Fuel Cell Technologies – 2023

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 can be used for a variety of applications across multiple sectors. The Fuel Cell Technologies (FCT) 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 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 back-up), and reversible fuel cells for energy storage. The subprogram's RD&D emphasis is primarily on heavy-duty applications where 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 FCT 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 FCT 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.

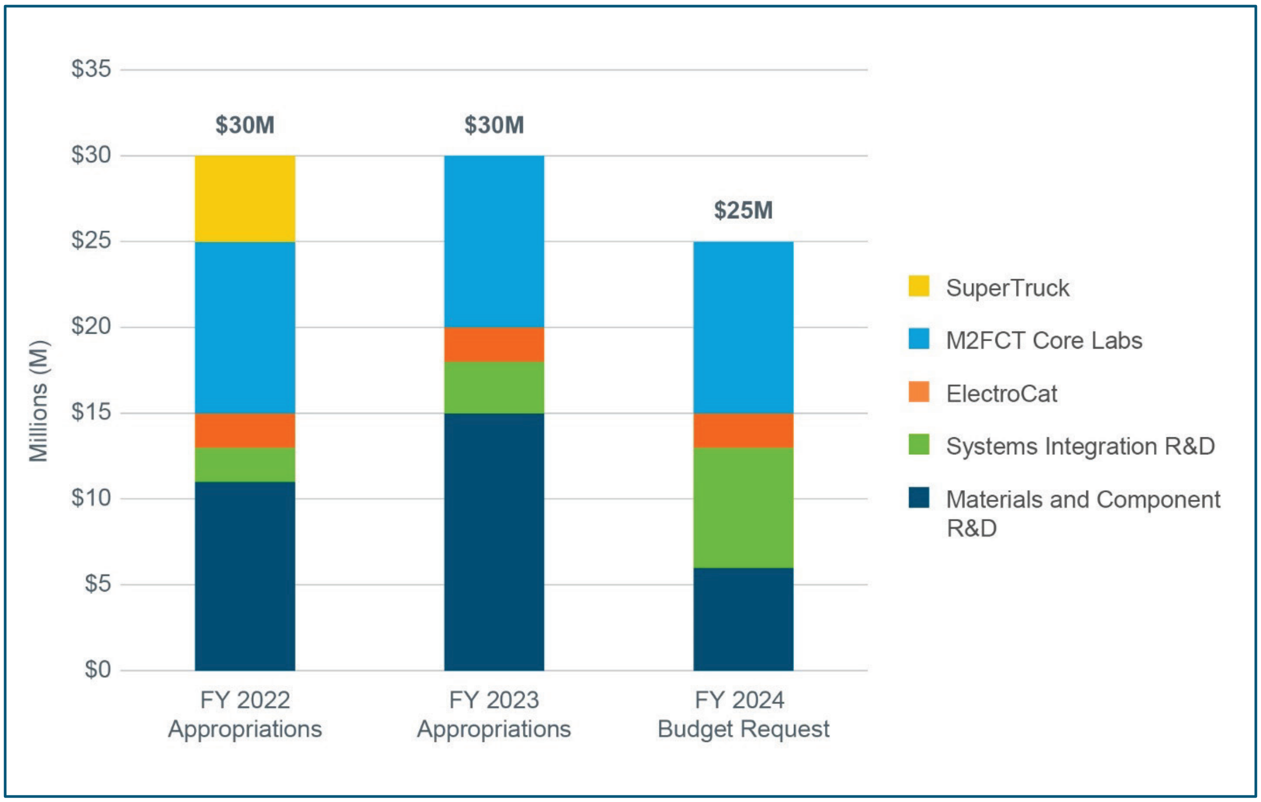
- Demonstrate heavy-duty fuel cell manufacturing capacity of 20,000 stacks per year in a single production line.
- Develop reversible fuel cells for energy storage applications that can achieve 40,000-hour durability and 60% round-trip efficiency at a cost of $1,800/kW.

Budget

The Fiscal Year (FY) 2023 appropriation for the FCT subprogram was $30 million. In FY 2023, the subprogram funded fuel cell materials and components, as well as systems integration RD&D, with a focus on reduced cost and enhanced durability and efficiency for heavy-duty applications. Funding was dedicated to the two national laboratory consortia, the Million Mile Fuel Cell Truck (M2FCT) consortium and the ElectroCat (Electrocatalysis) consortium, with M2FCT receiving a majority of the consortia funding (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 FY 2024 budget request for the FCT subprogram is $25 million. Activities planned for FY 2024 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.



In FY 2024, the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]) provisions on clean hydrogen manufacturing and recycling (Section 815) will fund manufacturing RD&D and component supply chain development and establish a recovery and recycling consortium for fuel cell and electrolyzer systems. BIL funding will also be allocated to establish a national-lab-led consortium focused on roll-to-roll manufacturing.

Annual Merit Review Results

During the 2023 Annual Merit Review, 33 projects funded by the FCT subprogram were presented, and 23 were reviewed (a breakdown by budget category is shown on the right). The reviewed project received scores ranging from 2.5 to 3.4, with an average score of 3.1. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 23 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	10
Systems Integration R&D	11
ElectroCat	1
M2FCT Core Labs	1

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

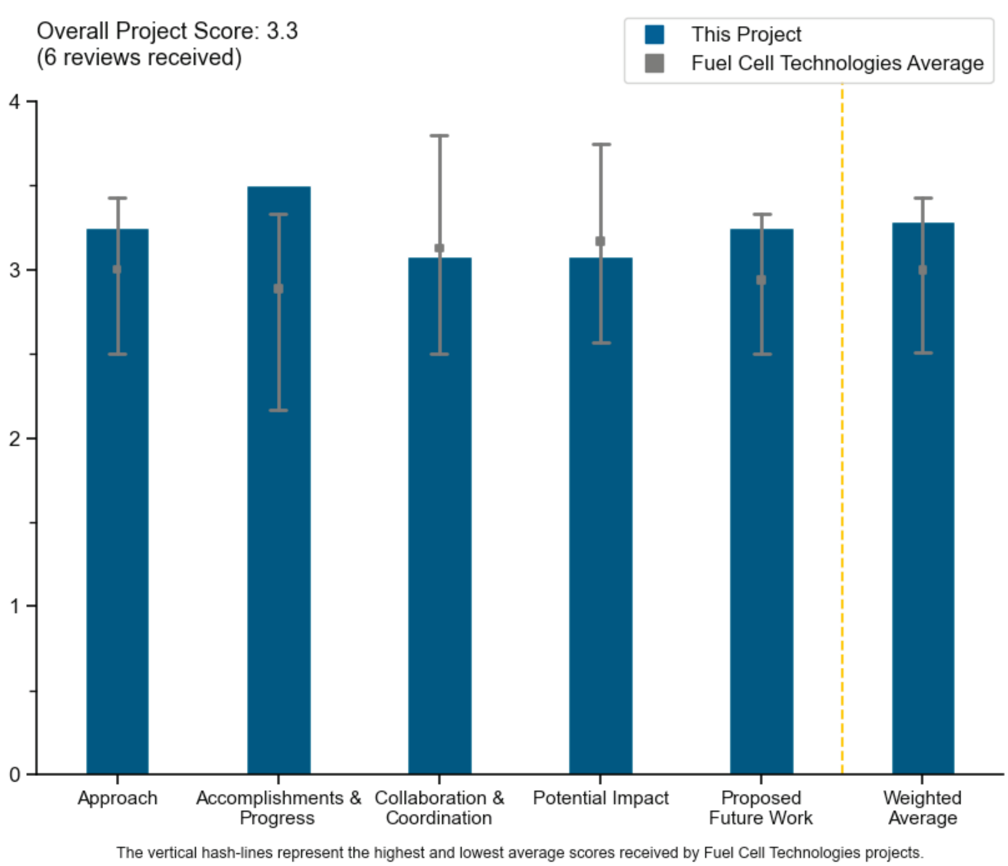
Deborah Myers, Argonne National Laboratory, and Piotr Zelenay, Los Alamos National Laboratory

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 (PEM) fuel cells, 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



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 principal investigators (PIs) continue to use up-to-date methods to pursue delicate tasks in revealing and improving the performance of PGM-free electrocatalysts for the ORR, oxygen evolution reaction (OER), and hydrogen evolution reaction (HER). The work is systematically done in a synchronized manner between the experimental and modeling efforts. A large volume of synthesized materials has been evaluated for activity and durability properties. The research efforts are well balanced between the participants from different national laboratories, with clearly defined roles, deliverables, and achievements. The PIs manage to fully utilize unique expertise and capabilities within the consortia network of national laboratories and perform cutting-edge research on PGM-free materials.
- High-throughput materials design, synthesis, and characterization are employed to execute the projects, which is very good. This approach can greatly accelerate the development of novel catalysts for both fuel cells and electrolysis cells. This is clearly an ambitious effort to develop non-PGM catalysts; however, the end-of-project goals are still substantially lower than the DOE targets. While this is a low-technology-readiness-level (low-TRL) project, it would be useful for the PIs to outline a techno-economic scenario in which these catalysts could be commercially viable. Assuming the best possible technical outcome, clarification is needed on the path to potential cost savings from non-PGM catalysts and whether the technology could potentially be competitive with state-of-the-art PGM catalysts. The team is doing a good job using high-throughput synthesis and machine learning techniques to refine the Fe-N-C catalysts. These approaches, however, seem to be better suited for optimization efforts and may not be suited for developing the type of breakthroughs needed to close the gap with PGM-based catalysts. The increased focus on water electrolysis applications is encouraged, as there seems to be more potential for these catalysts in alkaline exchange membrane (AEM)-based electrolysis.
- There are several PGM-free catalyst synthesis approaches. Identifying the factors limiting the active site concentration and making attempts to improve would be impactful. The use of metal dopants such as bismuth, molybdenum, and tantalum are very interesting and new. The use of electrochemical studies on the impact of sulfonate anion poisoning of the active site is commended.
- The project has a great combination of theory, machine learning, high-throughput screening, testing, and analyses. The improvement in ORR activity that the consortium has been able to demonstrate year over year is amazing. However, the consortium has not mentioned durability targets. If the material is not stable, it will never become practical. All PEM fuel cell work is focused on the Fe-C-N system, but Fe is clearly incompatible with the PEM membrane. Therefore, there is virtually no interest from industry. The shift toward AEMs is good.
- The project team is diverse and strong for the goals of developing PGM-free catalysts for both fuel cell and electrolysis applications. The only critique is that not all the critical barriers to adoption of the materials are being addressed. The truck and electrolyzer lifetime needs are distant from the project goals.
- The use of Fe in the PGM-free catalyst as the active site is not recommended from a membrane durability standpoint. Alternates such as Mn and Co are strongly recommended. Small parts-per-million quantities of Fe have major implications for membrane durability. Even though there are approaches to mitigate Fe dissolution via carbon shell coating, it will be challenging to stop Fe from dissolving completely. More information is needed on the performance targets and how they align with the high-level stack cost targets and cost walk.

Question 2: Accomplishments and progress

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

- Progress and accomplishments are separated and presented by two efforts: PGM-free fuel cell cathode catalysts and PGM-free catalysts for electrolyzers. In both cases, overall accomplishments and progress are featured by quarterly milestone charts, including technical description and data analysis. The progress is justified and compared against the DOE technical targets. Regarding PGM-free ORR catalysts, a total of 12 milestones are listed, with 6 of them completed, 2 partially completed, and 4 on track. Considering the timelines, projected duration, and past legacy of the consortium, the milestone status seems appropriate and is self-explanatory testimony about the most recent progress and associated achievements. Overall, the PIs have presented a compelling track record that builds on previous results and continues to tackle challenging technical targets. The following efforts are distinguished and executed in systematic manner:

- Two-step, two heat-treatment synthesis of the Fe-N-C catalyst was evaluated for improved control of Fe dispersion, morphology, and composition within a nitrogen-doped carbon support. These efforts resulted in 59% and 44% performance improvement at 0.80 V and 0.675 V, and 23% and 15% improvement compared to the Fiscal Year (FY) 2021 and FY 2022 baselines, respectively. The performance was measured in the membrane electrode assembly (MEA) under the same conditions: cathode loading: 4.0 mg/cm^2, 1.0 bar air pressure, 100% relative humidity (RH); anode loading: 0.3 mg_{Pt}/cm^2 Pt/C, H_2, 700 sccm, 1.0 bar hydrogen partial pressure, 100% RH; membrane: Nafion-211; cell: differential; MEA size: 5 cm^2; temperature: 80°C.
- Fuel cell durability performance of the N-C/Fe catalyst after 10,000 cycles also showed improvement in the MEA, under the same or similar conditions to those listed above. Initial activity at 0.80 V was 92 mA/cm^2, while after 10,000 cycles, activity was 45 mA/cm^2, which exceeded the anticipated activity target in FY 2023.
- Novel synthesis methods were used to obtain the hollow structure of Fe-N-C catalysts from tannic acid-etched precursors based on metallic organic frameworks. The hollow structure was particularly targeted for utilization of a porous structure that leads to enhanced catalyst surface area. These structures resulted in improved specific activity measured in the rotating disk electrode (RDE), which is likely due to mesopores in Fe-N-C catalysts.

The high-throughput synthesis of the ORR catalysts is the consortium's main signature, and it brings an impressive display of over 300 different catalysts that have been synthesized and evaluated by various machine learning guided methods, including ball milling, chemical vapor deposition, and pyrolysis.

- The machine learning effort resulted in 14 new samples that were synthesized by the adaptive learning approach, which led to 600% higher ORR activity compared to similar catalysts prepared elsewhere by the same method. Moreover, these efforts exceeded the predicted target from FY 2022 by discovering four new catalysts with 33% higher activity than those in the original dataset.
- Statistical analysis of synthesis conditions was performed, and it revealed the importance of synthesis variables on the activity and demonstrated relevance of the cooling rate.
- High-throughput chemical vapor deposition (CVD) was in particular focus with utilization of the parallel CVD reactors that enabled fast screening of applied conditions. The highest mass activity of 23.1 mA/mg at 0.8 V was reported in RDE, while stability was improved upon addition of a second metal chloride.
- ORR activity of the high-throughput system was evaluated in 26 samples in initial synthesis, with the highest activity for 1.2% Fe + zeolitic imidazolate framework (ZIF)-8 after pyrolysis at 1050°C. Initial and mass activity after five potential cycles were included in the machine learning model, which predicted synthesis conditions to achieve higher ORR activity. Maximum mass activity was 19.3 mA/mg at 0.8 V, measured in RDE, while ten catalysts had no activity loss or improved activity after five potential cycles.
- Visualization of the catalyst was improved through imaging and automated spectroscopy of metal atom sites in a graphene-based two-dimensional model M-N-C catalyst system. Researchers used low-voltage imaging and electron energy loss spectroscopy (EELS) to observe at least ten N-C and ten Fe-N-C sites.
- Density functional theory (DFT) has been used to identify stability descriptors for the PGM-free ORR catalyst. In most cases, corrosion of local C/N facilitates dissolution of transition metal, while increased graphitization promotes stability.
- Effects of anions on the Fe^{3+}/Fe^{2+} redox and ORR were studied, revealing that sulfate or bisulfate suppressed Fe^{3+} reduction, enhanced ORR, and interacted more strongly with the Fe center than perchlorate anions. These findings were explained by modeling with an explicit solvation effect on Fe-redox and ORR activity and were extended toward an ionomer effect. It was found that SO^{3-} binding to Fe is a dominant effect of Nafion in a non-defected catalyst, the only system that can be assessed by modeling.

  - Additional capability of the high-throughput activity evaluation was achieved by a multi-channel flow cell. Its accuracy and reproducibility were verified and compared to RDE. This effort was applied to both fuel cell and electrolyzer catalysts, and it achieved consistency within 5% between the ORR and OER mass activities measured in the flow cell and RDE.

  Regarding PGM-free OER and HER catalysts, there are 13 milestones listed, with 8 of them completed and 5 on track. Considering the timelines, projected duration, and past legacy of the consortium, the milestone status in this portion of the activities also seems appropriate, and it is self-explanatory in regard to the most recent progress and associated achievements. Overall, the PIs have obtained valuable results that continue to tackle challenging technical targets. The following efforts are distinguished and have been executed:

  - Established MEA performance baselines for a PGM-free anode and cathode: Anode-Ni/C/ and Cathode-$NiFe_2O_4$, with current density 1.0 A/cm^2 at 1.811 V (high-frequency-resistance-free).
  - An OER La-Sr-Co oxide catalyst was optimized to improve electronic conductivity and surface area and was compared to a commercial IrO_x catalyst.
  - An NiFe aerogel catalyst was evaluated before and after OER. It was found that the heat-treated catalyst showed structural change; small crystallites before testing were converted to a highly active (oxy)hydroxide layered structure, while no structural change was observed after heat treatment at 500°C, owing to the presence of large, morphologically stable crystallites. Durability of NiFe aerogel exceeded the FY 2023 OER annual milestone. The performance was 1.53 V at 10 mA/cm^{-2} at beginning of test and 0.35 mV/h in a 72-hour test.
  - NiFeC nanostructured OER catalyst underwent a durability evaluation for 72 hours at 10 mA/cm^2 and also met and exceeded the FY 2023 OER annual milestone.
  - OER performance was compared in an alkaline exchange membrane water electrolyzer (AEMWE) and RDE, and it was found that OER activity trends in RDE testing were only partially observed in an AEMWE. Electrode fabrication, activation, and test conditions play a key role in maximizing AEMWE performance of catalysts.
  - Adaptive learning for designing OER electrocatalysts resulted in a matrix with 30 samples for synthesis and characterization in order to build an initial database for developing machine learning models.
  - Atomic-scale models of OER electrocatalysts based on DFT calculations have improved the understanding of complex OER catalyst surfaces. For instance, it was found that the energy for O vacancy formation mechanisms is not energetically unfavorable.
  - HER catalyst development has demonstrated an impact of the synthesis method on activity. It was found that the heat treatment under a reducing atmosphere (5% H_2 in N_2) is a key factor in improving HER activity, which is still 300 mV behind the PGM catalyst.
  - PGM-free catalyst loading at the cathode has a major impact on electrolyzer performance.
  - Anion exchange ionomer degradation evaluations revealed a loss of capacitance during deionized water testing, negatively affecting performance.
  - Capability development was achieved by in situ Mössbauer spectroscopy for OER catalysts, which showed predominance of Fe (III) at all potentials and an increase in particle size with open circuit voltage.

- There is significant progress in developing electrocatalysts for both fuel cells and electrolysis cells. The achieved performance meets the DOE goals.
- The ElectroCat team is making good progress toward the project goals. The performance and durability data shows continuous progress compared to the benchmarks.
- This project appears to be achieving the contract goals and is demonstrating steady improvements.
- The targets are now based on hydrogen–air performance, which is good. Measuring the proton transport resistance in the thick PGM-free catalyst layers and checking its contribution to the overall voltage loss would be useful.
- The improvement in ORR activity that the consortium has been able to demonstrate year over year is amazing. However, hitting the project's activity "target" has little impact if it is not durable.

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 Consortia established an impressive collaboration network between participating national laboratories, academic institutions, and industry partners. Considering the novelty in the approach and fundamental challenges of PGM-free materials, the selection of participants is well balanced and reflects maximal utilization of expertise and resources in highly synergistic manner.
- Multiple DOE national labs, universities, and industries are involved in this project, which is excellent collaboration among institutions. Additionally, the demonstrated achievements validate the collaboration efforts.
- National lab responsibilities are clear from the milestone tables, but in the accomplishment slides, it is not always clear where the work is being done. A note (or logo) in proximity to key technical results would help the viewer understand the roles of each of the national labs and the other collaborators. The work looks to be well coordinated and in line with project goals.
- The project has great collaboration between research institutions. Industry involvement in the work seems to be very light, perhaps because of the lower TRL for the technology. More involvement from fuel cell manufacturers and electrolysis manufacturers could be beneficial.
- National lab collaboration is strong; however, there is virtually no interest from industry or the international community.
- The list of collaborators is good.

Question 4: Potential impact

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

- The outcome efforts can be seen as pioneering work that brings together outstanding resources, world-leading experts, and a cutting-edge approach. The results are greatly benefiting the Hydrogen Program by establishing a number of performance benchmarks, material discovery, and unique resources to tackle utilization of PGM-free catalysts.
- The goals of this project are ambitious and, if successful, could have a large impact on the fuel cell and electrolysis industry. However, the gap between the DOE goals and the potential of this project to meet these goals is quite large.
- The project is in line with the greater DOE objectives. The objectives for durability should be given more attention, particularly a fundamental understanding of degradation mechanisms in PGM-free catalysts.
- The electrolysis performance is good. However, there is room to further improve the efficiency. Its current density at 1.8 V is not state-of-the-art.
- The impact of PGM-free ORR catalysts is not clear. Their performance and durability certainly are not aligned with heavy-duty automotive applications.
- The consortium would benefit from surveying industries' interests.

Question 5: Proposed future work

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

- Adaptive learning is being used to determine which material sets to focus on (and presumably, which material sets are not selected for further development). The future work plan is clear. There is one minor suggestion. The higher RDE performance, yet poorer electrolysis performance, of PGM-free materials compared to IrO_2 was blamed on ionomer interactions. However, KOH-supported AEM cells do not require ionomer, yet the same trend is true. The team should investigate why the PGM-free results do not translate as well as IrO_2 from RDE to electrolyzer.

- Future work is well balanced and constantly builds on the knowledge established by the consortium. The PIs should consider how to bring closer experimental and modeling efforts, considering discrepancy between the two. Modeling effort has fundamental limitations to tackle real-world complex structures beyond ideal model systems. Along those lines, one can argue about the direct applicability of modeling outcomes toward technical targets and deliverables. An obvious outcome on the future work should be the need for additional fundamental studies.
- The future work is well organized and is in line with additional technical advances that are needed to meet the project targets. While this is a catalyst project, it would be useful to address the presence of Fe and the challenges of membrane durability for fuel cells. The rates of peroxide and other reactive species are expected to be different (perhaps lower) than those of PGM systems. Work to address this topic would help reviewers understand the long-term potential of these catalysts.
- The proposed future work is clear and feasible.
- The consortium would benefit from surveying industries' interests (i.e., identify the catalyst system with the largest impact).
- Proposed future work would benefit from an alternative to an Fe active site and efforts to include active site concentrations.

