between PtCoNiCr and baseline Pt catalysts in the kinetic regime with a fuel cell. It is unclear how (or if) this discrepancy is explained. The different operating temperature may be a reason. Differences in catalyst loading may be another reason.

Question 3: Collaboration and coordination

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

- Advent has done an excellent job transferring technology from LANL (ion-pair HT-PEM and new electrode binders) and BNL (active oxygen reduction reaction [ORR] catalysts that are better at tolerating phosphate). The presentation had one slide on LANL data (fuel cell polarization) with the phosphate-tolerant electrocatalyst. The data showed good performance at low loadings of platinum group metals. Advent has also collaborated with the National Renewable Energy Laboratory on roll-coating electrodes and membranes.
- Advent is doing all the right things to advance this HT-PEM technology. Technology assessment for land, sea, and air applications with major original equipment manufacturers (OEMs) is a significant accomplishment. It would be good to see the power specifications of the fuel cell for the various applications.
- The engagement of many potential end users is truly impressive, considering the relatively low performance and maturity of this technology. This engagement appears to indicate that there is a strong hunger for higher-temperature fuel cells.
- Coordination between project partners seems good, and the project seems to be active in collaborative assessments with industrial partners to find potential applications.
- Programs with 12 industry participants were either established or are currently being negotiated. All team organizations appear to be engaged.
- Advent is collaborating with three national labs. It might be beneficial to partner with vehicle manufacturers who might be able to provide guidance to accelerate the project's progress. Although

collaboration with LANL is shown, it could be suggested that Advent also work with the M2FCT consortium to perhaps improve the project's impact on the fuel cell industry.

Question 4: Potential impact

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

- This project is one of the few projects (if not the only project) that HFTO is supporting on non-PEMFC technologies. The project uses a higher-risk approach that justifies continued DOE investment, and the fact that Advent is providing most of the funding is excellent.
- Advent has demonstrated technological breakthroughs in HT-PEMFCs. Advent has developed in-house, scalable manufacturing methods for the ionomers and has identified two external suppliers (not BNL) for sourcing the electrocatalyst. The team has commenced work on developing HT-PEMFCs with the new materials for aviation with Airbus.
- Advent is leading some innovative work that can significantly contribute to Hydrogen Program goals. If they are successful, Advent might address the adoption of fuel cells into mobility applications. A focus on durability versus performance might be key to meeting the Hydrogen Program objectives.
- The project has made significant progress toward the overall objectives. For long-term feasibility and meeting cost targets, the project should evaluate MEAs made from commercial catalysts manufactured at scale and, moreover, using current MEA manufacturing methods. This path is critical to estimating the cost of manufacturability and to advancing the technology closer to commercial scale. It is recommended that the project make MEAs using the current roll-to-roll process in the industry and not technologies developed at national labs, which do not have commercial-scale manufacturing experience.
- The project has made clear, significant progress in improving the performance and scalability of ion-pair HT-PEMs. This technology has clear advantages for heat rejection, which may be helpful for transportation applications, although many of these applications also require good operational flexibility and efficiency, which have not been demonstrated. The project does not clearly identify the applications that match the profile of strengths and weaknesses for ion-pair HT-PEMs, which makes it difficult to assess potential impact and alignment with the Hydrogen Program goals.
- Claimed system simplifications beyond the reduced heat exchanger size are not described. Lower parasitic losses are claimed. This claim is unlikely, as the compressor is the most significant parasitic loss by a large margin. Performance and degradation metrics are far from DOE targets. The cost is currently unclear because the catalyst loading has not yet been reduced to the target level of 0.3 mg Pt/cm^2 (total amount for the anode and cathode).

Question 5: Proposed future work

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

- This phase of the project ended on March 31, 2024. The team is looking to optimize the gaskets, GDLs, and other aspects of the cell architecture to improve performance further. The team is also developing a thinner membrane that would be closer to what is used in LT-PEMFC systems. There is a high likelihood that the team will continue to improve fuel cell performance over time.
- Going forward, there should be a strong focus on investigating durability, including:
    - Determining the root cause(s) of the decay reported on slide 9.
    - Stating whether the team subjected this technology to cyclic operation and, if so, how the decay compares to steady state.
    - Stating whether the team has demonstrated repeated start/stop cycles, which are realistic in the applications being targeted.
- Proposed future work is reasonable but vague. The project is at the end of its term, so this lack of description is reasonable. However, it may have a new phase with the L'Innovator program.
- Advent has a plan to move toward thinner membranes, which is the right direction for this HT-PEM technology. The project is ending in 2024, so it is not clear what the proposed future work includes.

However, the application for this technology needs to be clear. It is doubtful whether this HT-PEM technology, at its current status, is viable for HD truck mobility applications.

- Advent's proposed future work may be focused on improving MEA current–voltage capabilities. This work does build on past progress. Per reviewer comments, it is proposed that Advent focus on showing durability in excess of 1 khr.
- The future work focuses on manufacturing scale-up, despite major issues related to unmet DOE targets.

Project strengths:

- Advent has successfully performed technology transfer on the ion-pair HT-PEM and electrode binder technology by LANL and the active ORR, phosphate-tolerant electrocatalyst by BNL. The team has successfully scaled up polymer synthesis and membrane manufacturing while also demonstrating HT-PEMFC performance. In a short stack, said materials have showed greater durability when compared to conventional PBI technology.
- The project is advancing a unique HT-PEMFC technology, with significant advantages for heat rejection and fuel flexibility. Good progress has been made with scale-up and demonstrations, as well as improvements in cell performance.
- The principal investigator's experience in HT-PEM and fuel cell catalysts is a strength. Continuing technology assessments with land, air, and sea OEMs is a significant strength of this project and will help to identify the best application areas for the HT-PEM technology. Collaboration with BNL and National Renewable Energy Laboratory for early-stage roll-to-roll MEA development has definitely helped this project, but Advent needs to look toward manufacturability for the future with industry leaders in the MEA manufacturing area.
- The team is developing fuel cell technology that could be game-changing for mobility applications.
- The project's strength is working on fuel cells that are different from conventional PEMFCs.
- A project strength is the enabling of a smaller radiator. Industry and team engagement are strong.