Project strengths:

- The project has done a good job of exploring multiple approaches to synthesizing PGM-free catalysts. The use of four different approaches demonstrates the team is seeking novel ways to achieve the desired structures. The templating approach to maximizing surface area is well described and supported by high-level imaging methods. Machine or adaptive learning techniques are employed to make the most use of the data generated to date and identify the best formulations or methods. DFT modeling to understand the mechanisms of catalyst activity is well presented. The team is well organized and well suited to tackle this challenging area.
- Leading experts in the field are pioneering the executed work. The outcomes from these efforts are already used by others as well-defined standards in terms of performance. The consortium is continually improving all aspects of utilization of PGM-free materials and will have long-lasting effects in the field of electrochemistry.
- The team is strong and is leveraging extensive experience and capabilities from a broad group of collaborators. The project continues to advance the state of the art for PGM-free catalysts and expand our fundamental understanding.
- High-throughput synthesis and characterization methods are employed to develop new electrocatalysts.
- The project has a good collaboration team and leading scientists in the field.
- A project strength is the strong innovation process.

Project weaknesses:

- The Consortia is meeting and exceeding expectations within the well-defined scope of the project. Having technical targets within a field that is not well grounded with a fundamental understanding is a very difficult set of goals to accomplish. The PIs are making outstanding efforts to overcome this and keep bringing new insight into the mechanism of operation for PGM-free materials. Despite many years of diligent focus on these materials, the field is still missing essential answers about the nature of active sites, electrochemically active surface area, and intrinsic catalytic activity. These topics fall into the category of fundamental research. Without a deeper understanding, it would be difficult to expect groundbreaking discoveries in PGM-free materials.
- While this is an ambitious project, discussion of where this catalyst might fit into the larger adoption of fuel cells or electrolyzers would be helpful. These catalysts will be lower-cost than PGMs, but the total system cost would be higher at today's performance (or even the project performance goals). A realistic analysis of the best-case outcome and what that means to the industry as a whole would offer some context.

- The gap in long-term durability between the application requirements and the technologies being developed is the main concern. If that gap cannot easily be bridged with incremental improvements, then improving understanding of the degradation mechanisms is needed.
- A weakness is the research on an irrelevant material set. There is no customer for the technology.
- The impacts and applications are not clear.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- The following additions to the project would be useful:
    - Increase industry involvement, even if that is just project guidance.
    - Investigate degradation mechanisms and potential high-risk–high-reward solutions instead of incremental advances.
    - Investigate why the PGM-free results do not translate as well as IrO_2 from RDE to electrolyzer.
- One suggestion is to address the issues associated with peroxide formation and the impact on the membrane. While recognizing that this is a catalyst project, it is still relevant to understand the role of this type of catalyst on the formation and degradation of peroxide or other reactive species. A non-PGM catalyst for AEM electrolysis should continue to be a focus. This looks to have more potential than the PEM fuel cell case.
- It would be great if some layered double-hydroxide materials could be studied as the OER catalysts for AEM electrocatalysis. For an example, see Park et al., “High-performance anion exchange membrane water electrolyzer enabled by highly active oxygen evolution reaction electrocatalysts: Synergistic effect of doping and heterostructure,” *Applied Catalysis B: Environment* 318, December 5, 2022, https://doi.org/10.1016/j.apcatb.2022.121824.
- Formulating a well-articulated, fundamentally focused research program based on the consortium’s immense legacy is recommended.

Project #FC-317: Stationary Direct Methanol Fuel Cells Using Pure Methanol

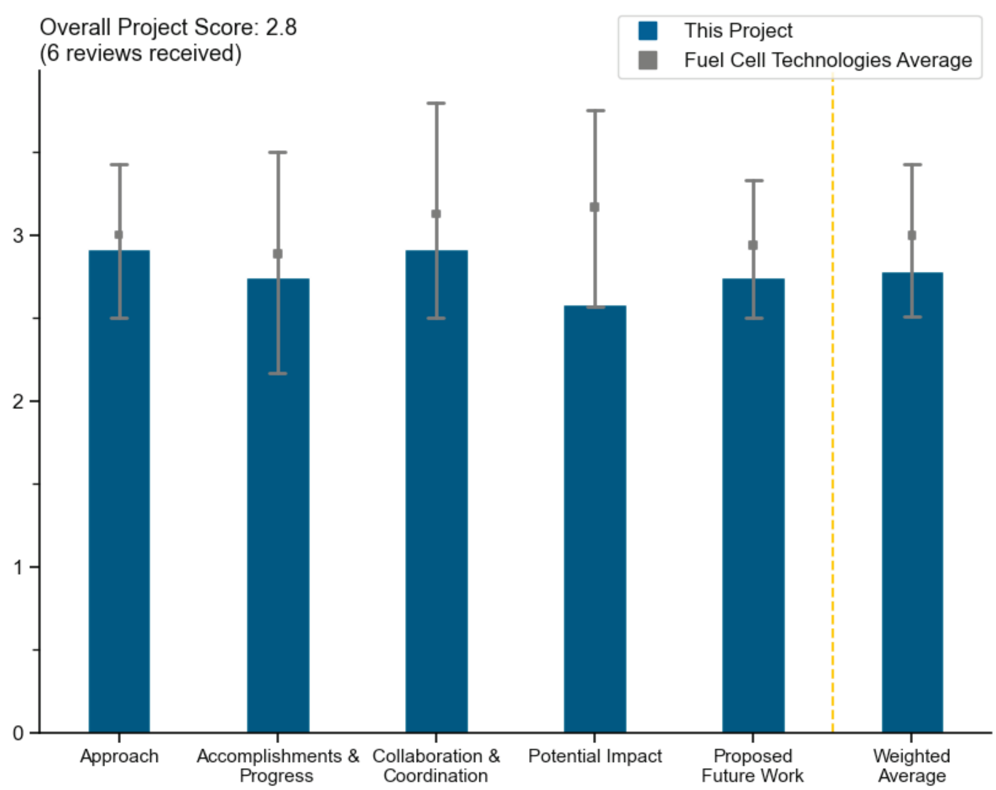
Xianglin Li, University of Kansas

DOE Contract #	DE-EE0008440
Start and End Dates	10/1/2018–3/31/2023
Partners/Collaborators	Kansas State University, University at Buffalo, Carnegie Mellon University
Barriers Addressed	• High platinum group metal (PGM) catalyst loading • Catalyst poisoning by methanol • High fuel crossover

Project Goal and Brief Summary

The project goal is to develop stationary direct methanol fuel cells (DMFCs) using pure methanol as the fuel. The project will address three critical challenges: (1) reduce noble catalyst loading and cost, (2) enhance cathode tolerance of methanol poisoning, and (3) decrease methanol crossover. The end-of-project goal is to deliver a 50 cm^2 membrane electrode assembly (MEA) and prototype that produces peak power density of ≥300 mW/cm^2 with total loading of ≤3 mg_{PGM}/cm^2. The project addresses the barriers of high platinum group metal (PGM) catalyst loading, catalyst poisoning by methanol, and high fuel crossover.

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 to develop stable, PGM-free and methanol-tolerant cathode catalysts and lower the anode PGM catalyst loading is good for lowering fuel cell cost. Methanol crossover and water management are key issues for DMFCs, so working on the electrode structure and hydrophobic layer to minimize methanol crossover and manage water transport are also good approaches. Passive feed and operating with high methanol concentration are good approaches to decrease the size of and simplify the DMFC system and potentially lower system cost. The stability enhancement strategies for PGM-free oxidation reduction reaction (ORR) catalysts are reasonable and appear to be successful approaches.
- The approaches are well planned. The approach includes the importance of determining the impact of operating point on degradation rate in MEAs and performing time-efficient evaluation of degradation acceleration factors on a single MEA.
- The approach is good because the team pursued multiple changes to enable improvements in the relatively poor performance of DMFCs.
- The work shows a good approach to meeting the barriers as identified. Some additional barriers to consider will be mentioned later, but the approach, as designed, is appropriate.
- The approach to use PGM-free cathodes should enable reducing PGM loadings to the target levels and should also help reduce reactions with MeOH that has crossed over to the cathode. The goal of operating on pure MeOH could help improve overall system power density if crossover and cathode poisoning can be reduced. The project used conventional membranes. Including some membrane work directed toward reducing MeOH crossover or some advanced membranes would be beneficial to the project. The impact of MeOH concentration on degradation should be studied. Conditions for the pure MeOH experiments were at lower temperature and lower air pressure than for 1 M MeOH experiments. It is not clear how much performance can be improved with varying conditions. Sensitivity studies using pure MeOH and varying other conditions should be performed.
- The relevance of this project is difficult to understand. Working on durability after reaching the performance targets does not make much practical sense. Some of the critical aspects that have rendered MeOH fuel cells impractical have still not been addressed and are not being addressed in this project.

Question 2: Accomplishments and progress

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

- This excellent researcher has made excellent progress toward the project goals. It is interesting that an MEA with a PGM-free catalyst was better. The project team has achieved the peak power density of 275 mW/cm^2 with no more than 3.0 mg/cm^2 PGM catalyst loading.
- The project goal was to demonstrate an MEA operating on pure MeOH with peak power density of ≥300 mW/cm^2 and total loading of ≤3 mg_{PGM}/cm^2. The project demonstrated good performance on 1 M MeOH, achieving 275 mW/cm^2. However, conditions for achieving 275 mW/cm^2 (on 1 M MeOH) are not normal conditions, and the temperature of 100°C at which this performance was achieved is likely problematic for durability. On pure MeOH, the project appears to have demonstrated only ~50 mW/cm^2, falling far short of the goal. At 0.5 V, near where the power density of 275 mW/cm^2 was observed, heat rejection will be an issue, as ~60% of the energy from the H_2 will be going to producing heat, and the temperature difference between the fuel cell and ambient is much lower than that for a combustion engine. The project demonstrated good performance of the PGM-free cathode and was able to increase current density at 0.5 V with the PGM-free catalyst from ~50 mA/cm^2 in 2019 to over 125 mA/cm^2 in 1 M MeOH in 2023.
- The team did demonstrate DMFCs with high power densities (>0.25 W/cm^2) and relatively modest catalyst loadings (3 mg_{PGM}/cm^2) on 1 M methanol, although this maximum power density was obtained at very low voltage efficiency (approximately 33%). This low efficiency will result in a relatively large amount of fuel required, especially when one includes Coulombic efficiency losses as well (e.g., membrane crossover), which makes both the cost and weight less attractive. Additionally, the decay rates are unacceptable (e.g.,

13% loss in 20 hours), unless most of this decay is recoverable. Unfortunately, performance recovery was not attempted, so it is unknown whether these high decay rates are due to irreversible degradation. It appears that the anode catalysts developed by this team did enable improved kinetic activity, which was the key to enabling their best DMFC performance. It is not clear that the PGM-free catalysts were advantageous, since the performance was lower and the decay rates were still high. The barriers (fuel management layer and water management layer) did enable lower methanol crossover, but the cell voltage performance was substantially reduced.

- The team demonstrated some good technical accomplishments but did not seem to achieve all technical milestones and or the goal (power density + low catalyst loading + high methanol concentration + good durability) as a whole. It would be impactful to have demonstrated 300 mW/cm^2 using neat methanol 3 mg/cm^2 catalyst loading and good durability. For example, the team achieved 275 mW/cm^2 performance with 3 mg/cm^2—but with 1 M methanol, not a higher concentration of methanol. The team has also demonstrated some durability (only 20 hours) at ~175 mA/cm^2 using 1 M MeOH. Regarding DMFC performance using high methanol concentration, the concentration was not very high (~70 mW/cm^2). Stable, high-performing PGM-free ORR catalysts were developed, synthesized, and tested, showing good performance.
- Significant progress has been made to achieve the metrics. That said, the ultimate goal of 300 mW/cm^2 was not quite achieved. The Quarter 12 goal calls out 50 cm^2; however, it was mentioned that most testing was done at 5 cm^2. It is not clear whether the project made and evaluated 50 cm^2 MEAs.
- The performance target of 300 mW/cm^2 has still not been achieved. The 275 mW/cm^2 has been achieved at very impractical conditions for fuel cell operation (<0.3 V). Thermal management of a fuel cell operating under these conditions will be a huge challenge.

Question 3: Collaboration and coordination

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

- The intended contributions of each of the team members are clear. However, it is not clear how much Carnegie Mellon University contributed here, since optimization and characterization of the electrodes was not presented. Slide 19 noted a great addition: collaborations from researchers that were apparently not funded by the project.
- This project had a good team to develop a PGM-free catalyst, characterize electrodes, and manage the water transport issue.
- The project had an excellent team, and it seemed that there was quite good collaboration between the partners.
- The project had excellent collaboration among universities. No national laboratory involvement was noted.
- Coordination within the project was good. Collaboration with fuel cell companies was lacking. Collaboration with membrane companies or universities working on membranes would have been beneficial.
- The project needed to have an original equipment manufacturer onboard as a consulting entity on what is practical and what is not with some of the approaches being studied.

Question 4: Potential impact

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

- Because MeOH has a higher density than H_2, DMFCs could provide higher total system specific power and power density than H_2 proton exchange membrane fuel cells (PEMFCs) if DMFC power densities can be improved. If there is carbon-neutral methanol available, this could provide a path for decarbonizing energy-intensive applications.
- Unfortunately, the stated impact of the project is not well aligned with the focus of this project; it is not really clear why DMFCs are attractive for “forklift and stationary power applications” (Slide 2) or how this project will help to enable these applications. Nevertheless, DMFCs can potentially be used in a variety of

applications, if the performance and cost are substantially improved. DMFCs are not a major focus of the Hydrogen Program (the Program), which is understandable since substantial improvements to this technology are probably required in order to make DMFCs commercially viable for anything other than some niche applications. However, the Program should continue to invest a small amount of its funding into fuels for PEMFCs other than hydrogen since this gaseous fuel is not ideal.

- The potential impact of a technology (stationary DMFCs using pure methanol as the fuel) powered by methanol and emitting CO_2 is nebulous and inconsistent with the worldwide direction toward hydrogen and zero-emission goals. It is uncertain whether the project should continue to be pursued other than as a curiosity or as a U.S. Department of Defense application. DOE has driven three or four fuel cell technologies to market. The cost of developing a technology to the demonstration stage has taken at least $1 billion per technology and decades per technology. Developing to market such a technology (stationary DMFCs using pure methanol as the fuel) will take a billion dollars and decade(s).
- While DMFC certainly has its place, how DMFC improvements fit into the Program's long-term goals could have been better discussed. From the technology transfer activities, it appears that a quite small application has been targeted. It is unclear what would have to improve to increase the application of DMFC toward broader applications.
- The peak power density goal and catalyst loading goals do not seem impactful, as these targets have been achieved by others in the DMFC field.
- The impact of MeOH fuel cells is difficult to comprehend without any information on durability.

Question 5: Proposed future work

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

- Future work was proposed. However, the project is complete at this time.
- The project has ended.
- The project is completed.
- The comparison of the MeOH fuel cells being developed under this work with battery drones was confusing. It was not clear what the application of the fuel cells developed here will ultimately be.

Project strengths:

- Overall, the project did a good job of outlining the current limitations of DMFC and working to directly attack the most significant hurdles that the industry faces. Significant progress was made as compared to literature data toward the project goals.
- The researcher is an excellent, knowledgeable, and open researcher, fully expert in all the details of the project.
- The project team and approach are strengths. Some good technical accomplishments were achieved.
- The project had a good team that utilized key capabilities from multiple institutions.
- Non-PGM catalyst work was a strength.
- Catalyst fundamentals were a strength.

Project weaknesses:

- While methanol poisoning was discussed at length, it was not clear if there was a concern of CO intermediate poisoning on the anode. Some work has been published investigating additional ternary allows that could allow for further mitigation. With regard to the membrane, it was unclear whether the project investigated O_2 permeability due to the very high differential pressure favoring the cathode. Additionally, it was unclear whether fuel crossover had been studied as a function of thickness of the membrane. That would be a way to improve fuel efficiency. Seemingly, the project did not identify the degradation mechanism, given that the degradation rates are quite high (1–2 mV/hr vs. µV/hr expectations for other fuel cell types). It should be clarified whether degradation is simply catalyst poisoning (whether MeOH or CO) or whether other things contributed to membrane degradation and thinning, which can cause cascading crossover effects. Finally, for the modeling work, limiting current, crossover current, and high frequency resistance were called out as fitted values. Since it appears that, to some extent, experimental data for those values does exist, perhaps a study should be conducted on whether their incorporation (i.e., fitting fewer other values) improves the quality of the modeling.

- The principal investigator should not use the title “Technology Transfer Activities” for work that does not actually involve any direct interactions with other institutions. Simply presenting that DMFCs may be an option worth consideration in unmanned aerial vehicle applications is not at all “tech transfer.”
- Methanol crossover remains a great problem. The cathode is made less reactive to eliminate the reaction there.
- The work being conducted is impractical from an application perspective.
- The project did not seem to have reached its budget period (BP) 2 or BP 3 goals.
- Performance under pure MeOH was low.

Recommendations for additions/deletions to project scope:

- The Program should consider investing in liquid fuel options that have not received much attention to date but have the potential to be more viable than methanol. One option is aqueous rechargeable liquids that can be reversibly hydrogenated and dehydrogenated electrochemically, which is a much broader class than conventional liquid organic hydrogen carriers. More on this topic can be found in M. L. Perry, “Electrochemically-Rechargeable Liquids in Highly Flexible Energy Storage Systems,” *ECS Transactions* 104 (2021), DOI 10.1149/10401.0023ecst.
- Effort should be spent on validating application potential and durability.
- If the project continues, national laboratory involvement should be increased.
- Membrane work should be incorporated in any future work.
- There are no recommendations. The project has been completed.
- Recommendations are not relevant because the project has ended.

Project #FC-323: Durable Fuel Cell Membrane Electrode Assembly through Immobilization of Catalyst Particle and Membrane Chemical Stabilizer

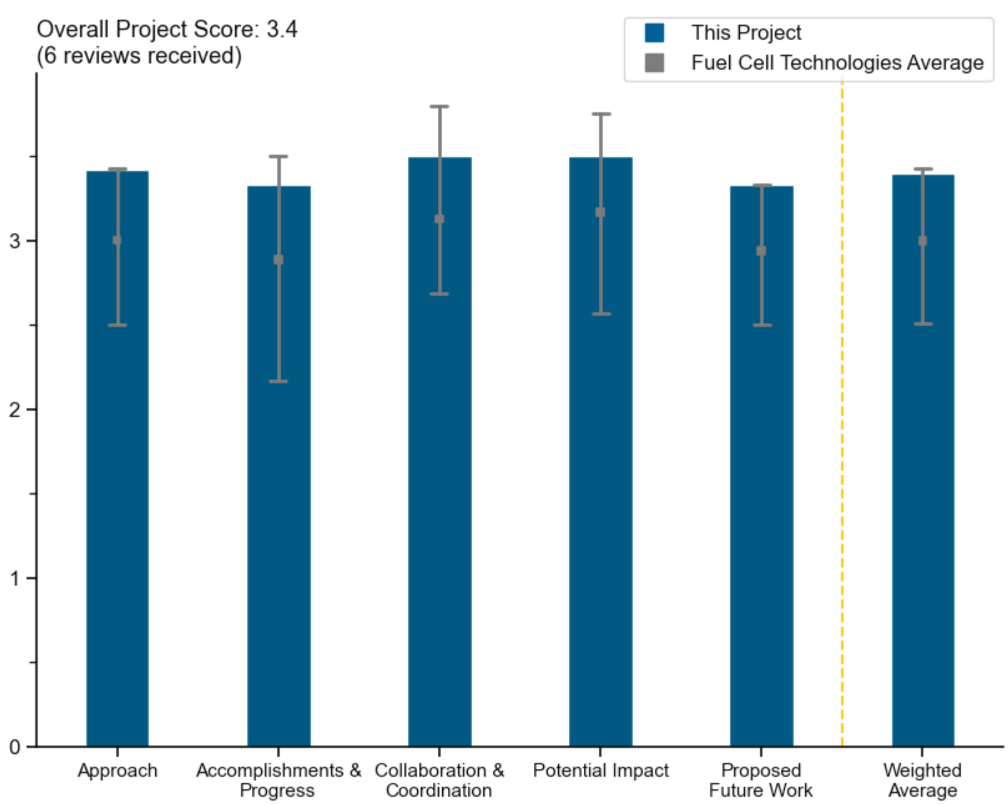
Nagappan Ramaswamy, General Motors, LLC

DOE Contract #	DE-EE0008821
Start and End Dates	10/1/2019–5/31/2023
Partners/Collaborators	3M Company, Pajarito Powder LLC, Colorado School of Mines, Cornell University, M2FCT Consortium
Barriers Addressed	• Durability: <10% power degradation after 30,000 hours • Cost: ≤0.2 mg_{Pt}/cm^2 cathode Pt metal loading • Efficiency: >65% efficiency to decrease fuel cost

Project Goal and Brief Summary

This project aims to develop highly stable catalysts and more durable membrane materials for use in direct hydrogen-fed proton exchange membrane fuel cell (PEMFC) membrane electrode assemblies (MEAs) in medium-duty and heavy-duty truck applications. The materials will feature low cost (using less platinum group metal), high fuel efficiency (greater than 65%), and high durability (lifetime of one million miles). If successful, this project will deliver highly durable MEAs for PEMFC applications to enable use in heavy-duty trucks and will elucidate the fundamental degradation mechanisms.

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 is delivering durable MEAs based on improved anchoring of Pt on carbon support and Pt–ionomer modifications, including doping of the ionomer with heteropoly compounds and cerium. The project tasks are executed in a synchronized manner between the participants. Focus has been placed on improved durability for heavy-duty applications. The research efforts are well defined between the participants, including the deliverables and achievements. The project is also relying on the Million Mile Fuel Cell Truck (M2FCT) infrastructure to utilize unique expertise and capabilities within the consortia. Based on the timeline, recent achievements, and the fact that this will be the final year of the project, the approach in this effort is well justified.
- The scope and approach were focused on very relevant challenges facing broader PEMFC commercialization (stabilizing the Pt catalyst and maintaining membrane lifetime). To speed up progress on meeting these objectives, it is recommended that all DOE projects clearly identify gaps for each review period in a self-review and address these gaps in their paths forward. Regarding Pt stabilization, the approach is consistent with other work in the field, and the project demonstrated good execution, as highlighted by the spectroscopy. It was unclear whether the improved mass activity and power density at end of test was due to the Zr treatment or the mesoporous catalyst as compared to the high-surface-area carbon (HSAC) baseline. Further, based on the Pt utilization, a de-rate at lower relative humidity (RH) is expected. It is unclear how this will impact larger-scale, system-level testing and whether there will be a gap in the approach moving forward. Regarding membrane stabilization, with the goal of mitigating cerium (Ce) migration in the MEA, it was unclear how this compares to a standard powder material. The x-ray fluorescence (XRF) mapping clearly showed dissolution for both the heteropoly-acid–tungsten (HPA-W) and Ce nanofibers. It is unclear whether this was better or worse than current commercial solutions—and by how much. It would have been good to include an antioxidant baseline in the analysis and compare dissolution/migration rates throughout the testing and perform a cost–benefit analysis of these materials moving forward. The $CeNO_3$ clearly met the membrane durability targets, so it is unclear why this was not used in the Ce migration study. Further, feedback from 2021 asked if both membrane concepts could be combined, and the response was no, because they were both addressing the same problem. Given the current results showing a difference between the HPA vs. mechanical ceria-zirconia (CZO), perhaps both approaches could be effective for both chemical and mechanical mechanisms.
- Since both membrane and catalyst advances are necessary to achieve M2FCT targets for MEA durability, the proposed approach of parallel catalyst and membrane development is logical. It is not clear why the catalyst mass activity goal is only 30,000 cycles (instead of 90,000), and the platinum loading target (0.25 mg/cm^2) is much lower than what M2FCT is targeting. The 30,000 cycles is less challenging, while the loading is unnecessarily more challenging.
- The approach is excellent, with a carefully considered plan that is sharply focused on the most critical aspects of MEA performance and durability.
- The project approach is excellent and is directed at addressing the key heavy-duty fuel cell barriers of electrocatalyst durability and membrane durability.
- The approach is relevant from a scientific and industrial point of view.

Question 2: Accomplishments and progress

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

- The project has made good progress toward achieving project and DOE goals, specifically toward the catalyst. The ZrO_2-stabilized Pt on engineered carbon supports (ECSs) resulted in significantly improved performance and modestly improved durability after 90,000 cycles (slide 9). Per slide 9, a key challenge with the ECSs is reduced Pt utilization at low RH, potentially due to the presence of Pt within the pores of carbon with limited ionomer access. The membrane development approaches appeared to make progress in some areas but had shortfalls in others—e.g., the perfluorosulfonic acid (PFSA)+HPA blends showed improved open-circuit voltage (OCV) chemical durability, but the approaches did not appear to improve the durability over baseline under the combined chemical–mechanical test.

- Regarding Pt stabilization, good progress was made on targets (mass activity, power density per gram of platinum group metal); however, the area power density target was not achieved, and the percent mass activity loss was on the edge. It would be good to provide confidence bars on this metric. There was also some conflicting data on the Pt dissolution compared to baseline. The inductively coupled plasma mass spectrometry (ICP-MS) (slide 10) showed no difference in Pt dissolution; however, the particle size distribution showed a distinct difference in the Zr-treated sample. The presentation mentioned some anomalies in the Pt mass balance. It is recommended that the researchers look at Pt in the membrane to understand the difference between the treated and untreated catalyst. Another oddity was the corrosion conclusion in which the Zr treatment had greater carbon loss signal; however, the Pt utilization vs. RH trend remained unchanged. It would be expected that as you oxidize the carbon surface, you will activate Pt in the interior of pores, increase water sorption, and increase Pt utilization, as shown in the HSAC baseline sample. This did not occur in the Zr-treated sample. The presenter did not say whether there were any other clear corrosion signals. Further clarification of this behavior is required. Regarding membrane stabilization, the HPA exceeded the chemical stability goal and failed the mechanical durability; however, the summary table did not show clearly whether the CZO met the >500 hr target. It is not clear whether either of these were better than the $CeNO_3$ baseline shown in the summary chart on slide 4.
- The project accomplished technology advances both for catalysts and membranes that are relevant to heavy-duty fuel cells. The technologies clearly improve upon the project's baseline materials. It is not clear whether the technologies will meet the new M2FCT AST targets.
- The project is practically ended, with excellent accomplishments.
- Overall progress and accomplishments in this project have been excellent. Minor criticisms are that the "Pt–ionomer interface modification" approach was not discussed, aside from a brief mention that the approach had not been successful, and that no work on improving efficiency was reported. (The response to reviewer comments indicates that "our ultimate focus is to deliver an o-PtCo catalyst," but the project is essentially over, and no work on PtCo was reported in this presentation.)
- The project made incremental improvements in MEA performance. Most of the milestones associated with the go/no-go decision-making points are completed. The remaining efforts are dedicated to MEA optimization based on achieved strategies to improve durability. The project made progress by introduction of ECSs. The Pt-carbon interface was modified by including zirconium in the carbon support to better anchor Pt particles while maintaining high porosity and graphitization of carbon. Pt/ECS-ZrO_2 showed improvement in mass activity due to increased Pt content inside the pores, which leads to improved voltage at low current densities. The same catalyst exhibits improvement in electrochemical surface area and cell voltage at high current densities. Structural characterizations confirm homogeneous dispersion of the Zr that surrounds Pt particles. In addition, the effort focused on the membrane blended with HPA showed some loss in conductivity and difference in the hydrogen–air polarization curve during MEA testing. The PFSA-PFSA/HPA blended membrane exhibited improved durability, even with increased crystallinity, due to expanded polytetrafluoroethylene (e-PTFE) reinforcement, and 10 wt.% HPA blended membranes had higher water uptake due to the synergistic effect of sulfonic acid and HPA. The reinforcement by e-PFSA improved the mechanical property, and hence, the tensile strength was increased by a factor of two. Lastly, the CZO nanofiber additive showed improved chemical durability both in OCV durability and combined chemical–mechanical durability evaluations. Overall, the progress and accomplishments do show certain improvements. Nevertheless, the presentation and work performed fall into trial-and-error types of activities, with an obvious lack of systematic investigation. It seems that many different additives were evaluated, but it would be challenging to select what the real progress was in the design of MEAs.

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.

- This project has a well-defined network of collaborators and participants, including connection with the M2FCT and national laboratories. The selection of participants is well balanced, and the roles of participants are clearly identified.

- There was very clear collaboration and coordination between project partners and the M2FCT. The only recommendation to bring further coordination would be to include a gaps table with input from all parties, including from M2FCT. Discussion on the perceived technology readiness levels (TRLs) for each concept would be beneficial moving forward.
- The collaboration and coordination within the project appear appropriate. The collaboration appears largely in two groups: (1) the catalyst group and (2) ionomer groups. (They did not appear to overlap, which is likely appropriate.) It was somewhat unclear which partners conducted which specific parts of the work, e.g., slides 9 and 10.
- The project showed excellent collaboration between General Motors (GM), 3M, and Pajarito Powder. Two universities were also involved, but the impacts of their contributions were not highlighted as strongly in the presentation materials. For example, it was not clear whether Colorado School of Mines developed any of the membranes.
- This is a highly collaborative project, both within the project team and with M2FCT.
- The project was well coordinated with the M2FCT consortium.

Question 4: Potential impact

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

- The project targets are very well aligned with the Hydrogen Program. The progress made in this project provides potential solutions for further development and necessary understanding to drive broader commercialization. It is imperative that the challenges and gaps are overcome and evaluated as soon as possible in stack/system-level testing to determine the broader impact on the industry.
- The potential impact of improved MEA performance and durability through improved catalysts and membranes developed in this project cannot be overstated.
- The outcome from the project is beneficial to identifying the level of improvement in MEAs by different approaches used in the project. The project cannot be seen as highly innovative; however, the team's strong technical background comes with a substantial level of confidence that each task is properly evaluated. The project is expected to have a modest impact in terms of novelty but might have a compelling technical footprint.
- The project has demonstrated good advances toward development of ZrO_2 stabilized catalysts with high gas accessibility via engineered carbon. It is suspected that these approaches can be integrated with more advanced catalysts than pure Pt, enabling further improvements in performance/activity. However, the key gap with this approach that appears to remain is poor catalyst utilization at low RH, which may be intrinsic to the "catalyst buried within carbon pores" approach.
- The project is targeting the critical areas needed for successful implementation of fuel cells in heavy-duty vehicles.
- The project results will have an impact on the integration of domestically manufactured electrocatalysts into fuel cell systems of U.S.-based car manufacturers.

Question 5: Proposed future work

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

- The project end date was May 31, 2023, with remaining work focused on documentation and publications. Future work is to be done internally at project partner organizations.
- This is the last year of the project, and the listed set of activities is in line with the future work that should emphasize the final outcome through publication and presentations, deliverables, and scale-up of materials developed in this project.
- Given that the project is essentially over, there is not much future work, but some more discussion of overall next steps for the technology would have been helpful.

- The project only has one month remaining, so work is focused on product dissemination.
- The project has ended.

Project strengths:

- This project is executed by the leaders in commercialization of fuel cell technology. A well-balanced selection of topics presents a compelling and properly diversified strategy to tackle durability issues in fuel cells. Engagement of several industry partners warrants a highly technical and executive approach in addressing each task. Developed materials and strategies to mitigate degradation in MEAs could be applied immediately in MEA manufacturing, which would facilitate deployment of heavy-duty vehicles.
- The project was focused on two very important technical challenges for broader PEMFC commercialization. Progress was made with improved end-of-test catalyst performance and potential solutions for enhanced membrane lifetimes. Further, the project collaborators appeared to be well coordinated, with all contributing to the success of the project. A clear path forward for these materials was identified for development in GM's internal programs.
- The project consists of a strong team with excellent material and characterization capabilities. Led by GM, the project is aligned tightly to key gaps for commercial heavy-duty fuel cells.
- The project brings together an excellent team to tackle some of the most critical challenges in MEA design for heavy-duty vehicle applications.
- The project is targeting the critical areas needed for successful implementation of fuel cells in heavy-duty vehicles and has a good team of collaborators.
- The project has ended and achieved all milestones and go/no-go design points.

Project weaknesses:

- Identifying gaps would be beneficial to better understand the remaining challenges with a broader view on (1) how system operating conditions might affect the performance of these concepts (e.g., low utilization of ECS catalysts under dry conditions) and (2) whether these concepts clearly outperform incumbent technology (e.g., whether the CZO slows down Ce migration compared to the CeNO3 incumbent). It would also be beneficial to discuss the perceived TRLs for each concept, with commentary on the manufacturability of each concept compared to incumbent baseline technologies.
- The weaknesses are reflected in the lack of a systematic, rationally based strategy to select materials and explore their properties in a novel fashion. Instead, the project appears to be a trial-and-error type of effort that utilizes already known concepts. Most of the MEA durability tests were done for 30,000 cycles. Considering the well-connected research infrastructure between the project and M2FCT, identical MEA testing protocols for heavy-duty vehicles would be expected, but this was not the case.
- It is not clear whether the technologies developed will meet the M2FCT targets, and the project has insufficient time for further development.
- More focus on increased efficiency would be appropriate.
- The stabilized additive approaches were not able to achieve the targets.

Recommendations for additions/deletions to project scope:

- Although the project has limited time remaining, MEA samples could be provided to M2FCT for benchmarking versus the state of the art.
- The project is in the final stages, and therefore, any recommendations for deletion or addition to the research scope would not be constructive.
- The project is ending and in the wrap-up phase.

Project #FC-326: Durable Membrane Electrode Assemblies for Heavy-Duty Fuel Cell Electric Trucks

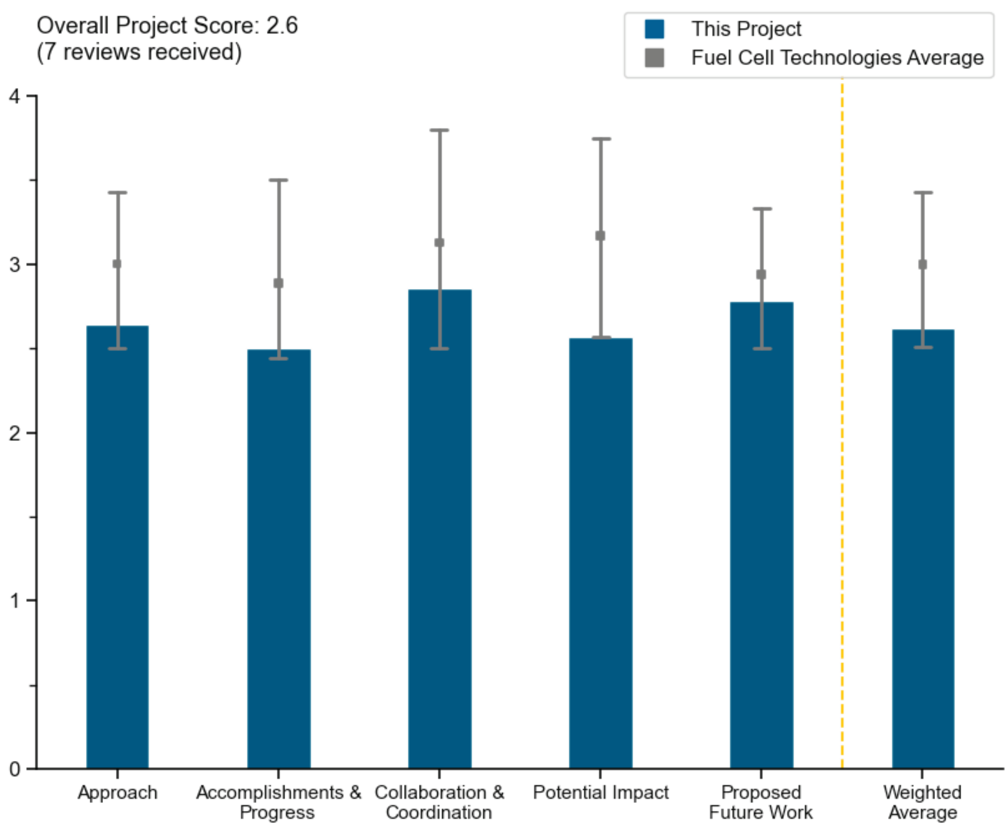
John Slack, Nikola Motor Company

DOE Contract #	DE-EE0008820
Start and End Dates	10/1/2020–12/31/2024
Partners/Collaborators	Carnegie Mellon University, Million Mile Fuel Cell Truck (M2FCT)
Barriers Addressed	• Durability: Improve stability of membrane electrode assembly for heavy-duty-truck-relevant operating conditions • Performance: Increase catalyst while reducing ionomer poisoning effects to achieve high power density and higher efficiency • Cost: Enable reduction in platinum-group-metal catalyst loading and improve ionomer utilization

Project Goal and Brief Summary

This project will fabricate, characterize, and evaluate a membrane electrode assembly (MEA) with a novel catalyst layer incorporating a "nanocapsule" electrode structure that separates ionomer and platinum to maximize activity while allowing ionic transport. If successful, this project will produce highly active and durable catalysts.

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

- This is an innovative concept, and this project is well-designed, with a combination of experimental and modeling approaches. A good microscale model of this unique catalyst layer can enable insights into what is limiting the performance. If the modeling work is good, then this project has the potential to improve the community's understanding of proton exchange membrane catalyst layers (which should be a major goal of this project, in addition to striving to develop an improved catalyst layer architecture).
- The project goal is very relevant for proton exchange membrane fuel cell (PEMFC) heavy-duty (HD) development, where reducing local oxygen transport resistance (RO_2) will help meet cost and durability requirements. The approach to this problem is novel and has clearly demonstrated reduction in both the dependent and independent RO_2. However, this nanocapsule concept raises risks that may have impacts on broader adoption. Now that the team has been able to work through some key processing challenges, it is recommended that the project address the following risks to the overall approach:
  - The length scales for proton transport in water through the interior of the agglomerate are long, and it would be good to validate the total catalyst layer proton resistance as a function of relative humidity (RH) and compare to the model results presented. In addition, more operating condition sensitivities should be performed to understand whether any other limitations are being introduced. There is concern that lower RH performance will contribute to a lost proton path. It would be good to build on the work presented, as the performance data was quite noisy and had significant performance loss at higher current densities. Comparisons should be made to conventional structures and processes.
  - With such large (1 µm) particles, there may be layer uniformity issues that would introduce noise (as observed in the polarizations on slide 11) and potential issues at larger scale. Layer uniformity can also affect membrane degradation behavior and introduce early membrane failures. It would be good to show scanning electron microscopy (SEM) cross sections to better understand these risks.
- The project focus is on developing a novel cathode catalyst layer architecture based on "nanocapsules" that have a high ionomer–carbon (I/C) exterior and low I/C interior. This approach seems to have reasonable expected advantages for catalyst activity and O_2 diffusion, which would improve the efficiency of and performance of fuel cells for HD applications. It is not clear how this structure is expected to address fuel cell durability, and the project portions focused on catalyst development seem to have been downselected out. The nanocapsule approach seems to have significant potential risks or drawbacks related to manufacturability and cell integration, and overall, the approach seems to be a fairly narrow focus for a project of this size. There is a lack of work comparing the novel electrode architecture to conventional electrodes.
- The project approach is to develop a novel electrode structure based on a nanocapsule approach, consisting of a core catalyst with minimal ionomer content surrounded by a coating of ionomer. While conceptually interesting, it is really unclear whether this could ever be manufactured on a mass scale. (It is unclear what an "emitter"-based process at scale would look like.) Additionally, it is unclear whether there will be issues with ionic conductivity/catalyst utilization within the low-ionomer cores at low RH, a critical requirement. (All data presented was at 100% RH.)
- The project aims to improve Pt utilization and activity via limiting ionomer poisoning and improving mass transport of reactants to the catalyst surface. The proposed "ideal" catalyst layer architecture (and associated modeling) supports benefits of an ionomer-rich shell and carbon-rich core but is completely reliant on synthesizing said architecture. Relevant parameters to optimize have been clearly identified, but possible synthesis barriers did not appear to be identified prior to beginning work. It is unclear whether the electrospray process is scalable to ensure throughput and quality.
- The core shell concept is not defined clearly. Slide 7 does not make clear what the role of polyvinylpyrrolidone (PVP) in the nanocapsule is or what the emulsion is. It is not clear how feasible the electrospray approach is for mass production.

- While goals and milestones were listed, they were not described as explicitly as expected. It seems like there have been significant roadblocks that were not explained in the presentation. The whole year's work seemed to be targeted only at addressing the comments from the previous year's review, instead of also making new progress toward a durability result.

Question 2: Accomplishments and progress

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

- Significant progress has been achieved on making catalyst layers with a novel architecture. It appears the team can now make nanocapsules with a variety of diameters, which could enable a wide variety of catalyst layer parameters. Exploring these parameters could lead to insights into the source of overpotential losses in these catalyst layers, especially if a validated model is developed. It is not clear how well the model fits the data or whether the modeling work is being used to direct what types of catalyst layers should be fabricated.
- Reasonable performance has been demonstrated with the nanocapsule electrodes so far, although without clear comparisons to conventional electrodes, it is not so clear what has been achieved. The principal investigator indicated that, so far, the uniformity of the nanocapsule catalyst layers was not good enough to enable clear comparison, but this is not a compelling reason not to present baseline comparisons. The catalyst down-selection was based on the supposed superior durability of the selected catalyst, although this is also somewhat unclear. The H_2/air performance of all three catalysts appears similar after the accelerated stress test (AST), and the selected catalyst performs significantly worse at beginning of test. It is not clear that the selected catalyst will give either longer life or better lifetime-averaged performance, given the presented data. Longer durability testing may be required to show a better end-of-test performance for the preferred catalyst. Recent results show an improvement in nanocapsule aggregate diameter, although it is not entirely clear that the single data point shown is not an outlier and that the process control required to get the needed uniform small aggregates has been achieved.
- The team demonstrated a clear impact on the sulfonate coverage and RO_2; however, it was not clear whether this benefited the performance and durability. It would be good to do both a performance and Pt dissolution durability comparison against a baseline with the same composition with standard processing. It would be expected that this concept may also have benefits on the Pt agglomeration rates and Pt transport into the membrane. Good progress has been made overcoming the major roadblocks (e.g., particle size). It would be good if this could be done even further and show the impact on layer uniformity. It would be good to determine whether there is a tradeoff between the particle size, layer uniformity, sulfonate coverage, and dependent/independent RO_2. It is not clear whether a dependence of the achievable particle size on the choice of catalyst and ionomer is expected.
- Overall, modest progress has been made. A limited set of durability tests was completed, additional modeling was done, and a good effort to decrease the nanocapsule agglomerate size appears to have occurred.
- Durability is in the title of the presentation, but the only mention of the actual durability of the catalyst was a brief mention of supplier AST tests. The only major accomplishment seemed to be an improvement of the catalyst layer production. There was also a good deal of comparison between the new catalyst fabrication method and the old, but there was no comparison to current state-of-the-art traditional catalysts. While the novel method and base science are very interesting, it would have been good to see more substantive comparison.
- The project has identified MEA components to be used in the project. It is unclear what rationale was used to determine optimum ionomer, membrane, and carbon support. The catalyst was chosen based on polarization performance after ASTs. The Supplier 3 catalyst had the lowest electrochemical surface area and voltage loss at 0.8 A/cm^2. Durability tests were not performed with the proposed catalyst layer architecture. No information about Supplier 3 and Supplier 2 catalyst composition was provided (Pt vs. PtCo or another Pt alloy). The primary accomplishment was achieving proper synthesis of catalyst particle nanocapsule sizes while preventing them from aggregating. Synthesis of ideal nanocapsules took 15 months and still needs to be optimized to ensure proper electrochemical performance and durability.

- The team has tested three catalysts in single-cell and short-stack. There is no mention of the number of cells/short stacks that were tested to obtain reproducible results. The mass activity loss for all the catalysts is much higher than the target <25%.

Question 3: Collaboration and coordination

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

- It is unfortunate that the novel catalysts from Georgia Tech and Northeastern University did not work out, but this is understandable. It is probably preferable to limit the catalysts here to more conventional materials, since there are plenty of parameters to explore here (i.e., the original project may have been overly ambitious and complex). The coordination with Carnegie Mellon University (CMU) seems good, but it is not clear that CMU's model has been validated or whether it is being used to guide the experimental work. The recent engagements with the Million Mile Fuel Cell Truck (M2FCT) consortium are good and should yield improved understanding of the catalyst layers being made here, and microscopy characterization can provide useful input to the catalyst layer model.
- There is good coordination with CMU and the National Renewable Energy Laboratory (NREL), both of which had a clear impact on demonstrating the project goals through modeling and characterization. The role of Georgia Tech and Northeastern University was unclear, given the evaluation and down-selection of commercial supplier catalysts; however, perhaps this was highlighted in past reviews.
- Nikola Motor Company (Nikola) is sending samples to national labs (the M2FCT consortium) for characterization and testing. Previously proposed collaborators were removed because of changes in scope of work. A majority of work seems to be performed within Nikola.
- In most slides, it is difficult to determine which members of the project team contributed. It appears that NREL has conducted some diagnostic measurements (sulfonate coverage) and CMU conducted some plasma-focused ion beam analysis of electrodes. Better leveraging of the great capabilities at the national labs and CMU would likely greatly accelerate progress.
- Roles for project partners were not presented clearly. It seems that CMU is providing characterization and modeling, while M2FCT is providing some characterization and diagnostics. This should be indicated more clearly in the future.
- The team has established collaborations with academic institutions and the M2FCT consortium. However, the role of academic institutions is not clear.
- There was some good explanation throughout the presentation of collaboration.