Project weaknesses:

- The only minor weakness is the benchmarking against LT-PEMFCs and alignment with some of the goals of M2FCT (e.g., both performance and durability). It would be nice to see additional data pointing out performance limitations (e.g., kinetics or mass transfer).
- The ion-pair HT-PEM technology has clear advantages for heat rejection, which may be helpful for transportation applications, although many of these will also require good operational flexibility and efficiency, which has not been demonstrated. The project does not clearly identify the applications that match the profile of strengths and weaknesses, which makes it difficult to assess potential impact. Very limited durability testing was presented.
- Electrode improvements that have resulted in the MEA performance are not clear. The principal investigator should publish the areas of development, ionomer down-selection, ionomer-to-carbon ratio, etc. that have resulted in the MEA performance improvement. There does not seem to have been an effort to scale MEAs using current industry MEA manufacturing methods. Manufacturability cannot be assessed based on national lab bench-scale technologies and capabilities.
- Use of the term "HT-PEM" is a weakness. This technology is not a PEM. Like PBI, it is simply a polymer matrix impregnated with phosphoric acid. The team should call a spade a spade. The project should be referred to as "next-generation phosphoric acid fuel cells (PAFCs)" since that description is far better and emphasizes that this project builds on PAFC technology.
- Most DOE metrics for HD applications have not been met, and plans to remediate the situation (membrane thickness reduction, tweaking the catalyst) are not expected to be successful. Approaches to lower the Pt catalyst loading and degradation rate were not discussed.
- A project weakness can be found in focusing on improving MEA current–voltage capabilities versus durability.

Recommendations for additions/deletions to project scope:

- The project is at the end of its term, but if it has a new phase with the L'Innovator program, the team should make a clear case for applications where weaknesses in efficiency and operational flexibility compared to LT-PEMFCs will not be a problem. This information is needed to clarify the potential impact of further work on this topic. It would also be important to have a picture of how much improvement is possible with advances in the technology. Future work should also include more durability testing, including testing under application-relevant duty cycles.
- It is recommended that the team either add durability to the project scope or show that durability at 25,000 hours is addressed.
- The focus should shift from a manufacturing scale-up to addressing the DOE targets that are not met. In other words, the team is trying to bring to the market a technology that is not ready to meet requirements.
- Durability cycles were not presented. Load cycling durability should be assessed for mobility applications.
- Recommendations are not applicable, as the project has ended.

Project #FC-363: Advanced Fuel Cell Vehicle DC-DC Converter Development

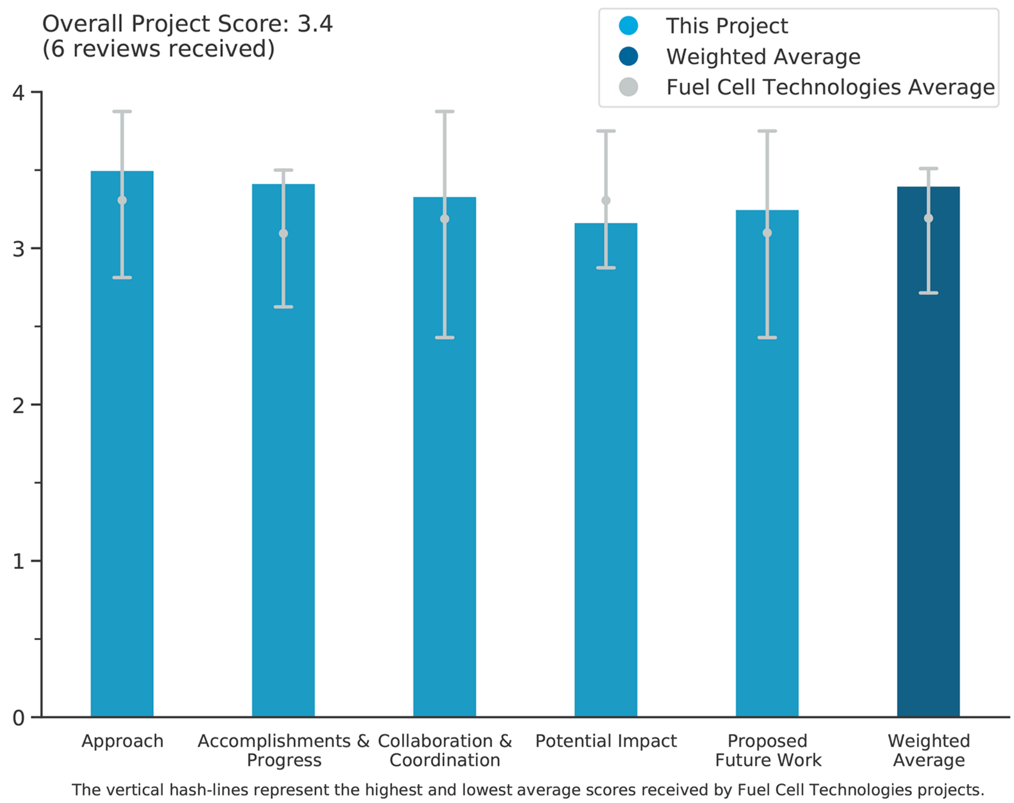
Vivek Sujan, Oak Ridge National Laboratory

DOE Contract #	WBS 1.4.0.650
Start and End Dates	4/1/2023–3/31/2026
Partners/Collaborators	Million Mile Fuel Cell Truck Consortium (M2FCT)
Barriers Addressed	• Safety • System efficiency • Durability

Project Goal and Brief Summary

The goal of the project is to develop a high-frequency power electronic direct current (DC)-DC converter architecture for fuel cell electric vehicles to enhance safety and durability while achieving high-power and high-efficiency targets. The project aims to create a flexible and scalable platform approach that meets or exceeds system isolation requirements for fuel cell power levels aligned with heavy-duty truck requirements. The project follows a platform approach, starting with safety and then developing a fuel cell DC-DC converter platform (100–400 kW). The design considerations include isolation levels, input/output current and voltage characteristics, parallel/series fuel cell stacks, current leakage pathways, operating efficiency, thermal management, and single/bi-directional power flow. The project proceeds through system modeling, detailed electrical system design, and component validation to optimize efficiency, cost, and durability. The project leverages the knowledge, characterization, and modeling capabilities of national laboratories to develop a scalable platform that supports the Million Mile Fuel Cell Truck (M2FCT) consortium. The project outcomes will contribute to pre-competitive system analysis, design optimization, and critical component characteristics, accelerating technology development for at-scale production.