Question 4: Potential impact

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

- Novel PEMFC catalyst layer architectures are a worthwhile investment for DOE, since the majority of PEMFC work to date has been mostly simple variants of Los Alamos National Laboratory's 1989 PEMFC technology. This project can enhance the community's understanding of PEMFC catalyst layers, as well as having the potential to develop a PEMFC that has improved performance and/or durability.
- The potential impact of this project is high and will depend on the ability to mitigate risks and close any other gaps that exist to scale this technology to commercial levels. To this end, the team should highlight its views on technology readiness level and all key challenges and gaps to commercialization. Significant work is required to clearly show the performance and durability benefits and achieve the scaling-up milestone.
- The project will have an impact on materials advancement after successful testing of multiple larger-area single cells and short stacks.
- The nanocapsule technology has a reasonably clear route to improve fuel cell performance and efficiency, which would be useful for addressing the goals of the DOE Hydrogen Program. However, it is not clear how this approach addresses the durability needs of HD applications, which are a key consideration. Also, the nanocapsule structure does not seem conceptually ideal for a catalyst layer, and it would be good to see

comparisons to more different architectures. It is not clear how amenable the electrospray process is to mass manufacturing of catalyst layers in comparison to other processes.

- Modeling efforts at Nikola predict improved polarization performance at every point along the polarization curve vs. a "conventional" catalyst layer architecture. However, no experimental observations support this claim at this time, owing to the time needed to optimize nanocapsule synthesis. In addition, no ASTs have been performed to determine how durable the nanocapsule architecture is vs. a more conventional catalyst layer architecture.
- The system has potential, but without some durability testing or cycling data, it is hard to see how much of a realistic impact the technology would have. While the improvements to mass transport at beginning of life are good, it needs to be shown that those benefits are maintained over full useful life.
- The project is aiming at a key barrier: better utilization of catalyst for HD fuel cells. However, the approach has some real challenges, and progress appears to have been quite slow.

Question 5: Proposed future work

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

- The proposed future work appears appropriate.
- All activities identified in the path forward are clear and will help drive the concept further; however, presentation of key gaps and risk strategy would be desirable. With the project over 50% complete, it is underspending, and it is unclear whether the project will be able to achieve its goal to scale MEA production when there is considerable optimization remaining to clearly demonstrate improved performance and durability on top of the processing challenges that come with scaling up.
- Proposed future work seems reasonable overall but somewhat vague; it mostly seems to just be a continuation of current activities rather than a clear next stage. This will reasonably result in improvements to the MEA, but it would be good to see some expansion of the planned work.
- Proposed work is valuable in optimizing nanocapsule catalyst design, but based on the information provided, it is not clear that the work will yield valuable results in a reasonable timeframe. Possible barriers to further changing synthesis and the scaling-up process for large-scale MEA fabrication have not been proposed.
- The proposed future work is good, but it would be even better if the modeling work was used to guide the fabrication work, which does not appear to be the current plan. This will require a validated model in which the team has a high level of confidence, which may be challenging to develop but could substantially improve the effectiveness of the development process.
- It would have been good to see more detail in the test plans for evaluating durability. Most of the focus still seems to be on catalyst production development.
- The team has several tasks to be performed before the end of the proposed project end date (December 31, 2024).

Project strengths:

- This project did well in overcoming processing challenges to successfully demonstrate the nanocapsule concept and demonstrate reduced sulfonate coverage and reduced oxygen transport resistance. Further, there was effective collaboration to characterize and employ modeling to establish some design boundaries. Specifically, the maximum particle size versus proton conductivity relationship helped address risk. The path forward should build on this analysis to further de-risk the concept before scaling up the process.
- The nanocapsule electrode structure seems to provide reasonable opportunities to improve catalyst activity and oxygen transport from limiting ionomer coverage on the catalyst. This may lead to practical electrode improvements but also presents an opportunity to learn from the behavior of an unconventional electrode structure.

- The project has a good team with the appropriate capabilities, including relevant experience in both the unique experimental processes required and catalyst-layer characterization and modeling. The concept is innovative and outside the classic PEMFC catalyst layer "box."
- The presenter gave a great description of the progress made toward addressing the previous year's comments. Also, there are really interesting results with the insensitivity of Fickian diffusion to relative humidity.
- The nanocapsule design allows for improved mass transport of reactants.

Project weaknesses:

- Providing clarity in the following areas would strengthen this project and build confidence that this methodology can have significant impacts in the DOE Hydrogen Program:
    - Confirm and validate the modeling results through measurement of the catalyst layer proton resistance. Additionally, measurement of the Pt availability at lower RH is required to better define catalyst functionality.
    - Demonstrate the translation between measured low R_{O2} and performance and durability, as compared to conventional structures and processes. Further depth in the analysis, such as catalyst activity and a voltage loss breakdown as a function of current density, would be beneficial.
    - Identify gaps and develop a risk strategy for scaling this concept. Expectations on processing should be provided throughout to address high-volume manufacturing requirements.
    - Address the uniformity risk to membrane degradation (future action).
- The project appears to have some very significant challenges in terms of approach and execution. The nanocapsule approach challenges include (1) questionable manufacturability, (2) potential fundamental challenges associated with catalyst utilization within the nanocapsule at low RH, and (3) conceptual structural collapse of the nanocapsule with carbon corrosion.
- The project scope is relatively narrow, focusing only on development of nanocapsule catalyst layers. It is not clear how this approach addresses durability challenges for HD applications. The project is lacking in comparisons to standard baseline catalyst layers to help understand the impacts of the nanocapsule structure.
- Ideal structures seem difficult to make. At scale, a post-fabrication acid wash is necessary to remove stabilizing additives required for the electrospray process.
- It is not clear that this project is fully utilizing modeling; instead, it appears to be primarily empirically driven.
- The team should interact more with M2FCT consortium member labs.
- So far, the project does not address the main problem of durability of the novel catalyst design.

Recommendations for additions/deletions to project scope:

- Providing clarity in the following areas would strengthen this project and build confidence that this methodology can have significant impacts in the DOE Hydrogen Program:
    - Confirm and validate the modeling results through measurement of the catalyst layer proton resistance. Additionally, measurement of the Pt availability at lower RH is required to better define catalyst functionality.
    - Demonstrate the translation between measured low R_{O2} and performance and durability, as compared to conventional structures and processes. Further depth in the analysis, such as catalyst activity and a voltage loss breakdown as a function of current density, would be beneficial.
    - Identify gaps and develop a risk strategy for scaling this concept. Expectations on processing should be provided throughout to address high-volume manufacturing requirements.
    - Address the uniformity risk to membrane degradation (future action).
- The project team should consider developing a robust and validated catalyst-layer model. Ideally, this model should also be relatively simple. An approach to developing an analytical solution for multiscale PEMFC catalyst layers has been described by Rob Darling (e.g., *Journal of The Electrochemical Society*

2020), which may possibly be modified and used to model these unique catalyst layers (e.g., treat the nanocapsules as agglomerates). It is suggested the team focus on improving a fundamental understanding, as much as striving for improved performance. For example, varying nanocapsule size may help to differentiate between the impacts of changes in activity and ohmic and transport losses, especially if this is combined with state-of-the-art characterization (for key catalyst layer dimensions) and a validated model.

- It is essential for the project to compare novel electrodes to good standard baselines for the future budget periods. The project should consider whether there are any electronic conductivity issues in the catalyst layer or loss of catalyst utilization from the nanocapsule structure, which may block electronic conduction out of each capsule with an ionomer. This seems to have been assumed but needs to be measured with cell diagnostics such as impedance. The project should also consider the manufacturing aspects of the nanocapsule electrodes. Clarification is needed as to whether this electrode structure can be manufactured at a high volume for a reasonable cost.
- The project should conduct extensive performance and durability comparisons against state-of-the-art conventional electrodes and make an assessment toward whether the approach is worth continuing. Additionally, the project team should assess and report on the manufacturability of the nanocapsule fabrication approach using the emitters.
- It is suggested that parallel investigations into nanocapsule catalyst layer activity and durability be moved up in the timeline to ensure that the project can optimize for them, given how long synthesis has taken so far.

Project #FC-327: Durable High-Power-Density Fuel Cell Cathodes for Heavy-Duty Vehicles

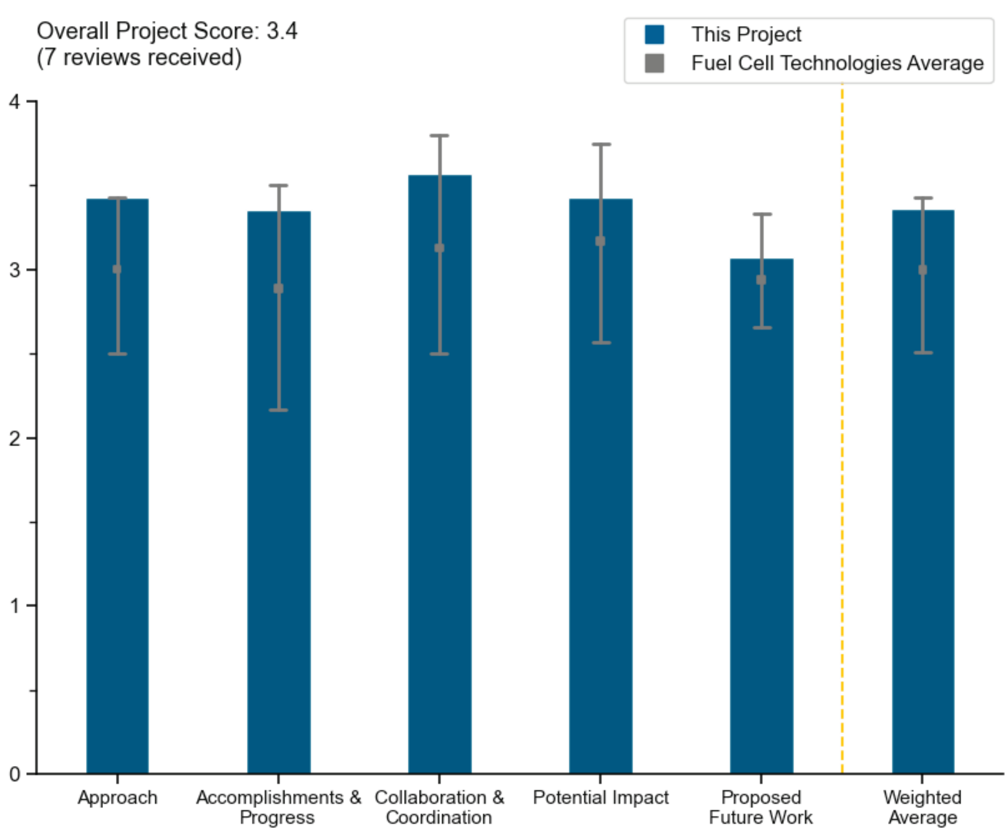
Shawn Litster, Carnegie Mellon University

DOE Contract #	DE-EE0008822
Start and End Dates	10/1/2019–3/31/2024
Partners/Collaborators	The Chemours Company, Ballard Power Systems, Inc., Million Mile Fuel Cell Truck (M2FCT) Consortium
Barriers Addressed	• Cost: Reduce proton exchange membrane fuel cell costs by reducing platinum group metal loading • Performance: Increase catalyst activity, utilization, and effectiveness by increasing solubility and permeability of ionomers • Durability: Increase the lifetime of proton exchange membrane fuel cells by reducing the loss of efficiency and power

Project Goal and Brief Summary

This project aims to (1) synthesize and implement a custom-designed ionomer that permits enhanced oxygen transport to the platinum surface for improved performance and durability, (2) demonstrate that the ionomer will reduce oxygen transport resistance in a membrane electrode assembly (MEA), and (3) optimize the design of the ionomer for commercialization. If successful, the project will facilitate low platinum loadings in an advanced cathode catalyst layer for heavy-duty vehicle MEAs.

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.

- Developing high-oxygen-permeability ionomers (HOPIs) and addressing concerns for device integration appears to be an effective approach to improving fuel cell performance, efficiency, durability, and cost for both light- and heavy-duty applications. The presentation makes a clear case that HOPI provides significant durability and efficiency advantages for heavy-duty applications, and the value for light-duty is clear as well. Project activities cover the main important aspects of the topic, including diagnostics for fundamental understanding of HOPI, durability testing, and investigations of manufacturability.
- The focus on HOPI as an improvement in electrode performance is obvious and logical. The team has unique capabilities to perform novel materials synthesis and to perform the characterization presented. The focus on crack improvement is reasonable.
- The team has done a great job highlighting the limitations and addressing them. The focus on integration has allowed the team to surpass many of the initial hurdles.
- Improving oxygen transport in the cathode is key to improving performance and reducing Pt loading. New ionomers specifically designed for use in the cathode are an excellent approach to overcoming this barrier.
- Advanced electrode ionomer is a promising research area. Even for heavy-duty applications with relatively high Pt loading, the improved oxygen reduction reaction activity and oxygen transport give great benefits. Cost-wise, because Pt loading is already relatively high in heavy-duty applications, performance gain is limited by further increasing Pt amount. It is likely more cost-effective to invest in advanced ionomers. However, much effort was put into optimizing electrode coating and mud crack mitigation. These areas are very specific to the material sets and processes used, and the learnings are unlikely to be transferrable to other material sets or other labs. Therefore, they are not very valuable to the community.
- The approach is well designed. A recommendation is to correlate the flux-based measurements for oxygen permeation with the microelectrode-based studies. The latter provides both the diffusion coefficient and solubility. A proper correlation between the oxygen permeability and HOPI structure is an important outcome of this project.
- The presentation outlined the project goals and progress well. It would have been good to see more detail on cracking after the accelerated stress test (AST) instead of just during the manufacturing process

Question 2: Accomplishments and progress

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

- Good progress has been made on all the project tasks, making clear evidence for the advantages of HOPIs and providing useful fundamental understanding through diagnostics, modeling, and characterization. Good work was done to address comments from previous Annual Merit Reviews, including durability testing to understand the stability of the HOPI itself. Manufacturability research is addressing concerns about cracking and brittleness of catalyst layers fabricated with HOPIs. Results are being disseminated through publications and presentations.
- The team has shown new data on HOPI A and HOPI B that included additional free-standing film data, cell performance, and durability. HOPI-based electrodes clearly show improvements in performance, and the increased focus on durability is reasonable.
- The novel polymers have shown significant improvements in performance and durability compared to the baseline, especially at high current density and low RH. There has been good development of the fabrication process to consistently and repeatably benefit from the improvements in ionomer.
- The project has hit nearly all of its goals and has surpassed nearly all of the performance technical targets. The researchers have developed some important insights that will be useful for other systems and materials.
- The project was able to replicate many of the findings demonstrated earlier. Modeling of the HOPI molecular structure and the effect on oxygen permeation is interesting and may be useful for future materials development. Reduction in electrode degradation rate is worth deeper investigation, as the reason

is unclear. The principal investigator has the capability to do degradation modeling. It would be interesting to elaborate the mechanism. The testing should also be confirmed in other labs. It is unclear what ASTs were used. Unfortunately, the most promising results were achieved only on non-state-of-the-art catalysts. It is necessary to understand why improvement was not obtained on state-of-the-art mesoporous carbon or Pt alloy catalysts.

- There were many very clear accomplishments that were outlined in the presentation. The HOPI B post-AST polarization curve is higher than the beginning-of-life sample in the mass transport region, which begs the question as to whether the sample was adequately broken in prior to the AST testing. If the polarization is still increasing, cycling should continue until a degradation rate can be determined, or a different break in procedure should be established to be able to meet peak performance sooner. Clarification is needed as to whether the current format of the AST does enough to address the brittle nature of the HOPI layer. More dramatic RH swings and post-test imaging should be performed to determine whether the cracking issue is resolved for lifetime durability.
- The accomplishments are well in line with the timeline of this project. However, it is important to design deposition methods that would entail lower variation of ionomer–catalyst interactions.

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.

- There is good integration between team members and the Million Mile Fuel Cell Truck (M2FCT) consortium. Results from the different labs are clearly focused to address the project goals, and key project tasks appear to have input from multiple partners combining their strengths.
- The mix of team members is appropriate, as well as the engagement with M2FCT. In particular, the participation of Chemours in this project is critical to its success.
- There are very relevant and interesting performance test results from Ballard. The project has good collaboration with Chemours and M2FCT.
- Good collaboration between partners Chemours and Ballard is evident. Collaboration with the national lab partners is well under way.
- The team has good focus, with clear roles and responsibilities.
- The team has worked well together.
- Collaborations were well explained and defined.

Question 4: Potential impact

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

- The project has clearly demonstrated that HOPIs can have significant advantages for heavy-duty fuel cell efficiency and durability, which are key goals. While not necessarily transformative by itself, this appears to be a clearly valuable technology that can advance heavy-duty fuel cells and can be combined with advancements in catalysts and operating strategies. The project work is clearly addressing key barriers for the DOE Hydrogen Program and has addressed concerns about the viability of the HOPI approach.
- Improvements in performance are important and enabled through the use of HOPI materials. Durability is rightfully an increasing focus, owing to the critical nature of improved durability.
- Improved understanding of the catalyst–ionomer interface will lead to future advancement.
- This ionomer has the potential to address many of the cathode limitations targeted by DOE.
- Cathode performance and durability are key for heavy-duty vehicle applications.
- This project needs closer commercialization partners for scale-up and large-scale MEA fabrication.
- It would be good to see more information on the scalability of the process, but the improvements are very promising.

Question 5: Proposed future work

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

- The project is approaching completion within the next year, and much of the proposed work seems to be “wrapping up” the project work scope. Future work activities that are viewed as high-priority before the project ends include understanding whether interactions between the HOPI and the catalyst surface may influence the catalyst degradation directly (in addition to minimizing the negative impacts of surface area loss, which has been clearly demonstrated). For instance, the observed trends for the PtCo catalyst with HOPI (less roughness factor loss, more high-current performance loss) may suggest accelerated Co leaching.
- The future work seems to be a continuation of existing work, which is reasonable but not particularly compelling. Crack mitigation strategies are presented as continuing, but it is not clear that this is the primary or only mechanism of performance loss of concern. A stronger focus on degradation and mitigation would be preferred.
- If possible, the project should develop an O_2 solubility/diffusivity protocol for HOPI thin films that can measure these values for film thicknesses that are more relevant for catalyst layers, i.e., below 500 nm.
- Much of the future work centers around continued process improvements. Some focus should be placed on evaluating mechanical durability and cracking under mechanical strain.
- The output from this project needs proper commercialization partners for scale-up and implementation in stacks.
- The best features of polymer, catalysts, and supports tested should be combined into a best cathode.
- Future work in the last year appears to be a continuation of previous tasks.

Project strengths:

- The project has clearly demonstrated advantages of HOPIs for fuel cell efficiency and durability, which addresses key barriers for heavy-duty applications. The project is effectively contributing a basic understanding of HOPIs, as well as addressing concerns with manufacturability of HOPI-based electrodes. The team appears well-integrated.
- The project deals with one of the most important aspects of the performance and durability of an MEA, as it focuses on controlling oxygen permeability at the catalyst–ionomer interface. This is also the first line of defense for MEA durability, especially for its long-term stability under low-RH conditions.
- The project has demonstrated scaled synthesis with distinct control of material chemistry and properties. The team has conducted detailed analysis and correlation between material properties and performance. The emphasis on integration has led to significant performance improvements.
- The HOPI shows better diffusivity of oxygen and a reduction of platinum loss into the membrane. There is a solid foundation in this project on both the basic science and the application.
- Strengths include a strong team, relevant materials, and a novel approach. Results to date have been promising.
- This is a great team effort, with good results.

Project weaknesses:

- It does not look like the researchers have measured the impact of the HOPI chemistry on sulfonate specific adsorption. Loss of performance enhancement is occurring at higher cathode loadings. It is likely that the project will need to develop strategies to improve the mechanical properties of HOPI.
- There is not enough work on scale-up and commercial implementation in terms of stack performance and durability data. More concerted efforts on developing deposition methods are needed.
- An increased focus on degradation, and perhaps additional mitigation strategies, would be potential areas of improvement.

- The future work scope seems like it may be mostly just a continuation of ongoing activities, and distinct efforts for final project goals are not that clear.
- The project could have better post-AST imaging and characterization of the membrane and ionomer layer.

Recommendations for additions/deletions to project scope:

- This is a well-run project, and performance to date has been as per targets laid out for the project. However, this project needs careful consideration for scale-up of the MEA and stack results.
- Optimization of electrode coating and mud crack is very specific to the material sets and processes used, and the learnings are unlikely to be transferrable to other material sets or other labs. Therefore, they are not very valuable to the community. The project team is advised to focus efforts on learnings that are more valuable to the community, such as understanding the mechanism that leads to improved electrode durability with HOPI and understanding why HOPI did not perform as well on PtCo/high-surface-area carbon (HSAC).
- Increased focus on durability/degradation as the primary remaining barrier would make the most sense. The project could forego some of the more fundamental studies, including medium-duty simulations that are less likely to have an impact in the project time remaining.
- An important priority for upcoming work would be to understand whether HOPI interactions are altering the catalyst degradation. It would also be useful to consider testing with another catalyst such as an annealed Pt/HSC, which may be more representative of catalysts selected for heavy-duty fuel cells in comparison to higher-surface-area Pt/HSAC and PtCo/HSAC.
- Additional equivalent weights should be tested, and the team should find a way to indicate different side chain chemistry (without revealing proprietary information) to facilitate interpretation of results.
- The data shows that an improved break in procedure might be called for prior to AST testing to develop a true degradation rate.