Project Scoring



Question 1: Approach to performing the work

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

- The project's approach to design and analysis is clear, straightforward, and well-stated. A detailed electrical engineering analysis of a variety of converter architectures is the only way to evaluate the options.
- The proposed development of a DC-DC converter architecture for heavy-duty vehicles (HDVs) using a top-down approach that emphasizes identifying and balancing key tradeoffs, while considering the key system configuration trade-offs and interactions, will benefit domestic fuel cell system developers.
- The team at Oak Ridge National Laboratory (ORNL) has presented a comprehensive approach to meeting its goals to develop an advanced high-power (>250 kW) fuel cell DC-DC converter. The project addresses two key project goals: efficiency and isolation safety. A critical barrier, isolation safety, is being addressed with optimized power electronics topology. The collaboration with the M2FCT consortium has presented the project team with an opportunity to integrate with other relevant efforts.
- This project has a very clear objective with well-defined target metrics.
- The project approach is sound.
- There appear to be no targets related to this project from DOE or the Fuel Cell Technical Team. The first approach should be discussions related to developing targets, which would greatly inform the approach and the relevance of this work. The described scale is for a flexible 250–400 kW range, which seems too high for the current fuel cell HDVs being developed, in many cases. M2FCT is modeling two systems—175 kW and 275 kW—while fuel cell HDVs have systems on the lower end. It is possible that the range up to 400 kW is valid for some original equipment manufacturers (OEMs), but the scale should go down to a lower power level. The higher power level is not produced throughout the entire drive cycle, especially at idle, and it is unclear down to what power level the DC-DC converter can go.

Question 2: Accomplishments and progress

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

- The project team's logical layout of configurations is particularly appropriate. The project team has clearly defined values for the correct parameters (e.g., $/kW, kW/kg, and kg/L) and efficiency. The graphical results included (e.g., how a key metric changes with frequency, number of phases, etc.) are an excellent way of determining trends and tradeoffs.
- The described 90 kW building block approach seems to provide substantial advantages in terms of cost, mass, and volume compared to existing commercial benchmarks.
- The project team has made excellent progress in understanding the tradeoffs of cost versus performance.
- The project team has clearly defined the project goals and is meeting the planned schedule.
- The total cost of ownership modeling is good, but the conclusion of a $40,000 saving potential is reliant upon hydrogen prices. These prices have no chance of leading to significant fuel cell adoption and thus are relevant only for near-term adoption. If hydrogen prices stay at $15/kg, fuel cells will not be widely adopted, so project and modeling decisions should be based on more competitive hydrogen prices. The design progress and modeling accomplishments seem appropriate for this level of funding.
- ORNL's accomplishments have enabled the researchers to better understand approaches to maximizing efficiency and addressing isolation safety. It is not exactly clear whether the project team has selected a specific power electronics topology; this may have overlapped with the Annual Merit Review.

Question 3: Collaboration and coordination

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

- ORNL has assembled a strong team on industry and a national consortium that can best direct the technology. This team, guided by ORNL leadership, will improve the likelihood that the project's power electronics will be incorporated into heavy-duty (>250 kW) fuel cell systems.
- The inclusion of Cummins on the project team as a DC-DC converter expert is critical. Cummins also offers expertise in fuel cell system configurations, and GE Aerospace has expertise in custom and high-efficiency converters. The project team would be strengthened by a collaboration with automotive industry converter manufacturers and with another fuel cell manufacturer to get another perspective (beyond Cummins') on tradeoffs within the overall fuel cell power system. The participation of Chemours for coolant expertise is a modest contribution.
- It is good that the project team has initiated collaborations with fuel cell truck OEMs, as these collaborations are critical to the value of this project. The project team should continue to expand these collaborations.
- It was good to see the project's collaboration with industry leaders such as Cummins and GE Aerospace.
- The project collaborations appear to have improved from Fiscal Year 2023. The collaborations can be further improved by understanding the current supply chain base and OEM plans. The need for a flexible power level with a DC-DC converter would seem to be for near-term production.
- The list of collaborators appears suitable for this project, but the absence of engagement with OEMs in Budget Period 1 is unclear. The proposed architecture may have a disconnect with system developers.

Question 4: Potential impact

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

- The project team's objective is relevant to improving the efficiency of heavy-duty fuel cell systems. The project team's effort to improve efficiency is key to the Hydrogen Program's goals. Improving safety could also help transition fuel cell systems into commercial applications.

- Improved efficiency would have a significant positive impact on hydrogen consumption and total cost of ownership.
- The impact of this project is highly relevant, as the DC-DC converter is a critical component that is difficult to source and is a common reliability problem.
- This project fills a need for the Fuel Cell Technologies subprogram that has received less attention from the Hydrogen Program.
- The relevance of this project seems undefined, owing to a lack of targets from DOE and/or OEMs. It would be useful to understand the current supply base of DC-DC converters and whether OEMs are having large issues with the supply base that clearly exists. The project does not seem to define the current baseline state of the art (SOA), so the overall improvement is unclear. The project should first define what the current baseline SOA is and develop targets. It is unclear if funding an improvement of 0.5% (e.g. 98% to 98.5%) is a more appropriate use of federal funds than improving the cathode oxygen reduction reaction catalyst, which can make improvements significantly higher than 0.5%. At this low level of funding, it seems valuable.
- This project could have a greater impact if the prototype system was designed for integration into an existing HDV system and demonstrated in that context.