Project #FC-330: High-Efficiency Reversible Solid Oxide System

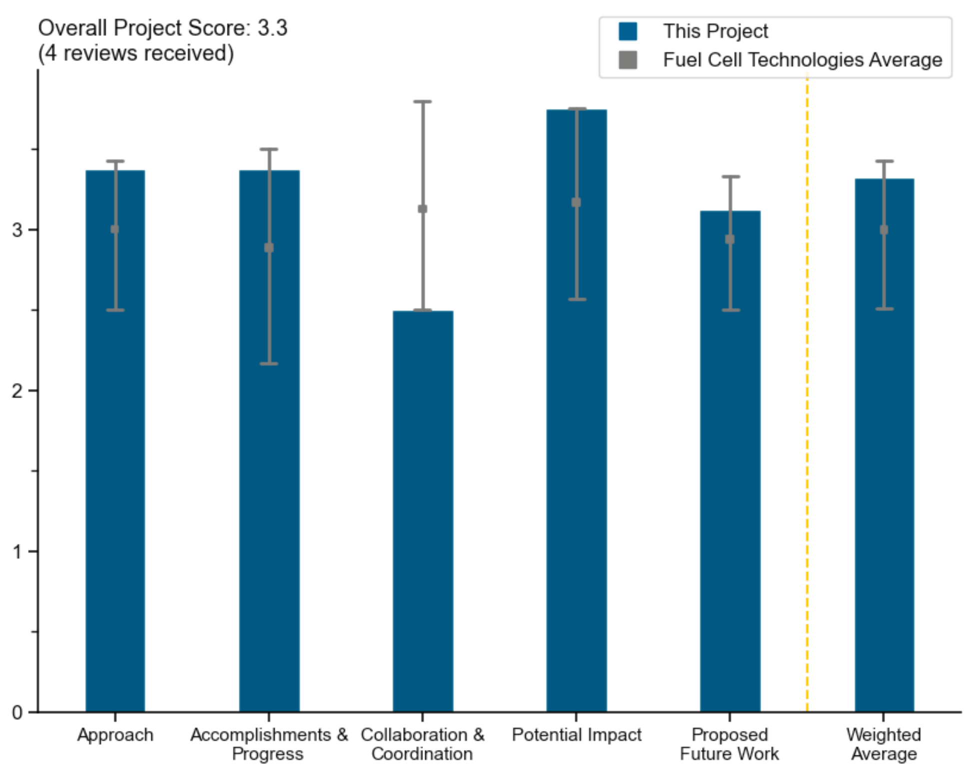
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

DOE Contract #	DE-EE0008847
Start and End Dates	10/1/2019–3/31/2024
Partners/Collaborators	Versa Power Systems
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Renewable electricity generation integration

Project Goal and Brief Summary

FuelCell Energy, Inc. (FuelCell Energy) will demonstrate a unitized reversible solid oxide fuel cell (RSOFC)-based system, rated at 3 kWe fuel cell power output and 15 kWe electrolyzer power input. The RSOFC system will integrate a novel hot water thermal energy storage system to demonstrate up to 60% system round-trip efficiency (RTE) in testing, with a path to ≥70% RTE. Techno-economic analysis (TEA) will validate the projected system costs, which are expected to be $1,000/kW and $100/kWh. The team will complete a system design and define the required operating conditions for the unitized RSOFC stack, including preferred pressurized operation to achieve the targeted RTE performance. Stack testing will validate the technical approach and operating conditions and will demonstrate RTE degradation of less than 5%/1,000 cycles over 100 cycles between fuel cell and electrolysis operating modes.

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 is excellent:
    - Develop storage system design and identify operating conditions that maximize the potential of the RSOFC stack and materials technology in meeting RTE performance and degradation goals.
    - Perform RSOFC stack testing to validate system-identified operating conditions (such as stack pressure of up to 10 bar) and to verify RTE degradation of less than 5%/1,000 cycles over 100 cycles between fuel cell and electrolysis operating modes.
    - Build and test a thermally self-sustaining RSOFC demonstration system, rated at 3 kWe output and 15 kWe input, and verify >50% RTE (equivalent to >60% RTE in larger systems) and RTE degradation of less than 5%/1,000 cycles.
    - Develop a technology-to-market (T2M) plan, including commercialization strategies and product specifications, by organizing an industry committee consisting of utilities and potential users.
- The approach of targeting high RTE is a wise choice, even if it compromises the traditional target of high-current-density operation in fuel cell mode. Circular cells make sense for limiting delta T (the difference between temperatures) for thermal management in fuel cell mode. It is unclear whether the assembly cost would increase drastically if larger-diameter cells were employed.
- FuelCell Energy has extremely high-performing cells but chooses to operate their RSOFC system at very conservative current densities (0.2 A/cm^2 in the solid oxide fuel cell [SOFC] mode and 0.6 A/cm^2 in the solid oxide electrolysis cell [SOEC] mode). By operating at low voltages in the SOEC mode, cell voltages are below the thermoneutral voltage point, so energy will be needed to keep the stack hot. It seems that this would reduce system efficiency. No details were provided on the demonstration test system.
- The overall approach is energy-balanced. However, the maximum efficiency of SOFC using H_2 as fuel is 76%. On slide 15, the table shows power generation efficiency of 80%, which is questionable.

Question 2: Accomplishments and progress

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

- More than 400 cycles at high RTE are shown. This is a significant accomplishment. The degradation also appears low.
- Good progress is being made. The focus is on demonstration. The project is achieving the major demonstration of a 150-cell pilot-scale RSOFC commissioned under the Hydrogen and Fuel Cell Technologies Office.
- Excellent progress has been made in both electrolysis mode and alternating SOFC and SOEC modes. The project achieved milestones in H_2 production rate, RTE, and degradation rate.
- Achieving >400 cycles over >2,000 hours in a 50-cell stack is a significant accomplishment, but 50-hour cycling times seem a bit too high relative to application requirements. Performance degradation levels seem relatively high but are reasonable given the state of RSOFC technology and the fact that FuelCell Energy is not scoped for cell development on the project.

Question 3: Collaboration and coordination

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

- The project demonstrated no university or national laboratory involvement, which may not be needed at the demonstration stage.
- It is hard to consider Versa Power as a collaborator since Versa is 100% owned by FuelCell Energy.

- A subsidiary of FuelCell Energy is the collaboration partner responsible for making cells and stacks.
- It appears that the collaboration is only with a wholly owned subsidiary.

Question 4: Potential impact

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

- RSOFC is one of a few technologies with potential for long storage durations. Although there is a long way to go, FuelCell Energy has demonstrated the promise of its RSOFC technology for grid-scale, long-duration energy storage.
- The project goals definitely meet the DOE objective of developing an RSOFC product with high RTE.
- The progress made demonstrates the great potential of SOEC technology for high-efficiency production.
- The potential impact of the technology is great but was not adequately discussed. Not a single slide was presented.

Question 5: Proposed future work

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

- Future work is appropriately focused to complete the following:
    - Develop storage system design and identify operating conditions that maximize the potential of the RSOFC stack and materials technology in meeting RTE performance and degradation goals.
    - Perform RSOFC stack testing to validate system-identified operating conditions (such as stack pressure of up to 10 bar) and to verify RTE degradation of less than 5%/1,000 cycles over 100 cycles between fuel cell and electrolysis operating modes.
    - Build and test a thermally self-sustaining RSOFC demonstration system, rated at 3 kWe output and 15 kWe input, and verify >50% RTE (equivalent to >60% RTE in larger systems) and RTE degradation of less than 5%/1,000 cycles.
    - Develop a T2M plan, including commercialization strategies and product specifications, by organizing an industry committee consisting of utilities and potential users.
- It is suggested that FuelCell Energy perform more single-mode electrolysis durability testing at multi-cell stack level for H_2 production, which is a major barrier for high-temperature electrolysis technology advancement. Performing more degradation diagnosis on the cells and stacks is also suggested.
- FuelCell Energy's future plans seem reasonable. Its plan to explore different conditions in its system makes sense, and the TEA may further inform condition space that should be explored. It is not clear what level of thermal integration is being attempted in the demonstration system.
- A clear understanding of T2M and TEA is pending. Results will provide guidance for the near-term applicability of this technology.

Project strengths:

- The project team demonstrates a good understanding of operating conditions for achieving high RTE. More than 400 cycles with stable performance in both modes is impressive.
- The project is demonstrating long-term, high-performance H_2 production at multi-cell stack level, which is the foundation of future high-temperature electrolysis H_2 production systems.
- FuelCell Energy is performing the work in a logical and relevant progressive manner.
- Project strengths are (1) high-performance cell and stack technology and (2) long-term durability testing as a major project focus.

Project weaknesses:

- Cell size is a great concern. The number of cells required for a large energy storage system using RSOFC may add complexity to the system and increase assembly cost. It is difficult to estimate the complexity of the gas manifolds and the manner in which hydrogen will be collected, especially if the electrolysis is done at pressure.

- Researchers need to be aware of the thermodynamic limit for alternating operation of SOFC and SOEC when reporting RTE value. The best way to report RTE is the ratio of energy in H_2 produced and total energy consumed to make the H_2. In addition, the degradation rate is still significant in the single H_2 production systems.
- Testing conditions may not be completely relevant to the application (e.g., low current density in electrolysis mode, long cycle times). Another weakness is lack of true collaboration.
- The project team needs to quickly organize an industry committee consisting of utilities and potential users.

Recommendations for additions/deletions to project scope:

- The TEA should clearly state the effect of cell size on the overall economics of implementing the technology.
- The project team should (1) double-check the efficiency numbers reported and (2) perform degradation mechanisms analysis.

Project #FC-331: A Novel Stack Approach to Enable High Round-Trip Efficiencies in Unitized Proton Exchange Membrane Regenerative Fuel Cells

Katherine Ayers, Nel Hydrogen

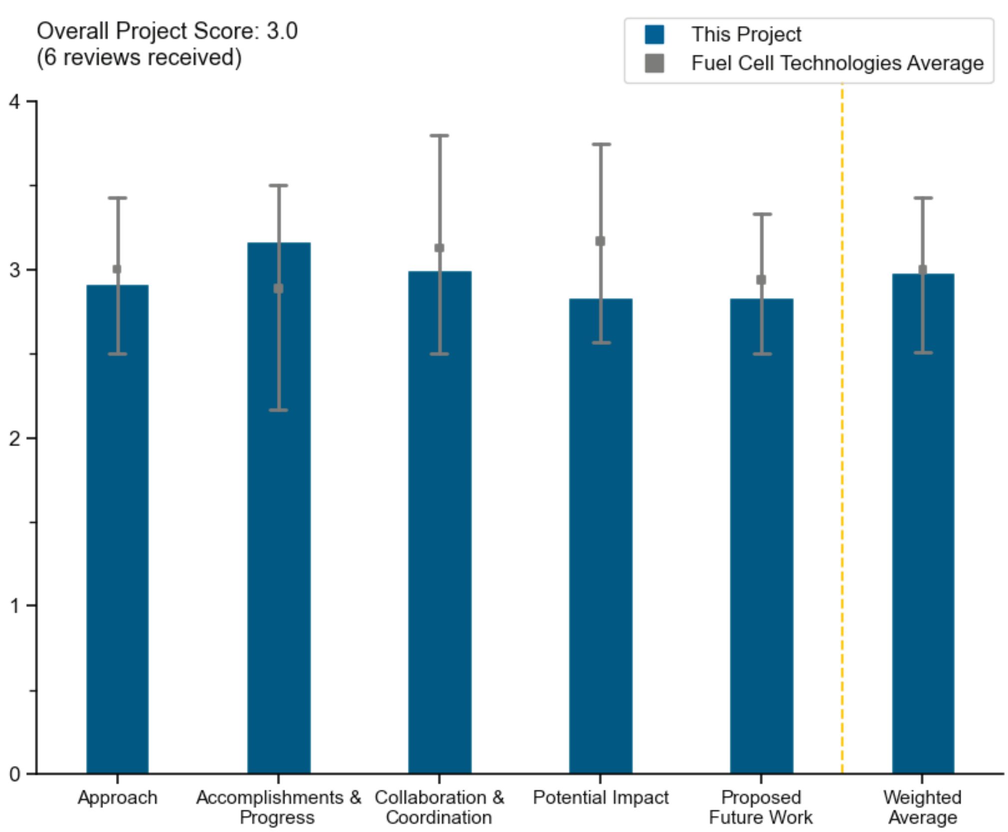
DOE Contract #	DE-EE0008848
Start and End Dates	4/1/2020–3/31/2024
Partners/Collaborators	Electric Power Research Institute, Southern Company, Lawrence Berkeley National Laboratory, Gaia Energy Research Institute

Barriers Addressed	• No barriers specific to regenerative fuel cells
	• Barriers regarding optimization between fuel cell and electrolyzer:
	  • Fuel cells (durability, cost, performance)
	  • Hydrogen production (capital cost, system efficiency, and electricity cost)

Project Goal and Brief Summary

The overall project goal is to demonstrate a unitized reversible fuel cell (URFC) system based on proton exchange membrane (PEM) technology that can achieve 50% round-trip efficiency (RTE) and reliable performance under relevant duty cycles, with projected costs below $1,750/kW. An early focus of this project is to develop a low-pressure electrolyzer membrane electrode assembly and stack design that much more closely resembles the fuel cell construction (i.e., thinner membrane), providing a pathway to higher RTEs for URFCs.

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.

- This is an amazing project with an approach that could be developed only by a leading electrolyzer developer. The perspective is unique. The approach is tailored to achieve the goals by addressing the key challenges.
- While there are no specific barriers to URFCs, the project does an excellent job of outlining the barriers individually to electrolyzers and fuel cells and working to balance those into a most ideal URFC. The team should define how this reversible fuel cell (RFC) project differs from previous attempts known in the public domain. The overall approach is good and effective. The approach to work at stack level and build an integrated test system to demonstrate URFC is good. The system analysis and use case is also useful for determining an impactful use case for URFCs. The usefulness of the outreach task for this project is unclear. Perhaps its target is to educate the electric utilities, and that is why the Electric Power Research Institute (EPRI) is involved. It is not clear why there are two milestones related to demonstrating 100 hours of electrolysis operation (one in Fiscal Year [FY] 2021 Quarter [Q] 2 and one in FY 2023 Q1). The project should clarify if something changed to warrant another electrolysis durability test and explain the reason there is no milestone for fuel cell durability testing. It may be useful to have a milestone related to optimizing thermal management, pressurization, and water transport for the URFC.
- The goal of this project is daunting; work on RFCs has been pursued for decades, but the status of the technology is still a long way from being commercially viable for most terrestrial applications. The approach is good, with the overall strategy being to make the proton exchange membrane water electrolyzer (PEMWE) more like a proton exchange membrane fuel cell (PEMFC). This makes sense because the PEMFC supply chain is more mature than that of the PEMWE, and this project may thereby result in a spin-off benefit of improving the cost of PEMWEs. It is not clear what the actual targets are here with respect to both performance and durability (in either mode). The team should establish these targets and should consider the use of accelerated stress tests to assess durability.
- It sounds logical to leverage the principle of using the electrochemical cell for both directions of storing and consuming energy using hydrogen as the energy carrier, provided the stack is the most expensive component of the balance of plant (BOP). However, the targeted system scale is not clear from this presentation, being 50 W for the experiment or 500 kW for the model, and the expected cost breakdown for the system components for each case could help here (already requested last review).
- The challenge with the project approach is to start at the scale of a full stack. The RFCs face numerous technical challenges that are more appropriate to solve at the subscale/single-cell (full size) level. The key metrics for the project are loosely defined with performance and cost goals. There are no durability metrics. Nel Hydrogen (Nel) is a world expert in electrolyzers. Having just Nel work solely on both the electrolyzer and fuel cell technical challenges is surprising.

Question 2: Accomplishments and progress

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

- The project had excellent outreach and webcasts. Progress was made in identifying the key challenges:
    - Electrolyzers currently use thick membranes to tolerate the high differential pressure.
    - Modeling is needed to understand water transport in the URFC cell with respect to membrane properties and operating conditions.

  The work conducted on improving the performance and stability of cell operation has clearly been successful. There is good understanding of potential improvements that can still be implemented. Separate modeling shows how the operation time windows could change for different regions and applications (only briefly presented). However, collectively, these results do not underline any benefit of having only one (compromised) stack for electrolysis and fuel cell mode.
- The voltage and current plot as a function of time, demonstrating the 20 one-hour cycles accomplishment, shows that degradation is higher in fuel cell mode. It is good that the issue was identified as to why this was

happening (a mismatch in reactant feeds and stack temperature resulted in condensation) and resolved. It is good that the learning is shared with the community, but it is very generally described. More detail on the solutions would be beneficial to the community. It is not clear whether the size of the “one-cell URFC stack” (one cell is not a stack) used for the 20-cycle test was 25 cm2. If so, it is not clear that the cell size is sufficiently large to be useful. It is not clear whether the oxygen evolution reaction catalysts were tested with the Chemours reinforced membranes commercial catalyst, what the catalyst was loading, what the composition was, etc. More details should be given to the community. The targets for electrolysis and fuel cell mode to achieve 50% RTE should be clearly stated, along with what the achieved RTE is currently, from the test results. It is good to see that the electrolyzer continuum model fits the data well, as this gives confidence in the applied voltage breakdown to help guide where improvements can be made to improve the electrolyzer cell performance. It was not clear whether the model was validated with fuel cell data, too, or what it looks like. If the model was not validated, the team should explain. It is unclear whether the model can predict the durability of the URFC cycling between fuel cell and electrolyzer mode or whether the model can provide information about the operating conditions that will optimize the URFC performance and/or durability. It was unclear what will be done to translate the 25 cm^2 cell performance and durability to 86 cm^2 cell and then stack.

- The team has passed their budget period (BP) 1 go/no-go milestone and is continuing to improve the technology. Progress is being made, but since clear targets have not been established, it is not clear what the gap is between the performance demonstrated, to date, and what is required to be potentially viable. The fuel cell performance goal was not achieved at the stack level. The stack testing issues with the test stand/ test article point to a lack of priority on this project. More resources should be provided to this project so that it can get back on track.
- The project has satisfied nearly all of the targets to date, following the no-cost extension on BP 1. The fuel cell performance, listed as >0.75 V, is close to completion but not quite there yet.

Question 3: Collaboration and coordination

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

- It seems that appropriate partners are in the project to perform the tasks. The tasks seem to be independent and do not need much coordination between the project partners. Good progress and results for the tasks are shown from the project participants.
- The outreach component and modeling are good, although the impact of modeling results is not subtracted from the RTE.
- There is excellent collaboration with a national laboratory, industry coalition group, and a power company. No university was involved.
- The role of the project’s formal collaborators is clear (e.g., slide 17), but it is less clear what each of these institutions has contributed to date in some cases. This includes Gaia Energy Research Institute, since it does not appear that much techno-economic analysis work has been done to date. EPRI has been engaged with the outreach efforts, but it is less clear what Southern Company is doing. It is also not clear why much outreach is appropriate in this project, since the technology readiness level of regenerative fuel cells is not high enough yet to warrant this work; however, educating utilities on how hydrogen can be used with more mature technologies (e.g., PEMWEs and/or PEMWEs + PEMFCs) is valuable.
- While it does seem that the various partners have accomplished what was designed, the input and contributions from the other partners are far less than Nel’s scope. The scope that the other partners are contributing to the success of this project should be more clearly identified.
- Lawrence Berkeley National Laboratory (LBNL) is listed as a collaborator performing modeling. The fuel cell performance goal was met in a subscale cell. LBNL should be working with Nel to see how the performance goal in fuel cell mode can be achieved at the fuel cell size or stack level.

Question 4: Potential impact

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

- While URFCs have a very small space in the hydrogen world, as compared to isolated electrolysis and fuel cell systems, this project is doing an excellent job of applying fuel cell methodologies and thinking to electrolysis. This could ultimately lead to changes in BOP and system development that benefit both electrolysis and fuel cells and should be a growing funding opportunity for DOE.
- Nel correctly identified the greatest market impact and role of reversible PEMs: long-term storage, greater than 8–12 hours.
- The overall RTE target is set high at 50%, limiting current density to a level at which separate fuel cell and electrolyzer systems have difficulty justifying the capital expenditure investment needed (return on investment). Even if the combined BOP could be significantly simplified (not clear), the current performance is 100 mV shy of the target (which could be improved in the next year), but it does not leave any room for the proposed electrochemical hydrogen compressor (EHC) step to be implemented. Bottom-line advanced material solutions are needed to allow efficient, pressurized operation in both modes, since more complex BOP (work-around solutions) will defy the purpose of using a single stack.
- This technology is not critical to the Hydrogen Program because the same objectives can presumably be achieved by using a combination of a fuel cell and an electrolyzer. The primary benefit would presumably be reduced cost with a single system, and some key targets for this technology should be established so one can assess the potential impact, which apparently has not yet been done. Crudely, one would expect that the performance may be roughly one-half that of state-of-the-art PEMFCs and PEMWEs, since only one device is required here and one could tolerate a cell that costs twofold.
- The approach of this work to start from a stack renders this project less capable of success than if Nel started from subscale experiments and modeling. As such, the potential impact of this project will most likely be limited to a demonstration-type project.
- Ideally, the URFC can be higher-efficiency and lower-cost, but it is not clear whether there is a market pull for this.

Question 5: Proposed future work

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

- Proposed future work is excellent:
  - Electrolyzers currently use thick membranes to tolerate the high differential pressure. Future work will involve retuning the cell design to enable the use of more efficient, thinner membranes.
  - Future work will leverage Nel cell optimization experience to make cell stack design compatible with efficient fuel cell operation.
  - Future work will utilize basic computational fluid dynamic modeling to optimize flow field geometry.
  - Future work will use the LBNL model to understand the water transport in the URFC cell with respect to membrane properties and operating conditions.
- All of the planned future work is good, but one additional item should be added: establish preliminary performance and durability targets.
- While left vague in some cases (refine system cost models), the remaining proposed future work does specifically target the remaining milestones that are to be accomplished during the remainder of BP 2.
- The "refine system cost model" is long due and should be updated continuously with a clear application and scale in mind. This would also dictate the type of drive cycle pattern. Interestingly, the target rated capacity of 1 A/cm^2 fuel cell current vs. 2 A/cm^2 electrolyzer capacity already implies that the energy consumption rate is half that of the energy storage rate, perhaps corresponding to a day–night cycle, so it is not clear how long-term storage fits into this application. A minimum of 200 hours of testing is needed to flag inherent issues when considering the burning-in timespan of applied catalyst-coated membranes.

- One of the proposed future work items is to demonstrate 200 hours of operation under down-selected duty cycles with 50% RTE. It is unclear how the duty cycles will be selected, whether they will be based on realistic operations for energy storage applications, and what criteria will be used. It is unclear that the EHC system and cost model will be useful. This task seems to be extraneous. It may be more beneficial to focus on system analysis and use cases and whole-system cost analysis.
- The team should focus on meeting performance goals for the RFC at the stack level and show at least 100 hours of continuous operation. Then the team could look at improving the durability.

Project strengths:

- This is a very strong project. It does an excellent job of evaluating URFCs, which are understudied as a whole. The work does a great job of taking highly studied aspects of fuel cell technologies and trying to incorporate them into electrolysis to try to toe the line in terms of the system differences and needs.
- The project partners have deep knowledge and expertise in the fields of fuel cell and electrolyzer systems and their operation.
- Nel and LBNL could be very strong collaborators if the partnership is aimed at understanding the fundamentals of gaps in achieving performance goals.
- It is a good team with a nice combination of experienced industry and national lab members.
- One of the most capable and relevant electrolyzer entities is leading the project.
- It is a good team. The team made good progress.