Question 5: Proposed future work

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

- The team at ORNL proposed future work that clearly builds on past progress. The next steps will be to select a specific power electronics architecture that maximizes efficiency and addresses isolation safety.
- Future work plans are reasonable and necessary.
- Proposed work seems appropriate.
- It is unclear where and how the DC-DC converter system test will be conducted. The future work of the project team should include defining the current baseline SOA, defining overall targets, and conducting a larger industrial survey.
- The project team should explore the value proposition of low-cost architectures versus the ORNL stretch high-performance architectures. It is not clear which of the metrics in the project targets are most valuable.
- The proposed work follows a logical progression, but it appears that cost and performance metrics will need to be reassessed based on the actual design.

Project strengths:

- The graphical display of project results is a strength and is very informative. The in-depth engineering assessment of multiple converter architectures is a major strength. The consideration of modularity and how converters of multiple power ratings will be created for a common mass-manufactured repeat module is another strength.
- This project is the only publicly funded DC-DC development project. A flexible DC-DC converter (that is cheap and efficient) will help early developers. The increase in system efficiency of ~1% is certainly valuable.
- It is a valuable endeavor to refine the DC-DC converter to enhance overall system performance, efficiency, and durability. The project outcomes will benefit other DOE projects and the collaborators involved in M2FCT.
- This project is an effective study of fuel cell support equipment that is less examined in the Hydrogen and Fuel Cell Technologies Office. The scope and plan for the project is well-defined and aligned with the project budget.
- The project's strength is the team ORNL has assembled. Cummins, Daimler, and GE Aerospace are all in the heavy-duty fuel cell technology space. The project team's coordination with M2FCT is also a strength.
- It was good to see a deep dive into the design details and tradeoffs of one of the challenging components in a fuel cell system.

Project weaknesses:

- There are no project weaknesses in this reporting period.
- Cost is included in the evaluation criteria, but it is not listed among the numerical target metrics. The current status values of $/kW, kW/kg, kW/L, and efficiency are not numerically stated other than generic references in graphical displays. These values need to be explicitly defined so they may be compared against the project's end results. The presentation does not clearly state recommendations for which designs will advance into Budget Period 2. The presentation showed results, and the proposed future work calls for "detailed system design of up to two key architecture pathways," but the recommended key pathways are not defined. The concept of stretch targets is a good one but is poorly defined in the presentation. The project team should add clearer differentiation and categorization. The fuel economy graphs are interesting but lack a description of who generated them and how. In the fuel economy graphs, it appears that the fuel economy performance can be made nearly constant (i.e., a flat curve) as a function of power, but the reviewer did not understand this result and would like further explanation. Furthermore, the definition of "FC Base Blower" is not clear, as it (presumably) also includes a DC-DC converter.
- The project timeline is long for the size of the team and the budget. This project could have been executed in a shorter timeframe.
- The project has not adequately defined the current baseline SOA or overall targets.
- The project's alignment with next-generation HDV system design specifications is unclear.

Recommendations for additions/deletions to project scope:

- Perhaps collaboration with a commercial power electronics manufacturer could add an additional dimension to the project.
- The following are suggested adjustments:
    - The project should add a numerical target value for cost ($/kW).
    - The project team should state more clearly the current/starting-point values for efficiency, cost, kW/kg, and kW/L. The team should also more clearly define design differences (and metric impacts) between the target designs and the stretch target designs.
    - Current has a significant impact on the system, as it affects cost (of the chips) and efficiency, but it is not mentioned in any of the tradeoff graphs.
    - The project team should show how amperage affects the architectures.
    - In its responses to reviewer comments, the presenter noted that components are oversized by 50%–60%. While some oversizing is needed and desirable, this level of overcapacity seems extreme. Efforts should consider whether some cost reduction can be achieved by "right-sizing" components.
    - The team is asked to clearly state the specific key architectural pathways recommended for further design study in Budget Period 2.
    - At one point, it was stated that Buck, Boost, and Buck/Boost architectures were to be considered. The team should explain why the combined Buck/Boost architecture was dropped.
- More work should be conducted related to developing targets. In view of some HDV fuel cell development plans, the flexible scale of 250–400 kW should be expanded down to ~175 kW. Maybe the higher power level of 400 kW should be justified.
- The team should develop a weighting scheme for the key performance indicators so that different architectures can be compared to each other more quantitatively. These weightings should be developed through collaborations with OEMs.
- The project team should collaborate with suppliers and integration partners to develop a requirements document that guides design work. The team should also conduct a design review with the same stakeholders at the end of Budget Period 2.
- There are no recommendations for additions or deletions to project scope during this reporting period.

Project #MNF-BIL-001: R2R: Roll-to-Roll Consortium

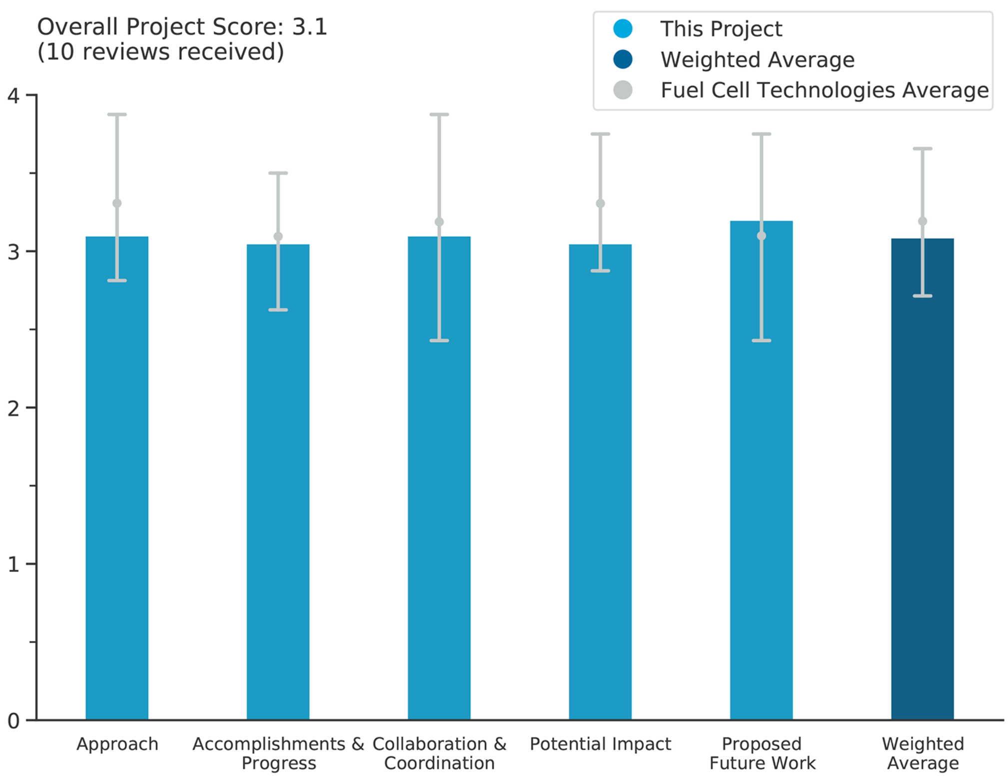
Scott Mauger, National Renewable Energy Laboratory

DOE Contract #	WBS 12.3.0.501/13.2.0.501
Start and End Dates	10/1/2023–9/30/2028
Partners/Collaborators	Argonne National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories, Strategic Analysis, Inc., University of New Mexico
Barriers Addressed	• Lack of high-volume membrane electrode assembly processes • Low levels of quality control • Cost

Project Goal and Brief Summary

The Roll-to-Roll (R2R) Consortium establishes the mission of efficiently manufacturing electrolyzers and fuel cells to meet the growing demand for sustainable hydrogen production. This project is accelerating advancements in electrolyzer and fuel cell production, aiming to lower costs and enhance the commercial viability of hydrogen as a clean energy source. By focusing on R2R techniques, the consortium seeks to streamline production, reduce material waste, and increase the overall efficiency of hydrogen fuel cell and electrolyzer manufacturing processes.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach is good. The project covers a very broad topic that has been divided into logical sub-tasks (e.g., membrane electrode assembly [MEA] fabrication, quality control [QC]) and cross-cutting topics (e.g., characterization, techno-economic analysis [TEA]). The focus on both proton exchange membrane fuel cell (PEMFC) and proton exchange membrane water electrolysis (PEMWE) is also good, including the proposed collaborations with the Hydrogen and Fuel Cell Technologies Office's (HFTO's) consortia on these technologies (e.g., the Million Mile Fuel Cell Truck Consortium [M2FCT] and Hydrogen from Next-generation Electrolyzers of Water [H2NEW]). The objectives are ambitious, and it will be interesting to see how much truly fundamental understanding can be developed and disseminated in these areas since optimal manufacturing processes tend to depend strongly on the actual material sets. The team should strive to discern scientific principles that apply to a broad set of PEMFC and PEMWE materials. It is not clear why large-scale synthesis of catalyst inks is included here, since this is not R2R technology, although it may be justified since ink properties, which do depend on synthesis processes, are important in the downstream R2R processes. Most importantly, the overall goals and objectives of this project strongly overlap with what industry does well.
- The reviewer was very glad to see a consortium focused on the scale-up process.
- The objectives of the consortium are clearly identified.
- The high-level approach outlined makes sense. Specific details are not fully elucidated owing to the stage of the work. Working with industry will be key to understanding the pathways to ensure effective private sector uptake. The advisory board is a good approach, but there should be additional avenues implemented to have broader collaboration.
    - Scale-up of leading M2FCT or other projects' leading material candidates is a valuable approach, as it will provide a realistic and needed scale-up effort.
    - The impacts of non-uniformities will be greater on durability than performance; therefore, performance testing should be considered only as a first-level screening. To understand and predict effects of non-uniformities on durability, the project will likely need to manufacture defects to have controlled studies and determine limits of acceptable defects.
    - The team indicated it will include input from the original workshop and the advisory board. As this is a complex topic, the team may need further input, either from additional workshops or from other collaborators.
    - It is not clear whether contamination effects are considered, e.g., incoming materials and contamination effects on ink properties and resulting device-level effects, but they should be.
    - The team should have personnel familiar with design for manufacturing and lean manufacturing approaches, e.g., Six Sigma, and determine ways to incorporate these approaches into the work.
    - There was some discussion during the presentation on whether the beaker approach was sufficient. The reviewer agreed with the presenters that critical parameters can be measured and a larger batch is not necessarily required. Using the learnings from the batch to create models and to design and study the flow reactor is an effective technique. The team should, however, collaborate/consult with industry to validate the approach.
- The project addresses the issues of lack of high-volume MEA processes, low levels of quality control, and cost. The challenges in scale-up will be developing processes at speed and with minimal defects to minimize scrap. The approach does not seem fully reconciled with the project barriers. The R2R approach is to focus on scaled synthesis processes, machine learning, and process modeling. The critical task of the QC tool and method development (defect detection) is in a different project, TA-001, but falls under the consortium. The presentation includes many activities, but no information is given about the amount of work taking place in each activity, and the consortium combines several efforts, so it is very hard to tell from the presentation which tasks are being emphasized.

- The catalyst scale-up of the Brookhaven National Laboratory (BNL) fuel cell catalyst seems irrelevant to the project. Tens of kilograms of material may be needed; the path from small-scale to relevant is not clear. It is also not clear whether the final goal is grams or tonnes of material.
- In addition, it seems that there should be an additional effort to scale an electrolyzer catalyst, as the project is 50% fuel cells and 50% water electrolysis (WE). Without any breakdown of the activities by cost, it is difficult to evaluate the project.
- Material/coating electrochemical performance also seems to be a key task for this consortium, but it is not clear where or how this is taking place, nor the amount of electrochemical evaluation expected.
- The consortium also does not explain what happens to all of the materials at the end of the experiment or testing. It is unclear whether they will be contributed to the DOE recycling consortium or how DOE will recuperate costs from the materials used in the R2R Consortium.
- This reviewer rated the approach 2.5/satisfactory because of the lack of details and quantitative information in the presentation (key performance indicators, goals, programmatic details).
- The labs have a robust diversity, equity, inclusion, and accessibility plan around internships and hiring; this is a strength for the labs.
- It is not clear why the team is exempt from having a safety plan with the Center for Hydrogen Safety for testing work. A general safety plan for dealing with the increase of solvent, R2R equipment, and hazardous materials (high-surface-area platinum group metal) would be warranted.