Project weaknesses:

- There are a few minor notes that can be addressed. It is unclear what Nel believes a realistic drive cycle is going to look like (hours electrolysis vs. hours fuel cell, operating conditions, complexity of switching between different operating conditions at changeover to/from fuel cell). Some of the data presented, including the key fuel cell data, is missing many operating conditions for reference. In the modeling work, while the agreement is, in general, quite good, there appears to be some deviation in Catalyst 2, 50°C, at higher currents. It is unclear whether Nel or LBNL has theories as to why and what can be done to improve those fits. It was mentioned that the cost target is $1,750 and that right now it is “about double” that target. More specifically, it is unclear which approaches are being implemented going forward to move toward the goal, or whether it is largely an improvement in manufacturing at scale that should be expected.
- The membrane material inherently suffers mechanical stresses when switching between immersed conditions in electrolyzer mode and “dry” conditions in fuel cell mode, and it is a well-known failure mode. It will be a huge challenge to run both modes efficiently with the same humidified gas conditions and deliver the same current density, but it is practically impossible to design a moisture-insensitive membrane. The application of thinner membranes may reduce resistance, but likely at the expense of lifetime.
- No fuel cell developer is included. If the goal is to “make a PEMWE more like a PEMFC,” then it is unclear why a PEMFC developer is not included. Not enough emphasis is made on establishing key targets.
- Not much detail is included about components, materials used, or operating conditions.
- There is a lack of subscale understanding.

Recommendations for additions/deletions to project scope:

- There are no recommendations to change scope; the work is appropriate as designed.
- The project should openly compare its current stack/system cost structure projected at different scales and compare against alternative commercial solutions such as pumped hydro (large-scale) or redox flow (small-/medium-scale). This will highlight the scope of the current business rationale.
- It is unclear that the EHC system and cost model will be useful. The task seems to be extraneous. It may be more beneficial to focus on system analysis and use cases and whole-system cost analysis.

- The project should add university input in the area of membrane electrode assembly optimization and thinning.
- The project should establish preliminary performance and durability targets.

Project #FC-333: Advanced Membranes for Heavy-Duty Fuel Cell Trucks

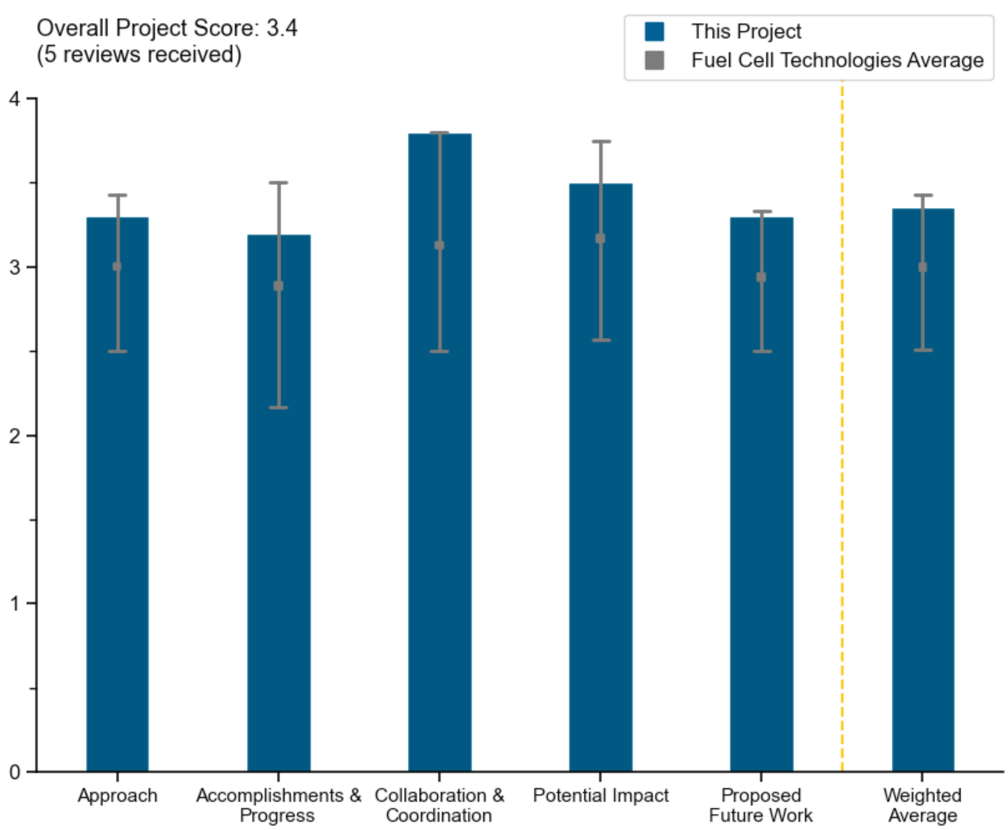
Andrew Baker, Nikola Motor Company

DOE Contract #	DE-EE0009243
Start and End Dates	10/1/2021–4/1/2025
Partners/Collaborators	The Chemours Company, Million Mile Fuel Cell Truck (M2FCT)
Barriers Addressed	• High-temperature and low-relative-humidity operation reduces conductivity and durability • Deleterious radical scavenger cation transport, especially at high temperature

Project Goal and Brief Summary

This project aims to develop membranes with optimized architectures that incorporate thermally stable ionomer chemistries and immobilized radical scavengers. If successful, the project will improve the lifetime efficiencies of membrane electrode assemblies in heavy-duty (HD) fuel cell vehicles, reduce the lifetime operational expenses of HD fuel cell systems, and improve their commercial viability relative to diesel energy sources. Nikola Motor Company (Nikola) is collaborating with The Chemours Company (Chemours) and the Million Mile Fuel Cell Truck (M2FCT) consortium 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 **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The team is taking all the appropriate approaches for assessing proton exchange membrane (PEM) composite durability and performance metrics for HD fuel cell vehicles. The project can be improved by understanding the structure and distribution of the weak acid polymer within the perfluorosulfonic acid (PFSA) blend. The M2FCT consortium partners should be able to help Nikola with this via advanced electron microscopy or x-ray scattering. The Fenton test should be abandoned. Although it is easy to perform, it is not recommended as a good predictor of a membrane's prospect to be stable in a fuel cell. It would have been helpful to see a techno-economic analysis on the manufacture of the new composite membranes with the weak acid monomer or weak polymer blended in. This should include the addition of cerium and the advanced cerium to the membrane matrix and reinforcement (HD-PFSA).
- The project has a major focus on immobilizing cation (cerium) additives for the purpose of increasing membrane durability. Other targets such as resistance, crossover, and mechanical durability seem to rely on state-of-the-art ionomer properties. The team has done a good job identifying two approaches to immobilizing additives: modifying the PFSA ionomer and blending a hydrocarbon that coordinates with the additives.
- Membrane durability is critical to achieving >25,000-hour operation in HD fuel cell systems. The approach builds on previous lessons learned to improve chemical stability of the membrane while also protecting it from attack by reactive species. Fenton's test is not the most representative test.
- This is a design of experiment to improve fuel cell membranes with cerium ions. The relative effect of the additive on durability conductivity and performance is not clear.
- The workplan should be a bit more systematic and designed to better deal with the issues that are appearing as the work is completed.

Question 2: Accomplishments and progress

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

- The Nikola team has shown the effectiveness of weak acids to strongly hold the cerium additive and prevent or minimize migration. Ideally, the weak acid functionality would be incorporated into the PFSA ionomer. The team showed progress to date, explained the issues encountered, and provided a plan to test alternative functionality for polymerization characteristics. This reviewer looks forward to next year's progress where weak acids are incorporated into the PFSA. The results show the hydrocarbon sulfonic acids are (surprisingly) good at minimizing cerium migration. This may have farther-reaching implications beyond stabilizing PFSA systems.
- Overall, progress is excellent. Most milestones have been met. The project has demonstrated significant performance improvement of HD-PFSA compared to current commercial PFSA membranes.
- The team has made progress on new membranes that satisfy or exceed area-specific resistance (ASR) and H_2 crossover performance metrics. The project also shows no significant membrane degradation after 3,250 cycles following General Motor's (GM's) highly accelerated stress test (HAST) protocol. However, there are conflicting (or confusing) results: the addition of hydrocarbon sulfonic acid (HCSA) and hydrocarbon weak acid (HCWA) lower membrane conductivity, even though an early slide shows the team exceeding state-of-the-art ASR. Perhaps the team helped this occur by using a thinner membrane (HD-PFSA).
- While the project has hit its early targets, there appear to be issues with the proposed Ce stabilizing chemistry, and it is not clear whether they can be easily addressed.
- The project addresses DOE goals, but this is not the first time this approach has been tried in this way.

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.

- Nikola has demonstrated effective collaboration with Chemours (new PFSA membrane development with weak acids; polymerization and testing of the project concepts via a blend of weak acid polymer with PFSA), Los Alamos National Laboratory (LANL) (cerium mobility testing), Oak Ridge National Laboratory (ORNL) (cerium particle imaging), the National Renewable Energy Laboratory (fuel cell testing and durability assessment), and Argonne National Laboratory (on-line inductively coupled plasma – mass spectrometry [ICP-MS] to monitor cerium dissolution from the membrane).
- Collaboration with two highly relevant industrial partners and very capable national labs (M2FCT) has resulted in excellent fabrication, testing, and analysis in a relatively short amount of time to expedite the membrane development.
- The collaboration with Chemours to identify a suitable weak acid monomer looks to be working well.
- It is good to see LANL has contributed cerium migration data and ORNL imaging data.
- Nikola is in close contact with DOE labs and team members to get feedback and guidance to develop these new membranes.
- The team is making good use of M2FCT resources.

Question 4: Potential impact

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

- HD vehicles are ideally suited for conversion to fuel cell electric power trains because of the long-range requirements and large impact on transportation sector decarbonization. HD vehicles' use as fleet vehicles facilitates their market introduction, maintenance, and establishment of a suitable refueling infrastructure. Other vehicles will be able to benefit from this infrastructure build-out to accelerate adoption of hydrogen fuel.
- The project's approach and results to date demonstrate that the strategy of weak acid additives is effective for retaining cerium within the membrane. The HD-PFSAs with advanced CeO_2 are showing promising durability results after HAST. The project team's approach should be changed to create a more chemically resilient PEM in the near term over state-of-the-art NC700 (Nafion™). There are some conflicting results between conductivity and ASR, but the project team plans to use low-equivalent-weight ionomers to offset the conductivity losses from the addition of the weak acid. Hence, there seems to be additional optimizing steps the project team can take to further improve the membranes' performance while also enhancing stability and resilience for HD vehicle applications.
- If successful, the new ionomer materials have the potential to greatly enhance polymer durability at high temperature and low relative humidity (RH).
- The potential impact seems to be primarily in immobilized cerium. If these strategies are successful, one would expect this approach to result in increased membrane durability in line with project and DOE goals.
- This approach is reasonable but a small innovation that is an incremental improvement of water-based PEMs.

Question 5: Proposed future work

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

- Using low-equivalent ionomers is a good idea to offset the loss in conductivity by the addition of HCSA and HCWA. It is suggested that the project work with a university partner or national lab to study the phase behavior of the HCSA/HCWA-PFSA blends.
- The milestone-driven targets for future work are well organized. Demonstration of a PFSA terpolymer with improved cerium migration properties has the potential to advance durability of this class of membrane.

- The plan is excellent. The reviewer is looking forward to ASR data for the new membranes.
- The project needs to develop more defined strategies to address the limited degree of Ce immobilization in the composite polymer. The project should add water uptake and Grazing-Incidence Small-Angle X-ray Scattering (GISAXS) to look at phase separation under relevant conditions.
- There is little innovation proposed. There is only an offering of more of the same.

Project strengths:

- The project has made very good progress toward the project goal of realizing a more chemically stable composite PEM via the addition of weak acid polymers incorporated into the PFSA materials and use of an advanced CeO_2 additive. The weak acid polymer retains the cerium within the membrane (maybe via a chelating effect). The new composite membranes satisfy the project goals' ASR and H_2 crossover metrics. The HD-PFSA demonstrates little to no degradation after 3,250 cycles of GM's HAST. Nikola has done a good job directing the project and engaging all partners to achieve the project goals.
- The team is focused on understanding the fundamental issues associated with cerium migration and implementation of commercially viable solutions. There is good coordination among Nikola, Chemours, and M2FCT.
- This is a reliable lab and team with good resources for developing a targeted application (heavy truck power) to make a case for fuel cells in the transportation sector.
- Beginning-of-life performance of the Ce-stabilizing ionomer shows promise. Ce-stabilizing membranes show good stability.
- The project has a good approach and a strong team, and there is good progress to date.

Project weaknesses:

- The slides and presentation were confusing at times. It seems that the team has yet to test the fuel cell performance and durability with the hydrocarbon ionomer with weak acid groups in the PFSA, as mobility was not completely mitigated and the membrane conductivity was lower. Hence, the progress made by the team has been a reinforced PFSA polymer with advanced CeO_2 (doped material). Plans are proposed to improve membrane conductivity with the hydrocarbon weak acid ionomers by using lower-equivalent-weight PFSA materials. However, it is unclear what is being proposed to immobilize cerium better.
- It appears that the first proposed mechanism of Ce immobilization is not likely to work as intended. More characterization of the impact of polymer mixing is needed, i.e., water uptake, phase behavior as a function of RH, etc. The current generation of new Ce-stabilizing ionomer does not appear to perform any better than the commercial standard. The work needs to be more systematic in analyzing/characterizing the material properties of the new ionomer and for the development of strategies to address all of the limitations that are coming up in the work.
- The technology is not very innovative. The project is mainly using known technology at large scale to meet a targeted application.
- The project has not yet deconvoluted the effectiveness of HCWA itself in quenching radicals vs. using Ce as radical scavenger.
- This project is effectively a cerium migration project (which makes sense, given the small budget size).

Recommendations for additions/deletions to project scope:

- The project team should:
  - Perform parametric testing of hydrocarbon membrane and PFSA–hydrocarbon blends without radical scavengers to determine in which cases they are truly beneficial.
  - Study radical scavenging of polymer as a function of pKa.
  - Compare pure HC with Ce to PFSA with Ce.
  - Use a hydrocarbon membrane with the same crossover current as PFSA.

    - Consider replacing Fenton’s test with more representative tests (e.g., 100-hour life tests at steady-state, dry conditions).
- The Nikola team looks to be addressing the main challenges with cerium immobilization. Implicit in this work is the need to show cerium is still effective, even if it is held captive by a weak acid. This is an implicit goal of the project but could be added as an explicit goal.
- The dramatically lower conductivity of the PFSA–hydrocarbon blends is a puzzling result and should be further explored with the M2FCT team.
- The project should innovate more. The team should consider higher-temperature proton conductors, such as ion-pair, protic ionic pendant groups, etc., to minimize water in the membrane as a route to membrane improvement.

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

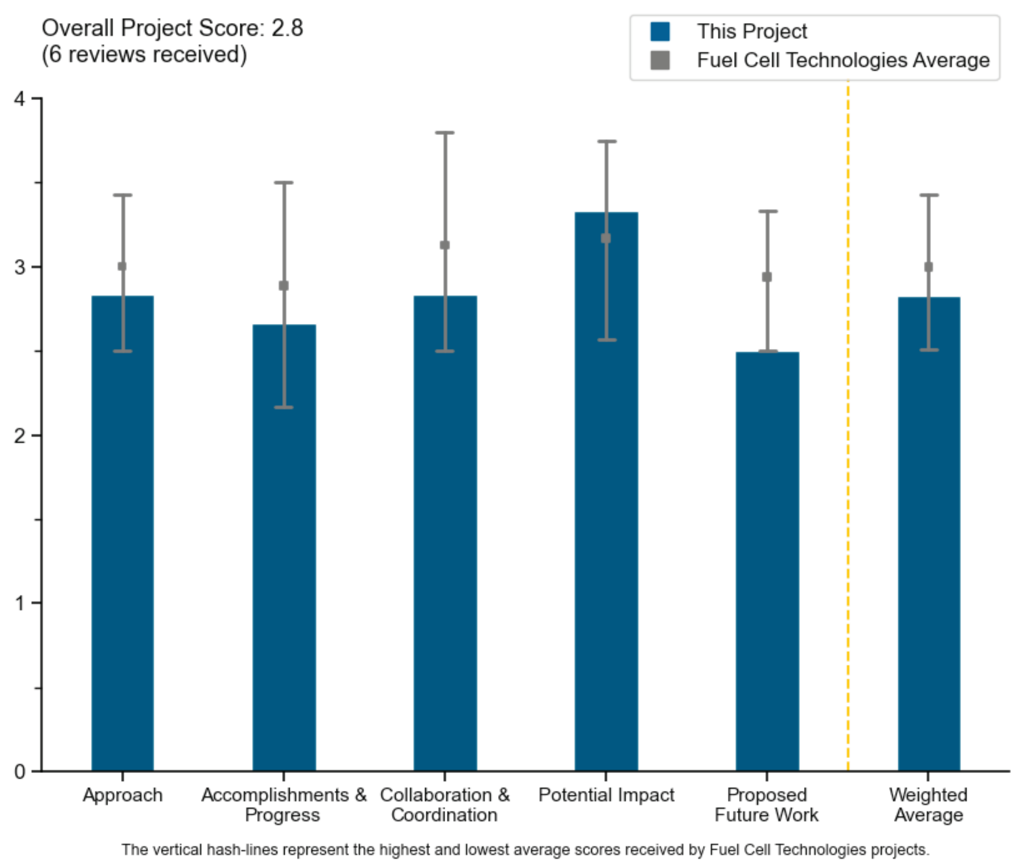
Tom Zawodzinski, University of Tennessee, Knoxville

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 (HD) 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 HD 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 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



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 project has a multi-pronged approach to modifying the acid groups of legacy polymers and non-fluorinated (hydrocarbon) polymers, as well as doping nanoparticles. The approach is promising and feasible for developing a high-temperature membrane for HD fuel cells.
- The project aims to develop hydrocarbon PEMs with adequate proton conductivity at 120°C and low humidity (35%–50% RH). The team aims to modify poly(arylene ether sulfone) (PAES) and Nexar with sulfonamide linkages that contain "ball" of sulfonic acid groups (i.e., branched aryl groups with sulfonic acid). The strength of this proposal lies in its straightforward chemistry to modify commercially available polymers (polysulfone) and Nexar to test whether the large concentration of sulfonic acid groups promotes proton conductivity under dry conditions. It is unclear why the team is working with Kraton's Nexar. Early PEM separators based upon sulfonated polystyrene by NASA were shown to rapidly degrade in fuel cell stacks. Perhaps the researchers should perform the chemistry they describe with thionyl chloride with the sulfonated branched polyphenylene by Ionomr Innovations (sold commercially).
- This approach is an attempt to modify pendant groups and polymer structure to raise the temperature to operate a fuel cell. The ball of sulfonates (BoS) approach has the potential to advance hydrocarbon ionomers and address a long-term challenge of low conductivity due to poor phase separation of the back-bone aromatic sulfonates. While the overall approach looks promising, the project organization and data presentation are not very clear. A better view of the technical plans and partnership with the Million Mile Fuel Cell Truck (M2FCT) consortium would be appreciated. This project is well positioned as the concern over polyfluoroalkyl substances (PFAS) grows.
- Many of the ideas being evaluated have been tried before and have not been competitive with conventional low-equivalent-weight perfluorosulfonic acids (PFSAs), even at 80°C, let alone 120°C. The one novel concept is the BoS, but there is no reason to expect these will not have similar issues to sulfonated poly para-phenylenes, such as poor mechanical durability and high swelling at the high ion exchange capacities (IECs) needed to meet resistance requirements.
- There is an abundance of alternative membrane chemistries proposed in this project. However, orderly progress toward the goal is limited. The project should show how something along the lines of "turning a particular knob" in the sample preparation has a certain impact on membrane conductivity.

Question 2: Accomplishments and progress

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

- Given that a no-cost extension had to be performed in budget period (BP) 1, the project has made very good progress, as the team has prepared membranes with the proposed chemistry of BoS on commercial hydrocarbon backbones. The team has shown a proton conductivity of 10 mS/cm at 120°C and 50% RH. Because the team is using a thin membrane, the project hit the project milestone of area specific resistance (ASR) of 0.08 ohm-cm^2 at 120°C and 50% RH.
- Identifying that the imide linking results in low yield and pivoting to the diazonium coupling is a significant accomplishment in advancing the materials development. The conductivity data was confusing and not well organized. Many results were presented as >100 mS/cm, while other results were presented to two decimals (i.e., 90.92 mS/cm). If two-decimal accuracy is possible in some cases, it is unclear why other cases were reported in such vague terms. The nomenclature of the samples is unclear. It would help to know the variables that were modified and how they related to the results reported. Water uptake, swell, and conductivity are poorly reported. These properties are interrelated and usually come with trade-offs. Summarizing these results more clearly is necessary for the reviewers and audience to see differentiation between this approach and other hydrocarbon ionomer systems. Understanding that the project is still in the early stages, it would help to have some basic mechanical property data (dynamic mechanical analysis, stress–strain, etc.) to know how this approach compares to others.
- The 0.08 ohm-cm^2 interim ASR target was met by measuring conductivity and calculating ASR assuming a 10-µm-thick membrane. A 10 µm membrane will no doubt require a mechanical support, which invariably

increases resistance, so it is questionable that the interim target has been met without an actual ASR measurement. There is no evidence that BoS in and of itself is more conductive than biphenyl sulphone: H form. The principal investigator (PI) claims that one of the goals is to advance the understanding of factors that influence performance and lifetime. However, the approach has not been systematic enough, nor has the analysis been in-depth enough as yet, to gain that understanding.

- There are limited measurements of conductivity at room temperature and higher temperatures for some other membranes. One figure was provided for conductivity vs. temperature, which, however, shows a decrease in conductivity starting at 100°C. The reduction could be due to reduced water uptake or a change in thermal stability, which should also be measured and investigated. The project could also benefit from a better comparison of the existing vs. new (developed) materials and how an improved screening method.
- A limited amount of data related to the major goal of the project was presented: an ASR of .02 ohm-cm^2 at 120°C and 50% RH. However, only one data point was shown at 120°C, namely 10 mS/cm, which is a bulk conductivity; significant impact on ASR comes from how thin one can make the membrane.
- The project is starting back up from previous work. This is the first year after a 10-year hiatus. Polymer development takes a long time. A review of earlier work was given, but minimal new results were offered.

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.