- The approach to compare components manufactured by the consortium with baselines makes sense, but it is unclear how the baseline technology (materials, processes, designs) will be selected. It is unclear whether the researchers will again benchmark commercial MEAs made using R2R processes and, if so, how they will ensure they are using common materials. If the team plans to benchmark against MEAs made using the same materials using batch processes, there will be no comparison to an industry best-in-class MEA. It is also unclear whether the processes the consortium is developing are universally representative of industry practices. The 50/50 cost share cooperative research and development agreement (CRADA) approach should provide significant value to small companies that do not already have high-volume production capabilities but will be less valuable to mature companies who already do. It is unclear at which scale the impact of manufacturing variations on device behavior will be measured. This sort of work is very difficult to do at a single-cell level. Stack testing with multiple cells is required to get statistical significance on defect/variation impact, which is likely to be beyond the consortium’s capabilities. It is unclear how the project will get sufficient data with enough details to take advantage of machine learning.
- The focus on improving the manufacturing is good. The approach to have cost-shared CRADA projects between the R2R consortium and industry is appropriate and should ensure projects focus on industry-relevant issues. It is not clear that scale-up is going to the appropriate size, particularly for catalyst synthesis using the batch reactor approach. The use of model ink systems replacing IrO_2 with TiO_2 and modeling of catalyst synthesis using Ag rather than Pt is interesting and could reduce some testing costs; however, it is not clear that the consortium knows which key properties need to be kept similar to the real system in the model systems to ensure they are good model systems. It is more complicated than just matching one or two variables such as catalyst volume fractions, ionomer mass fraction, viscosity of the ink or solvent, and hydrophobicity of the particle. Machine learning approaches generally require large datasets. It is not clear how the project will acquire the amount of data on manufacturing steps and parameters to be able to effectively apply machine learning tools.
- This is a $50 million lab project directed by major players in the catalyst-coated membrane (CCM) supply chain and original equipment manufacturers (OEMs). Major industrial players in CCM technology direct what the lab effort should be working on. A minority of the effort comprises CRADA projects with industry ($8 million) in which industry covers its own costs and shares background intellectual property (IP) and the lab effort generates IP to then license to the industry partner; that approach may not be appealing to the CCM players. Currently, material costs in ionomers, catalysts, and gas diffusion layers (GDLs) dominate the price of CCMs; the R2R machine coating costs are not that significant for today’s components. The approach in this project does not address the needed reduction in raw material costs of ionomers, catalysts, and GDLs. Therefore, it is unclear whether this project is a study of how CCM processing parameters impact MEA performance or how to design a process that has a reduced

manufacturing cost. The former may be more widely beneficial to all parties in the business of manufacturing CCMs.

- The project seems to focus only on the MEA manufacturing process for fuel cells and WE. The project should consider including the bipolar plate R2R process, which is also of high impact in making high-performance and low-cost fuel cell systems. The metrics of the manufacturing process should be defined with each design criticality that affects the performance and durability. It is recommended that the consortium clarify what the design criticality is for fuel cell/WE MEAs. Also, the consortium can cover a reverse approach; for example, the consortium can offer a design guide from a feasible manufacturing process capability such as Design for Six Sigma. It is recommended that the consortium clarify national labs' resources with respect to R2R manufacturing processes for the CRADA solicitation.
- The composition of the industrial advisory board could be improved with the addition of a member (3M, Mott Corporation, etc.) knowledgeable about GDLs, porous transport layers (PTLs), or framing materials.

Question 2: Accomplishments and progress

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

- As the consortium is very new, limited progress is expected. The team has designed and fabricated a parallel continuous flow reactor with in-line monitoring to explore the influence of synthesis conditions on the physical and chemical characteristics of the catalyst. The team established a reputable industrial advisory board that represents fuel cell and PEMWE OEMs, as well as suppliers of key components (catalysts, membrane, PTLs), and has held an industrial kickoff meeting. The project developed a process to use mock (Ir-free) inks with similar properties and IrO_x inks to do preliminary coating trials.
- This project has the potential to have big implications, as it could allow for an increase in manufacturing. Since the project just started, progress is limited.
- The project is in the early stages. The accomplishments to date are satisfactory. The development of a mock ink is an important step.
- This young project has assembled a good team and a framework of consortium organizational structure, so actual technical progress is limited but is well on track. It is unclear whether there will be a way to quantify cost reduction with targets. If the current R2R CCM manufacturing process steps add X to the system costs, it is unclear what the post-project target is for cost reduction due to advancements in R2R processing. This type of target was not clearly addressed.
- Progress has been focused on setting up the consortium and a CRADA with industry. The team has also set up the metrics for data to be collected for machine learning. The BNL catalyst scale-up is also under way, but the goals (how many kilograms, tonnes) are not explained. Baseline work is also being carried out on coating and drying. Presumably progress is also being made on defect detection, but this is reported under TA-001.
- The project has been active only since October 23, 2023. Accomplishments reflect the short time period. Synthesis of PtNi and PtNiN catalysts in flow systems is interesting and could prove scalable; however, it is not clear that these catalysts can achieve the same performance as the traditionally synthesized material. The development of tools for the drying studies could prove useful, but it is still early in the studies.
- The project is off to a good start in part because the team has momentum from previous DOE-supported projects. It is not clear why the team has been focusing on a PEMFC catalyst that has not been down-selected by M2FCT; this makes one question the reported coordination with M2FCT.
- There are valuable outcomes, but it is unclear what the design requirement is. For example, distribution of the catalyst particles is shown, but the design requirement on which it is based is not clear. It is unclear whether the narrow distribution is good or bad. In some cases, catalyst particle size may be intentionally dispersed to gain MEA durability.
- Results from batch and continuous catalyst synthesis reactors will be informative. However, there is a risk that the knowledge gained may not be useful for newly developed catalysts using different processes.
- The consortium is just beginning.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- It is good that the consortium is leveraging M2FCT/H2NEW expertise and methodologies. The industrial advisory board is in place. It remains to be seen how much useful information the board will share. The work to scale up next-generation materials developed through M2FCT, H2NEW, and other HFTO-supported programs/projects demonstrates collaboration within the labs and existing DOE projects. This work should definitely include U.S.-based industrial partners that are capable of and interested in commercializing these technologies.
- It is good to see that the project is incorporating the learning from some of the other DOE projects. As this project focuses on production, collaboration with the industrial advisors is going to be crucial to ensure the success and appropriate focus of the project.
- An advisory board of industry members is a good approach.
- Collaboration so far seems very good.
- Collaboration with many industry partners may make it difficult to keep IP separate among all the researchers and different industry partners. Some industrial advisory board members should be responsible for providing accurate material costs as a function of volume of production. This parameter is essential to proper design of manufacturing processes to most efficiently drive down costs. For example, if material costs are high, more labor costs could be a lower-cost solution as compared to more capital costs in manufacturing equipment that may not utilize materials most efficiently.
- The inclusion of multiple national labs in a consortium is always good, since it makes the labs work together instead of competing with each other and potentially duplicating efforts. The reported collaboration with M2FCT and H2NEW is good. The inclusion of Strategic Analysis, Inc., for TEA work is highly appropriate here. The establishment of an industrial advisory board is great, although the role of the board is not clear. It is worth noting that one of the key PEMFC labs (Los Alamos National Laboratory) is not included here. It is unclear whether this project is really collaborating with M2FCT.
- There appears to be good collaboration between the national labs involved so far. The fact that the industrial advisory board includes the Association of Roll-to-Roll Converters, General Motors, and Chemours—major companies knowledgeable in high-throughput manufacturing—is to be commended. A greater involvement of manufacturing equipment suppliers and manufacturers would be beneficial. Having a liaison to H2NEW and M2FCT is commendable. Collaboration with the newly formed recycling consortium (H2CIRC) was not apparent. Having a liaison to H2CIRC would be beneficial.
- There are five national lab partners involved, which will provide a significant range of expertise. There are only two subcontractors, which seems low. The industrial advisory board will provide important input. There are several potential areas for collaboration, and these need to be investigated further. There should be a mechanism for the broader supplier community to be involved, beyond the initial workshop. Perhaps an annual workshop would be worthwhile.
- Collaboration is underway with the project's recently released CRADA. The collaboration between the R2R Consortium, M2FCT/H2NEW, and TA-001 is not clear.

Question 4: Potential impact

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

- The project has the potential to have a large impact on scaling production, particularly for some of the advanced catalysts being developed. Contributions in R2R coating and metrology to measure coatings may be made.
- With strong leadership from the National Renewable Energy Laboratory and DOE, the R2R Consortium has the opportunity to be a leader in R2R development if the team can focus on finding methods to overcome the barriers identified in the project.

- This project is crucial for the Hydrogen Program's goals, as R2R is the only way to increase manufacturing capacity at scale.
- Scale-up of developed technologies is critical to achieving DOE cost goals.
- The R2R process is a high-impact area for MEAs and bipolar plates. However, the approach of this consortium is adequately shown so far.
- The project is very well aligned with DOE objectives.
- This is not a great use of DOE funding since this type of work is not especially high-risk, and it is also what industry tends to do well, once they have decided to invest in making a particular component. Multiple companies are making good MEAs for PEMFCs and PEMWE today, so there is no major technical barrier being addressed here. Industry also prefers to keep manufacturing processes as "trade secrets" vs. applying for patents, since manufacturing patents are notoriously hard to enforce. Therefore, it is unlikely that industry will share a lot of information with the R2R Consortium. Additionally, unlike MEA recycling processes, there is no obvious reason to develop universal MEA fabrication processes. With recycling, having industry-accepted processes is beneficial since the industry can design components for these end-of-life (EOL) processes, and no one is currently recycling PEMFC and PEMWE components today. In summary, some process development work is appropriate for DOE to fund, but this is not such a project, as it is currently structured.
- It is unclear how the consortium will help accelerate fuel cell and PEMWE production. Industry already has capacity to meet the target of 20,000 heavy-duty fuel cell stacks per year, and there are clear plans to reach the PEMWE target of gigawatts per year. Additionally, some of the challenges the consortium aims to address, particularly MEA fabrication processing at volume, have already been addressed by industry in the United States. This technology is core to U.S. industry and is not typically ever disclosed publicly. If the consortium solves these challenges and shares the information publicly, the United States actually risks losing its advantage. Competitors around the world are watching and learning from the work done at DOE. This is especially true for those countries who will not honor U.S. IP.
- Cost vs. log of manufacturing volume plots should be replaced with log of the cost vs. log of the cumulative manufacturing volume plots. These are expected to be linear with the slope related to the learning rate. The learning rate can then be compared to established values in similar fields for comparative purposes. Furthermore, estimates are easier to create with linear plots. The current cost vs. log of manufacturing volume plot curves are asymptotic, reducing confidence in estimates.
- There is concern as to how efficient the project will be in terms of lowering total material and manufacturing costs.

Question 5: Proposed future work

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

- The correlation of R2R processing conditions used to make CCMs to the CCM performance can be useful to all. Lab-developed IP invented during a CRADA project could be offered at no cost to the CRADA industry partner; if the industry partner does not practice the technology developed, then it can be licensed to others. This would make the CRADA part more attractive to industry partners.
- The proposed future work is appropriate for the team's current objectives.
- The project has appropriately identified future work needed.
- The proposed future work is well-laid-out. The focus on modeling and TEA is critical. The go/no-go milestone for 2024 should include a basic uniformity requirement, not just a comparison to previous efforts. For the comparison basis, there should be a measure, e.g., 20% improvement, rather than just "better."
- The project seems to focus on only MEA manufacturing processes for fuel cells and WE. The team should consider including the bipolar plate R2R process, which is also high-impact, to make high-performance and low-cost fuel cell systems. Metrics of the manufacturing process should be defined with each design criticality that affects the performance and durability. It is recommended that the consortium clarify what the design criticality is for fuel cell/WE MEAs. Also, the consortium can cover a reverse approach; for example, the consortium can offer a design guide from a feasible manufacturing process capability such as

Design for Six Sigma. It is recommended that the consortium clarify national labs' resources with respect to R2R manufacturing processes for the CRADA solicitation.