- APS has provided some polymers, and ORNL applied a Nexar-based model.
- The team makes good use of DOE resources and collaborators.
- The project team is appropriate, and there seems to be good collaboration between Saito at ORNL and Zawodzinski at UTK. It is unclear what APS has done on this project at this time.
- UTK and APS look to be coordinating well, but there is a lack of M2FCT contribution. Engaging the national labs where possible should advance the project.
- The project should collaborate with the M2FCT partners more for assistance with material selection and characterization.
- Collaboration with another organization was reported; however, it was not clear how much technical interaction happened

Question 4: Potential impact

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

- The proposed work has much potential. Simplifying the heat and water management in the fuel cell stack and shrinking ancillary balance-of-plant units (e.g., the radiator) necessitates materials that can operate at 120°C and 50% RH. Furthermore, it is important to devise new PEM materials that are non-fluorinated, given regulatory concerns of PFAS that may lead to the phase-out of PFSA ionomers. This project can satisfy said research areas.
- Hydrocarbon membranes have long fallen short of fluorocarbon membranes, especially in the areas of conductivity at low humidity and mechanical properties. If the BoS approach proves successful, it could provide a pathway to competitive fluorine-free ionomers.
- The project goal for developing new membrane materials that can operate at higher temperatures could improve membrane electrode assembly (MEA) efficiency and durability, which supports the fuel cells subprogram goals and objectives for achieving the HD targets.
- If the goals of this project are met (ASR and durability at 120°C), it would provide a great step to enabling commercial HD fuel cell system designs.
- Although a membrane that meets the goal of .02 ohm-cm^2 ASR at 120°C and 50% RH would provide a large benefit to system design, it was not clear how close the team is to getting to the target with this project.

- This approach is to modify the pendant group and polymer structure to raise the operating temperature of fuel cells. However, the rationale for and the effects of changes are not clear, so prospects for improvement are not promising.

Question 5: Proposed future work

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

- The listed activities are in line with the overall project timeline and goals.
- No clean plan was presented to indicate this project will meet either the performance or durability targets. A 10-µm-thick unsupported membrane is required to meet the interim ASR target, and a 4× reduction is needed, so there is no more room to go thinner. Increasing IEC is likely to increase swelling and solubility. No plan was provided for how durability will be assessed. This family of materials (sulfonated aromatics) has proven to be less durable than PFSAs. The future work included controlling solubility and swelling, but no clear indication of how was provided.
- Some effort should be spent on PEM durability and examining other hydrocarbon backbones beyond PAES and Nexar. The fuel cell durability was mentioned briefly at the end and during the question-and-answer session. The budget for the project is relatively small, and it limits extensive durability testing. The investigators should publish their review (in preparation) on hydrocarbon PEMs. A good deal of work was performed in the past. Summarizing the previous results will help the community move forward. However, not much has been done on hydrocarbon PEMs under hot and dry conditions.
- This approach is to modify the pendant group and polymer structure to raise the operating temperature of fuel cells. However, the rationale for, and the effects of, changes are not clear. While the effects of changes may raise the operating temperature, it is difficult to judge the prospects for success.
- The proposed future work identifies the broad areas that should be addressed in this project. However, a clear plan is lacking. Statements like "broader range of backbone chemistry" are not especially informative.
- Not much progress was evident with the limited data presented on the membrane ASR of the proposed approach.

Project strengths:

- The PI seeks both to develop new materials and to understand the fundamental properties that control conductivity in this class of ionomers. The progress to date on polymer synthesis is reasonable for this project stage. Identifying challenges with the imide linking group and changing strategies is a positive pivot for the project.
- A few promising hydrocarbon PEM candidates were developed with BoS, and they promote decent proton conductivity at 120°C and 50% RH. The project team was able to satisfy their go/no-go milestone for BP 1, despite the no-cost extension. The proton conductivity of 0.08 ohm-cm^2 is good for 120°C and 50% RH.
- The multi-pronged approach makes it possible to discover materials that could otherwise not be accessed. The exploration of hydrocarbon materials is a strength.
- This is the only DOE-funded active project focusing on developing membranes with improved performance and durability at 120°C.
- There is an abundance of novel membrane chemistries proposed here.
- The team is experienced and understands what is needed.

Project weaknesses:

- The multi-pronged approach makes it difficult to identify the key developments or isolate factors that lead to improvements. The properties reported to screen and characterize the membranes are limited. For a project that aims to develop high-temperature materials, thermal–mechanical stability should be assessed as well. The synergy between the activities should be clarified better. The project could benefit from a better delineation of how the information flow will take place between tasks or materials (chemistry, processing, composite formation).

- The main weakness of the project is the selection of backbones studied. The styrene-type backbone in Nexar will probably not hold up to reactive oxygen species in a PEM fuel cell. The PAES backbone should fare better. The scope of work should include more detailed plans to assess durability for PEM fuel cell operation for HD vehicles.
- The PI reported that several polymers have been made, but there is little characterization presented. Overall organization could be improved. The role of M2FCT should be clarified. The plan for functionalized cerium nanoparticles (CeNPs) is unclear.
- The approach is unlikely to achieve the goals. The project uses a non-systematic approach (too much trial and error). No details of future plans were provided. Limited characterization data and analysis have been provided.
- Essentially no data on new membrane ASR was reported at target conditions.
- The cause and effect of changes is not clear.

Recommendations for additions/deletions to project scope:

- The project could benefit from collaboration with the ongoing HD vehicle membrane activities, including the use of existing membrane properties as a baseline for screening and comparisons. This could be followed by some MEA testing. More systematic and fundamental measurements of the materials are needed, especially because the chemistry and acidity are modified in these systems. Proposed future work on composites and durability should be kept—but with an explanation of the down-select process.
- There are a number of "knobs" that can be turned to achieve targets; the following are some that were not really addressed:
    - Air operating pressure: 50% RH, 120°C at high air pressure is a different animal as compared to low pressure; furthermore, counter flow gas feeds could help with membrane ASR for membranes with close-to-target performance.
    - Membrane thickness: One way to drive down ASR is to lower membrane thickness; in this project, the other system implications of this approach could be addressed later if membrane thickness could be driven to sub-10 µm effectively.
- There should be more focus on the relationship between key material properties such as water uptake, conductivity, and mechanical properties. Comparing these properties within the experimental membranes, but also with suitable baselines such as traditional sulfonated poly(ether ether ketone), will allow the reviewers and audience to see the advantages (or lack of advantages) of the new materials. M2FCT should be enlisted to conduct small-angle x-ray scattering or other techniques to investigate ion channel formation for the BoS systems compared to traditional hydrocarbons.
- The project should consider the following:
    - Share IEC and swelling data for all samples.
    - Show proof of ability to make thin films.
    - Report CeNP content.
    - Do mechanical testing (elongation to break, stiffness).

  Furthermore, ex situ conductivity measurement at 120°C and 50% RH (100°C dew point) is very difficult. Humidity is more easily controlled when doing in situ ASR measurement in a cell under increased pressure.
- Fuel cell membranes are complex and depend on having a number of properties in the electrolyte at the same time (e.g., ion conductivity, temporal stability, low adsorption on catalysts, and proper transport of hydrogen and oxygen). The team needs to make a better case for how changes in membrane components affect the properties (cause and effect) and prioritize accordingly.
- It is recommended that the project team perform accelerated stress testing of the most promising PEM variants in a fuel cell.

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

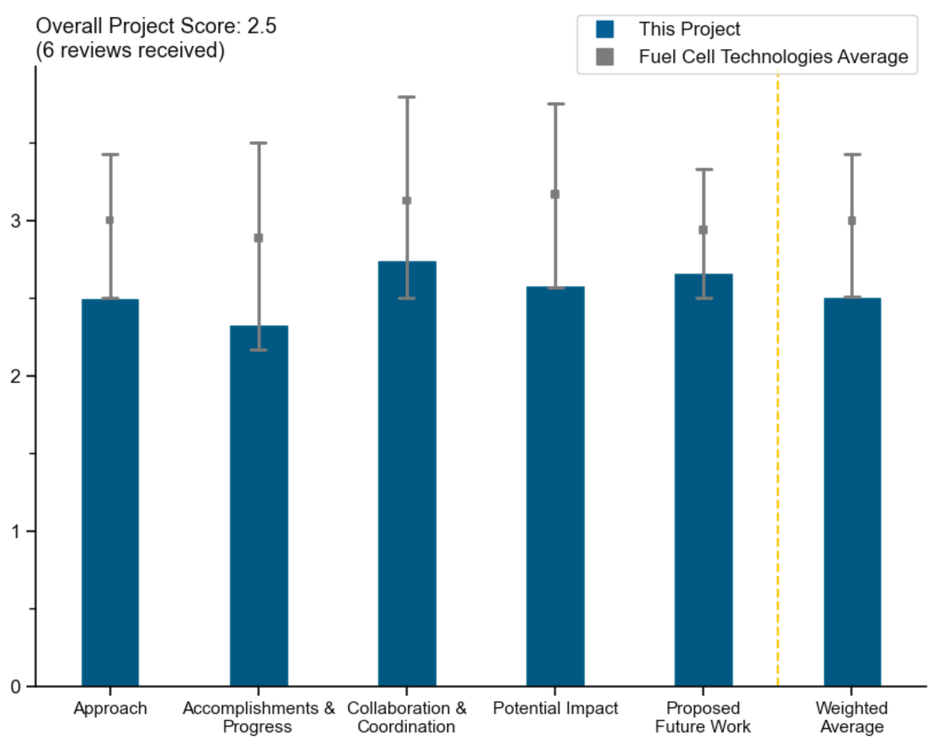
Jean St-Pierre, Cummins Inc.

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 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, a study on advanced manufacturing methods to reduce production costs will be undertaken. 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 **2.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The high-level approach is reasonable, with MEA, system, and plate approaches. However, there are limited details on actual approaches, and therefore, the approach is difficult to assess. No details on MEA changes, plate flow field design, or e-turbo approaches are provided. The stack cost project is not planned until later in the project. Initial modeling should be presented to provide estimates of potential feasibility to meet cost targets. The cost review in Quarter 6 may provide some information; however, the details are not clear. The use of commercial-scale cells and stacks, as well as the 5,000-hour tests planned for later in the project, provide very relevant data and provide a good complement to other more fundamental projects. However, the lack of detail on the materials and design reduces the value of this work. The project team has stated that all data on MEA testing will be fed to ANL for model validation. This information will be an important aspect of the work to derive value from the testing. The statement of project objectives (SOPO) targets chosen are relatively low compared to DOE HD targets. The presenter was not able to provide any justification. Changes to highly accelerated stress test (HAST) conditions may have significant impacts on the stressors and mechanisms accelerated.
- Developing a PEMFC that operates at >100°C is very challenging, since state-of-the-art proton exchange membranes (PEMs) require water to work effectively, and most PEMFC degradation mechanisms are accelerated exponentially with temperature. Therefore, ideally, a breakthrough in PEM technology is needed, which is not the focus of this project. Although the activity losses can be reduced with higher temperature, this is typically offset by higher ohmic losses, especially at higher current densities when operating at higher temperatures is most advantageous since that is where high heat rejection rates are needed. Even if the goals can be achieved with conventional PEM materials, then the durability targets become far more challenging. However, since some new materials have been developed recently, it may be worth trying to develop a PEMFC system that is capable of >100°C operations.
- The project approach is to develop a novel fuel cell system suitable for HD fuel cell applications through a bottom-up design and/or selection of key components (bipolar plates, MEAs) from single cell to stack to system. The project will achieve this through integration of advanced high-temperature ionomer/membranes, turbo compressors, and flow fields via improved compression molding. There are a few shortcomings. The project does not appear to be addressing one of the critical barriers, which is catalyst durability. Also, it is unclear whether the accelerated stress test (AST) durability protocols selected are representative of the known stressors for catalyst and ionomer. For example, it is unclear how the "50 acceleration factor" on slide 8 was determined.
- It was good to see the plan updated to run a 10 kW rather than a 1 kW stack, which would have been only one or two cells. The project does not use a representative durability test with known acceleration factors at the chosen high-temperature operating conditions. The project's target peak power density of 0.8 W/cm^2 at 0.3 mg Pt cm^2 is not very ambitious. Such a large (900 cm^2) active area will be very challenging, both to produce and to do stack assembly at high volumes. Cummins mentions they are already having trouble with compression molding. They have identified machining as an alternative, which will be much more expensive. It is unclear whether roll-to-roll MEA manufacturing will be demonstrated within this project.
- The approach provided as a set of milestones and deliverables just lists known tasks that are required to build a stack and test this in a lab. There are no specifics on how this project is addressing the critical barriers of improving (1) the high-temperature capability of the MEA, (2) stack cost vs. radiator cost for a 200–300 kW system, or (3) power density of the composite plates (not just the current density but the entire power density [kW/liter]) of the stack.
- Demonstrating a 1 kW stack in Budget Period (BP) 1 before building a 100 kW stack in BP 2 is a good approach. However, the go/no-go decision of only 0.3 A/cm^2 at 0.75 V is very low and needs to be made more stringent.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and DOE goals.

- The Gore-1 membrane was selected for a 10 kW short stack test. No work on bipolar plates or the turbo compressor was reported this year. Minor changes to the plate were introduced, but why they were introduced was not reported. A model was developed that predicts polarization curves at two different sets of conditions, both at 110°C. The project should confirm if the model is accurate at lower temperatures as well, where there may be liquid water present. Durability tests were run on two types of Gore membranes. The protocol was based on a General Motors HAST protocol but at higher temperature, which likely significantly reduced the mechanical stress by reducing the magnitude of the humidity cycles. The membranes had different thicknesses and stabilizers, so the researchers could not isolate what led to the increased durability of the Gore-1 membrane. There was no comparison of performance for the two Gore membranes. No catalyst analysis, such as electrochemical surface area or mass activity loss, was presented, nor were any mass transport or ohmic losses reported.
- No data was provided on bipolar plate design accomplishments in terms of pressure drop and ability to push the boundaries. Results presented in 2022 were all normalized, with limited information on the critical aspects that were stated as key project objectives, e.g., (1) Push the boundaries of compression molding technology with graphite/polymer composites; (2) Form fine flow field channels and achieve practical pressure drops at high pressures. At a minimum, results could be compared against literature or internal baselines (only channel-to-channel variability data was provided). The model fit seemed fine, but the presenter did not outline how this will be used to drive design. A significant number of potentiostatic ASTs were completed while monitoring H_2 crossover. The results on H_2 crossover over the 48-hour test duration seemed to be within noise, with no trends observed. They did not provide any indication of why the Gore-1 membrane is significantly more durable, and no analysis was done. The stack hardware design chosen was a traditional design. The design reviews would provide some benefit, but it would have been good to see some improvements in design as a result of the funding. MEA results exceed the SOPO target, but there was no indication of composition, and therefore, no learning was shared. The project used an implied acceleration factor of 50 to state a performance loss of 20 mV for 20,000 hours in the field. This is an incorrect assumption. A 500-hour AST test is a reasonable test duration but is not necessarily equivalent to 25,000 hours. Additionally, the test conditions were different from Million Mile Fuel Cell Truck (M2FCT) conditions.
- The project has not yet built the stack but does have a no-cost extension. The team has promising single-cell data, which (one hopes) can be reproduced in a stack. Only two sets of MEA durability data were shown. It is better to run shorter tests at this stage and run more of them to get some statistics, rather than just run one long test for >2,000 hours. Better to project out from fluoride release rate (FRR) and thickness change over, say, the first hundreds of hours at various conditions instead of running just one condition for >2,000 hours.
- The performance polarization curves indicate that the voltage is at 0.3 A/cm^2 and >1 W/cm^2. However, there is no mention of how these values are linked to the DOE target tables of 68% peak efficiency and 25,000-hour life. For the project-related goals of (1) demonstrating high-temperature-capable MEAs and (2) fine flow field channels to achieve practical pressure drops, there is no mention of the internal status before the project vs. what was accomplished throughout the project. The accomplishments feel more like re-testing Cummins' internal baseline(s).
- The primary accomplishments appear to be stack hardware design completion (few results shown), selection of the Gore-1 membrane for the 10 kW stack demonstration, model validation, and completion of a series of ASTs. Since these AST conditions are new and differ from existing protocols, it is unclear how relevant they are toward predicting durability under end-use conditions. Overall, the project appears to be behind schedule, but it is difficult to assess by how much.
- It is not clear why stack design is a major focus of this project, since higher-temperature operation should not have a major impact on the non-repeat parts, such as end plates and bus bars. Clarification is required if this is due to Cummins' not having yet established a robust stack design. The project appears to be significantly behind the proposed schedule, but no showstoppers have been identified.

Question 3: Collaboration and coordination

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

- The addition of more input and assistance from the M2FCT team is good. The inclusion of the Pajarito Powder catalyst is also a nice addition, since catalyst durability is a major issue that warrants more attention here.
- There is very good collaboration with Gore, Dana, and M2FCT.
- The project has good interactions between original equipment manufacturer (OEM) and supplier, but this is not a true collaboration. It feels more like Gore and other sub-contractors are providing parts based on specifications from Cummins. Collaboration with M2FCT was mentioned, but no test plan or results were presented. The planned work to test MEAs through M2FCT and ANL data analysis of the stack would improve this score for the next review.
- Cummins is getting membranes from Gore, although they seem to be commercially available membranes, so it is not clear what Gore is doing other than providing materials. Dana will be providing the plates for the stacks. There is no evidence of contributions from ANL or M2FCT.
- Several partners are listed, but there is no indication of significant collaboration. The commercial partners are supplying materials only. The work with M2FCT is not outlined.
- It is unclear if there is significant collaboration with other institutions. Clarification is needed as to whether they are acting simply as suppliers or co-developers.

Question 4: Potential impact

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

- Building stacks and operating them under hot dry conditions will provide the Hydrogen Program (the Program) with excellent data toward HD application of fuel cells.
- Project goals are relevant and support targets for HD vehicles. Milestone targets are low and do not appear to push the envelope of capabilities.
- The project has potential for modest impact to advance against the barriers for HD fuel cells.
- If the project is successful and demonstrates membrane durability at a peak temperature of 110°C, that aligns with Program goals. If the project is successful in producing high-quality compression molded plates that meet cost targets, that would be valuable. Machining will not.
- The project is expected to address either efficiency (68%), durability (25,000 hours), or cost (80$/kW). It is unclear how any of the proposed work and the accomplishments listed so far are linked to these goals. It feels like this project is getting tunnel vision and focusing mainly on cost reduction through increased operating temperature. However, there is no analysis or data showing the impact of temperature on the cost of the fuel cell system. While it might help Cummins to reduce the cost of the radiator, it not a part of the fuel cell system and not included in the DOE targets table.
- The potential impact of this project is not clear, because it is not evident that the key benefits of a PEMFC that operates at >100°C have been sufficiently quantified. It is unclear what the savings are. The reduction of the radiator size in fuel cell electric vehicles (FCEVs) is clear, but the cost benefit of this is not substantial. Many FCEVs that operate at <100°C have been successfully demonstrated. In sum, this appears to be a high-risk, low-potential-impact project.

Question 5: Proposed future work

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

- The proposed work plan to build a 10 kW stack and share data and materials with M2FCT is excellent. This should help the Program.
- Proposed next steps are logical, based on this reviewer's understanding of the project plan.

- The project plans appear to support progress toward project goals, but lack of detail provided on approaches make this question difficult to assess.
- The proposed future work is okay, but it is not clear why a 10 kW stack demonstration is warranted, unless small cells are demonstrating that the team's performance and durability metrics can be achieved. Presumably, the stack work is being prioritized here because one of Cummins' key objectives is to mature the company's stack design for any operational envelope.
- Future work needs to focus on identifying gaps to the project goals and specifically addressing those, not just a list of tasks to build and test a stack. It would be good to add the following for future work: (1) the impact of operating temperature on stack/compressor cost and durability, (2) the impact of key design features to improve power density of bipolar plates, and (3) a cost estimate and modeling of compression molded bipolar plates to pressed graphite plates.
- The project will conduct postmortem analysis of membranes from a durability test, including x-ray fluorescence (XRF) for stabilizer distribution, to determine failure modes. There is no plan to validate the claimed AST acceleration factor, and no future work on the turbo compressor is planned. Perhaps it is no longer part of the project. The team should prioritize addressing quality issues with the compression molded plates.

Project strengths:

- The project aims to integrate advanced flow field and turbo compressors to enable efficient operation at high pressure, a promising approach to meeting performance objectives.
- The team and principal investigator have a good deal of potential to make a meaningful impact and progress toward achieving the DOE goals toward HD fuel cell systems.
- Cummins' building fuel cell stacks for HD operations and sharing the data and materials with DOE is excellent for the Program.
- Strengths include the OEM, the project's operating at commercial-scale approaches, and the project's working with good suppliers and commercially relevant materials. The work is addressing high-temperature operation.
- The recent addition of more involvement by M2FCT should help establish better objectives (e.g., performance targets) and test methods (e.g., ASTs).
- Stack performance and durability data will be provided. Gore provides state-of-the-art membranes.

Project weaknesses:

- Crossover data during potentiostatic ASTs for the different membranes were not compared at the same conditions, making it difficult to make clean comparisons. Selected durability protocols have not been proven to include all membrane failure modes, especially stabilizer redistribution due to humidity gradients. The mitigation strategy for plate manufacturing of machining will not meet cost targets.
- The project lacks fundamentals, baselines, and sufficient material and/or design information to provide values to others. It is understandable that that some degree of normalization is required because of the commercial nature of designs. However, more attempts should be made to provide information in a format that will provide some value to others. Low targets have been set.
- The project does not have clear long-term objectives or targets. It is unclear what performance and durability measures are required to make a >100°C PEMFC viable.
- The project does not seem to be making significant efforts toward addressing the key barrier of HD fuel cell catalyst degradation, which would be expected to worsen substantially at the elevated temperatures this project appears to be targeting.
- The project team currently has tunnel vision, with a focus on enabling a cheaper radiator rather than trying to address the fuel cell system goals and barriers.
- More progress needs to be made with single-cell MEA durability testing.

Recommendations for additions/deletions to project scope:

- The project should report the FRR results, stoichs, and flow orientation for the HAST test. The performance model should be validated on the full active area cell over a wider range of conditions including lower temperatures at which liquid water may be present. Electrode analysis and diagnostics should be included.
- Any 100 kW stack or something bigger than a 10-cell stack should be removed from the project. This project is not a technology demonstration project. Rather, the focus should be on doing the following:
    - Use the polarization curve reported, along with the membrane crossover and compressor power data, to estimate peak efficiency.
    - Establish a plan to close the gap.
    - Conduct a cost estimate of the stack for various design options to demonstrate progress toward a $60/kW fuel cell system.
- The project should increase analysis of test results and provide conclusions. Data on baselines is needed, and real progress must be shown. Targets should be adjusted to better match DOE targets.
- Only two cells operating with different MEAs under a HAST-type test were shown. It would be good to expand this rapidly to other conditions. There is no real need to run 2,000-hour tests so early in the project when still selection is ongoing. It would be better to understand durability under various conditions.
- DOE should request that Strategic Analysis assess the impact of >100°C PEMFC systems, if this has not been done recently.