- There are probably already models for coating and drying processes and characterization tools, given the ubiquitous nature of these processes in industry, that can be adapted to these materials. New models likely do not need to be developed.
- The proposed future work is listed only as activities; there are no project goals, so it is difficult to determine the scope of what the team hopes to accomplish. It is also not clear how the work will be split between fuel cells and WE.
- The project is new and still needs to define clear priorities.
- It is mostly all future work at this point.

Project strengths:

- The team possesses strong technical capabilities across the national labs to complete the planned work. The opportunity for small businesses to leverage the 50/50 cost share CRADA could benefit U.S. start-ups that need help scaling up and commercializing their technologies.
- This project is crucial for the Hydrogen Program's goals, as R2R is the only way to increase manufacturing capacity at scale. The guidance of the industry will be essential.
- The project leverages a consortium approach used successfully in other instances to bring industry, national labs, and universities together to solve industry issues collaboratively.
- This is a new project that is poised to solve key issues with the nascent R2R technologies for fuel cell and electrolyzer electrodes.
- The advisory board has members from the appropriate organizations to guide the work to industrially relevant issues.
- A strong team has been assembled, with a well-laid-out plan to advance manufacturing knowledge.
- The approach, collaboration and coordination, and proposed future work are strengths.
- A great lab-led team could make significant developments.
- The national labs' resources for R2R manufacturing capabilities are a strength.
- The team has many good resources and collaborators.

Project weaknesses:

- The project does not have key performance indicators and includes efforts on miscellaneous activities such as scaling niche catalysts. Project milestones are qualitative and should be turned into specific, measurable, achievable, relevant, and time-bound (SMART) milestones. There is a disconnect with technology barriers and project tasks. Coordination with the recycling consortium and/or recuperation of materials costs is not clear. It is not clear where and how MEAs will be electrochemically evaluated. Funding allocations for R2R vs. M2FCT, H2NEW, and TA-001 are not clear, nor is their relationship clear.
- This project is unlikely to provide much benefit to companies that are already using R2R MEA technology and could actually end up teaching the world things some in the industry in the United States already know. The principal investigator claimed the consortium will file IP on developed concepts and look to license to OEMs and suppliers. Preferably, taxpayer-funded IP should be available to all U.S. manufacturers.
- It is not clear the project will generate/have enough data to be able to effectively implement machine learning tools. R2R manufacturing of MEAs is now getting closer to commercialization and into a realm where IP in manufacturing and competition between companies become more of an issue and getting companies to share data/results is more difficult.
- Novel and promising catalysts may not necessarily be synthesized by methods selected for detailed investigations. Data should be plotted in a manner that leads to a learning rate facilitating comparisons and estimations.
- Collaboration approaches and alignment with industry and other related efforts, including IP considerations, are not fully developed.

- It is unclear how the money and IP generated with this project will be retained in the United States to ensure the success of U.S.-based companies.
- Weaknesses include industry involvement, particularly understanding of system engineering processes for design and design verification.
- IP developed could be tricky to commercialize.
- It is not clear why DOE investment is really needed here.

Recommendations for additions/deletions to project scope:

- The project seems to focus only on MEA manufacturing processes for fuel cells and WE. The project should consider including the bipolar plate R2R process, as it is also high-impact, to make high-performance and low-cost fuel cell systems. Metrics of the manufacturing process should be defined with each design criticality that affects the performance and durability. It is recommended that the consortium clarify what the design criticality is for fuel cell/WE MEAs. Also, the consortium can cover a reverse approach; for example, the consortium can offer a design guide from a feasible manufacturing process capability such as Design for Six Sigma. It is recommended that the consortium clarify national labs' resources with respect to the R2R manufacturing process for the CRADA solicitation.
- Most PEMFC and PEMWE developers would prefer highly integrated cell components, such as a five-layer unitized electrode assembly (UEA), which consists of a CCM (or MEA) plus the GDLs or PTLs. These UEAs may also include some sealing features, or even seal materials. To the best of the reviewer's knowledge, no one has developed a truly R2R process to fabricate UEAs, and this would therefore be an excellent technical challenge for this team. This may even include developing GDLs and PTLs that are roll goods (although some options do exist today). In summary, R2R production of UEAs is a sufficiently hard and higher-risk challenge that may warrant DOE investment.
- Many companies have already been working on R2R manufacturing for many years; work should be focused on innovation and not re-discovering what companies worked on solving years ago. The guidance of industrial partners will be essential. If the objective is manufacturing, the project should focus on collaboration with suppliers of electrolyzer components rather than focusing on developing every single component. It is important that the time and money are directed to ensure the success of U.S.-based companies and not foreign companies.
- While not technically R2R technology (but neither is catalyst scale-up), this team, working together with M2FCT, could be well-suited to study, fundamentally, what is happening during EOL MEA/stack testing and develop less expensive concepts for faster, less expensive (i.e., less hydrogen usage) EOL qualification testing. If the consortium plans to scale up M2FCT catalysts, it should look to actively engage at least one catalyst supplier.
- Catalyst scale-up should be deleted, as it is irrelevant to R2R. The team can find an abundance of different materials with different properties already commercially available. A full programmatic review is required. Hopefully, the industry board can help the R2R Consortium prioritize and focus.
- It would be useful to see more effort dedicated to inline quality measurement and corrective/preventative action to reduce the production of out-of-specification material and increase first-pass yields. The project should bring the quality control as far ahead in the process as possible.
- Lean manufacturing should be included. Design for manufacturing principles should be considered. The durability testing approach needs further development to understand acceptable limits of non-uniformities.
- The composition of the industrial advisory board could be improved with the addition of a member knowledgeable about GDLs, PTLs, or framing materials.
- More emphasis should be placed on process to performance testing rather than designing processes for cost reduction. The project should add a liaison to H2CIRC.