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

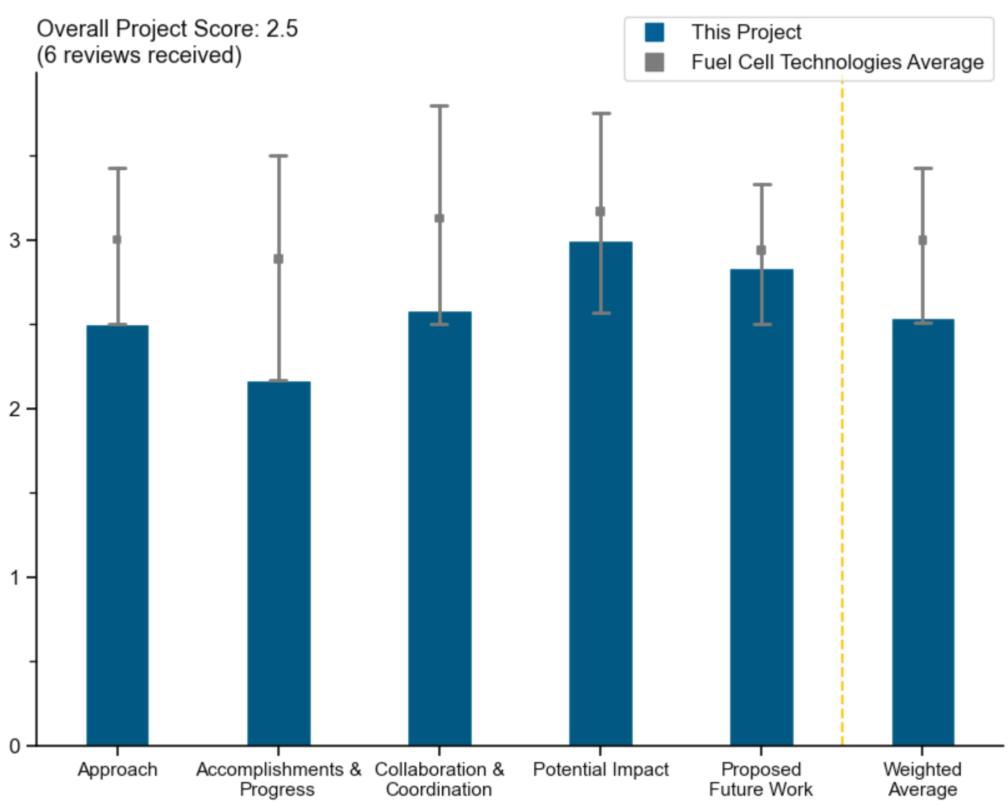
Karen Swider-Lyons, Plug Power Inc.

DOE Contract #	DE-EE0009248
Start and End Dates	10/1/2021–6/30/2024
Partners/Collaborators	Argonne National Laboratory, M2FCT
Barriers Addressed	• Performance: High catalyst activity, low mass transport resistance, low electronic resistance interfaces • Manufacturing: Supply chain, translate lab equipment to high-volume manufacturing

Project Goal and Brief Summary

Plug Power Inc. (Plug Power) 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 **2.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The milestones in slides 7 and 8—especially the 840 mW/cm^2 power density at 0.769 V—are excellent and very aggressive. Building 5 kW and 100 kW stacks and sharing data with the Million Mile Fuel Cell Truck (M2FCT) consortium would help the DOE Hydrogen Program.
- The project overall seeks to develop high-performance, domestically manufactured fuel cells, via material screening (membrane electrode assembly [MEA] via accelerated stress tests [ASTs], BPPs, seal materials) and design and building of an automated stack assembly machine. The overall approach is largely experiment-driven, which is appropriate.
- The goal of using commercially available materials and high-volume manufacturing processes to produce heavy-duty vehicle (HDV) cell stacks is good since this is the most expeditious route to developing a viable product for potential HDV applications. However, what is currently being done by the team is not good. The project is running two very different test protocols on two different hardware platforms (single cells and short stacks), which makes comparisons of these apples-and-oranges results very difficult and is unlikely to result in learning anything really useful. It is unclear what running an AST protocol on short stacks would yield. The desired diagnostics are hard to do on stacks. One should do ASTs on single cells to determine whether the cell materials are prone to degradation due to the known proton exchange membrane fuel cell (PEMFC) decay mechanisms. The highly accelerated stress test (HAST) being done with the single cell is not the most appropriate AST to use, as was pointed out by one of the reviewers from General Motors who helped develop this HAST. The principal investigator's rationale for running a much milder AST on the short stacks was that the fuel cell community needs to show that PEMFCs can meet the HDV durability targets. It should be noted that multiple PEMFC-powered buses have now demonstrated >30,000 operating hours. What is really needed here is to show that Plug Power can build stacks (using the company's state-of-the-art, high-volume production processes) that can meet the HDV targets.
- The approach slide focuses on the validation of the ANL HD durability model. This looks like a reasonable approach and will provide value. The specific details that are to be shared are, however, not clear and may negate the actual value achieved. So far, there is little data on the types of materials used. Increased information will increase value of the project for others, including DOE, and will enable better guidance from reviewers and the research and industry communities. Several underpinning technologies are listed on slide 3. However, aside from the work on plate coatings, there is little in the project that addresses these. There is no information on what is being evaluated, i.e., which vendors, how many vendors, vendors of which components, etc. There is a reasonable amount of durability testing and diagnostics planned. These activities need to be complemented with end-of-life materials characterization and the data shared. The use of the HAST-type conditions for voltage degradation is not appropriate, as this was designed for membrane degradation. The very different conditions used for the single-cell vs. short-stack testing make comparisons difficult. Understanding differences between cell and stack durability testing when trying to make conditions as similar as possible would instead be a valuable approach.
- It is wonderful to see that this project is leveraging the high-volume production methods to provide stack-level data toward progressing HD truck DOE goals. However, there is no clear plan to establish the gaps toward any of the following HD goals: peak efficiency (68%), durability (25,000 hours), or cost. The approach feels like this project is trying to integrate various sources of catalyst, membrane, and other cell materials to see if progress can be made toward one of these goals. It is not clear where the team's state-of-the-art materials are compared to the DOE HD goals.
- While the general scope of work makes sense, there are not enough details on the materials and designs used and absolute results to assess the value of the approach. Plug Power is using an AST designed to accelerate membrane damage as a metric for performance loss. Also, for some unknown reason, the team used different lower current densities in the single-cell and stack tests, which, as expected, led to less degradation in the stacks.

Question 2: Accomplishments and progress

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

- No power densities were reported. Plug Power claims potentiodynamic and potentiostatic corrosion tests were completed, but no results were reported. This is critical, especially with the claim that uncoated stainless has satisfied all requirements. If that is true, it is unclear why a more expensive titanium option was considered.
    - The resistance scorecard is difficult to follow. It is unclear whether it is new data that was generated as part of this project.
    - Also, reported catalyst coated membrane (CCM) resistances, which are typically of the same magnitude as the BPP–gas diffusion layer (GDL) resistance, are very low in this project.
    - The automated leak detection is the most intriguing work, with a demonstrated 14-second cycle time. It is not clear whether the tests are done at a cell or stack level or whether the cells are at the nominal stack compression levels during these tests.
    - Also, as Plug Power is ultimately getting MEAs from Johnson Matthey, one would assume Johnson Matthey has a pinhole/crossover spec on incoming MEAs.
    - Compression set is a function of stack materials, designs, assembly method, and operating conditions. It is unclear what Plug Power’s approach is to reduce compression set. It is also unclear how the claimed reductions in compression set are affecting performance losses or durability.
    - Using different durability protocols between single-cell and short stacks severely limits the value of the comparisons.
    - ANL should be modeling the results of the durability tests to see whether the lab agrees with expected results. It is very surprising to see no performance loss in the stacks after 20% electrochemical surface area loss. It is unclear whether this is the expected result.
    - The stack MEAs do not appear to be fully broken in, whereas the single-cell MEAs do. It is unclear whether there are different break-in protocols on the two platforms.
- The work is said to include extensive screening of CCMs and GDLs; however, no data is shown. No actual data is shown for plate testing, and the data shown on slide 9 was not generated in this project. Leak detection in an automated system with a cycle time of 14 seconds is a good accomplishment. The low-compression set materials work is useful, but value to others is only achieved if additional information is shared, e.g., at least the material classes used (specific grades do not need to be revealed). The very different conditions in the cell vs. stack testing result in difficulty in comparing test conditions. There is good data mapping temperature and conditions of training stack. Sharing of fluorine data would have been useful.
- The results presented suggest a modest amount of work was completed over the past budget period in terms of the stack AST and stack/single-cell AST correlation work. Progress was made on high-speed MEA pinhole detection and metal BPPs.
- It is very good to see some stack-level data and the cells being tested on accelerated protocols. The test data being presented does take significant time and effort to plan, execute, and analyze. However, this significant amount of data has not necessarily translated to any significant accomplishment, which is likely because of a poor approach.
- It is unclear whether slides 10, 11, 12 and 13 show accomplishments from this project. Slides should be clearly marked with the specific progress on this project. It would have been helpful to see more data presented regarding the milestones.
- The team has already collected considerable data, but the data obtained to date is of limited value.

Question 3: Collaboration and coordination

This project was rated **2.6** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration with M2FCT and labs is excellent. It is unclear whether there is any collaboration with materials (catalyst/membrane/GDL) suppliers. It would be good to mention some of these, even if their names need to remain confidential based on agreements.
- ANL's role is in this project was not clearly communicated. Presumably, ANL models will be used to determine what the load profiles might be in different HDV applications. This is needed, but it is doubtful that Plug Power would use ANL's system model to project the stack load profiles, since one would assume that a fuel cell electric vehicle (FCEV) developer with Plug Power's experience would then have a superior idea of what the stack load profile might be (e.g., how the load is shared between the PEMFC and the batteries in a hybrid FCEV). In short, all ANL is providing is HDV load profiles. Slide 22 states that Plug Power's durability data will be integrated into ANL's model, but the value of this is not clear since Plug Power is not generating real-world data here and the AST results are not very helpful for ANL's system model. It is good to see M2FCT's durability team involved here, since Plug Power can use the consortium's help in establishing the appropriate AST protocols, comparing the company's results with AST results obtained by M2FCT, and using M2FCT's capabilities to examine post-test components that show evidence of significant degradation.
- It is expected that the collaboration with ANL and M2FCT will be relevant and useful, providing critical data to ANL for stack durability testing and providing significant MEA characterization by M2FCT to feed into that analysis. However, no specific information on M2FCT characterization is provided. No other partners are included.
- Plug Power, with its significant buying power, has the ability to bring in various international suppliers and vendors to develop an HD MEA that can simultaneously meet the efficiency, durability, and cost targets. While the project has listed some partners, the direct network of world-class material providers is a hidden benefit/collaboration that is key.
- All the work presented was done by Plug Power. ANL is a sub and could provide valuable modeling of performance and durability data, but this work has not started.
- It is unclear how significantly ANL and M2FCT have been involved with the project to date.

Question 4: Potential impact

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

- The intended impact of this project is well aligned with DOE goals. If the approach and execution is improved, then this project could be highly valuable, especially if Plug Power is willing to share the key findings, such as the performance losses observed and the results of teardown analysis.
- Developing stacks with state-of-the-art MEAs and evaluating their durability and sharing that data with the community will contribute to achieving DOE research and development goals and objectives. The project has the potential to lower manufacturing barriers.
- The approach to help ANL validate the HD model using Plug Power stack data is extremely valuable. The extent of details that will be shared will govern the extent of that value and is not currently clear. If successful, the project will enable Plug Power to meet goals and is likely to support supply chain advancements, e.g., stack leak testing equipment. The lack of information provided on materials and designs severely limits additional value.
- The project has the potential to help decrease the cost of domestic fuel cells by developing high-volume manufacturing for stacks comprising high-performance and durable MEAs.
- The project goals, if met, could have a significant impact toward meeting the DOE goals for HD trucks. This project has a correct goal and a good network; however, the approach needs to be modified to ensure that the potential impact can translate to actual, meaningful impact.

- It is unclear what is unique about this project for HD applications. At the end of the project, there will be a 100 kW stack, which is low power for HD. Cost benefits are not quantified. The automated leak testing is novel and potentially impactful. One hopes more details on how this is done will be provided.

Question 5: Proposed future work

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

- The plans for future work are reasonable, assuming Plug Power comes up with a stack test that accelerates voltage loss faster. Otherwise, the project team will not be able to forecast HD durability within the timeframe of the project. Plug Power should provide more details on the plate coating durability assessment. Plug Power should disclose some details about the MEA and plate materials used in the project. Other projects disclose much more (platinum group metal loading, plate materials, etc.).
- The project has proposed a good deal of work toward making a better MEA. However, the proposed future work does not clearly lay out what the gaps are and how the project team intends to close them. Perhaps the team already has a good idea on what the gaps are and a clear plan to close these gaps and simply has not clearly communicated that plan. Conversely, perhaps the team is still figuring out what the gaps are and how to close them. If the latter is the case, then the project needs to leverage either internal capability or ANL's capability to do a deep dive of the latest MEA results and pick apart the key factors contributing to the gaps in performance targets and lay out the MEA designs based on those.
- The proposed future work on slide 20 is all good, assuming that recommended modifications to the AST protocols and stack testing are implemented. More active engagement with the M2FCT team could help with making these needed changes.
- The next steps appear logical, based on work completed and the approach to Phase II.
- The work shown is planned in a logical manner. The lack of accelerated testing for the stack is a shortcoming.
- More details are needed on advanced MEAs and how the aggressive targets are going to be met.

Project strengths:

- The prime is a viable FCEV developer with extensive fuel cell manufacturing experience. This can help determine the status of PEMFC cells and stacks that are produced using commercially available materials and relatively high-volume manufacturing processes. The principal investigator appears to be open to constructive recommendations.
- Single-cell and short-stack testing and comparison of degradation effects will provide some value, although conditions could potentially be better chosen. Other strengths include testing of trends for MEAs when comparing ASTs, commercially relevant materials and designs, the high-volume automation approach, and equipment sourcing.
- The project has a good team and a wide network. Further, Plug Power brings in huge scale-up capability to have a meaningful, measurable impact toward zero-emission commercial vehicles.
- Strengths include a focus on an automated cell leak detection method and a plan to engage ANL for performance and durability modeling.
- Good progress has been made toward stack testing, considering the no-cost extension and the actual amount of money spent on this project. There is close collaboration with M2FCT and labs.
- The project is focused on addressing the key challenges with developing high-volume stack manufacturing.

Project weaknesses:

- Most of the results that were shared are well known and expected, such as an inlet-to-outlet temperature increase in a stack. Comparisons between short-stack and single-cell results are meaningless, as they use different protocols. Protocol comparisons should be done on the same platform. Platform comparisons should be done using the same protocol. The project team is using a membrane AST to study voltage loss, which is not accelerated in that protocol. Plug Power also modified the HAST protocol, increasing the lower current density to 0.1 A/cm^2, making it less stressful. No beginning-of-life performance comparisons were conducted between the single cells and short stacks. No details were provided about MEAs (Pt loading, membrane thickness) or plates (based materials, coatings, active area) used in stack tests.

- The stack AST testing may need to be assessed; it does not appear to be very accelerated (almost no decay after 500 hours). Considerations should be made to ensure that the stack protocol is capturing all relevant degradation modes (it seems to be going a bit easy on catalyst cycling).
- The approach is the biggest weakness. It feels like the researchers are trying to test all possible combinations, hoping to get lucky and find something that works. It would be better to leverage the project's very capable team, test capabilities, and production scale-up and direct resources to solving the gaps.
- The presentation could use more clarity on the project goals and the progress made toward those goals.
- A weakness is the current durability test plans.
- Limited material information and test data were provided. This makes it difficult to further assess approaches. A list of materials characterization tests to be completed is not included.

Recommendations for additions/deletions to project scope:

- The project is asked to:
    - Report absolute voltages from stack tests, noting that other stack projects are showing actual polarization curves rather than relative voltage loss.
    - Report details of plate corrosion tests, including test setup, protocols, and results.
    - Share details of the recovery protocol and report recoverable vs. non-recoverable performance losses.
    - Report fluoride release during durability tests.
    - Provide cell-to-cell performance variation in the stacks.
    - Conduct cost analysis, or at least provide enough details to Strategic Analysis so that they can quantify the benefits of this project.
- The team should develop an improved durability plan, which should ideally consist of the following: (1) using the new DOE AST for HDVs on single cells to determine whether their cell materials are robust (Plug Power's results can be compared to what M2FCT obtains on other cells using different materials and assembly methods), and (2) operating short stacks using a protocol that mimics the expected operation in an actual HDV application. When performance decay does occur, the team should consider using the simple polarization-change approach as a starting point to determine the type of degradation occurring (see M. L. Perry, R. Balliet, and R. Darling, "Experimental Diagnostics and Durability Testing Protocols," in *Modern Topics in Polymer Electrolyte Fuel Cell Degradation*, M. Mench, E. Kumbur, and T. Veziroglu, Editors; Elsevier, Denmark [2011]). Additionally, presenting delta-V (mV) vs. current density (A/cm^2) is preferable to plotting "percent voltage" vs. current density and still allows one not to show actual cell voltages (if that is considered proprietary).
- More information should be provided on materials used and data generated. It is not expected that specific grades would be shared, but some minimal information should be provided. There is a good set of durability test and diagnostics planned. These need to complement end-of-life materials characterization and the data shared. Cost projections for the stack and system should be included. Explanations are needed of how technology underpinnings on slide 3 are relevant to the project outcome. The results for single-cell vs. stack may provide value. It will be important to further analyze cycles and stressors (voltage, temperature, relative humidity, time, cycles) to draw correlations. The materials characterization will be very useful. Looking at the trends vs. MEAs will also provide useful information. Data on fluoride loss during degradation testing should also be provided.
- The project needs a clear plan for identifying and closing the gaps of state-of-the-art MEAs toward DOE goals. A simple waterfall chart to communicate the same will be helpful. Further, it is not clear if this team has leveraged ANL's capability toward modeling the degradation results from the tests conducted so far. Modeling the degradation would be helpful to provide additional pathways to close the gap toward durability and provide estimates for the acceleration factors for the project ASTs.

- The goal of the stack testing should not be to operate the stack in a benign condition to prove long lifetimes but to actually operate the stack under stressful conditions and then, using that degradation understanding, to extend lifetime either through materials improvements or system operating strategies.

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

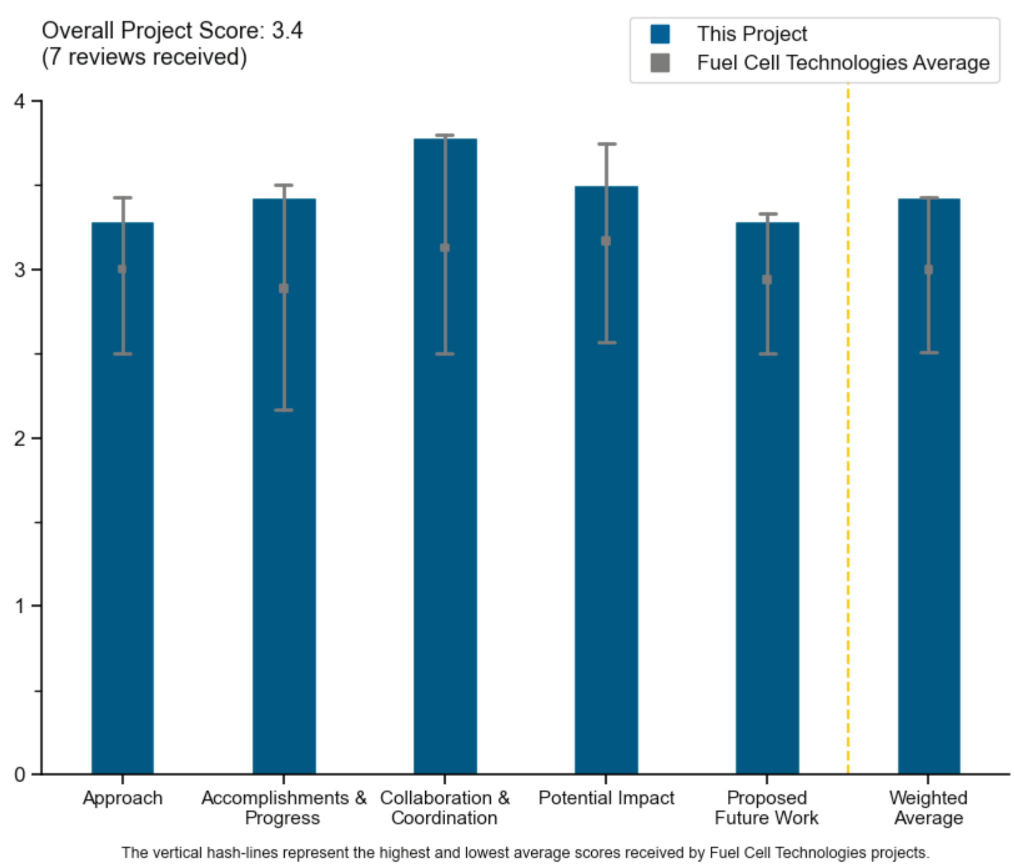
Rod Borup, Los Alamos National Laboratory, and Adam Weber, Lawrence Berkeley National Laboratory

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 (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



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 consortium totally covers development of key components/materials and system integrations (stack development and system modeling) for HD applications. It is very good to focus on key attributes for HD applications, efficiency, and durability. Here are some suggestions to consider additional study to reinforce the consortium.
  - Test Protocol Development for Stack Development: As mentioned, durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define accelerated stress tests (ASTs) at membrane electrode assembly (MEA) level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack conditions are different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be appropriate for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation.
  - Other Balance-of-Plant (BOP) Component Development: It is very good to have air management projects in the consortium. The air compressor is the largest peripheral power in the HD fuel cell system, and efficiency of the air compressor is critical. The hydrogen blower in the anode loop is also an important component, and the domestic supply is poor for HD application. Active recirculation of the anode loop is important for containing the hydrogen purge and improving the efficiency. It is highly recommended that projects be created for hydrogen blowers for HD application.
- This is a challenging presentation to review, given the broad scope for the Million Mile Fuel Cell Truck (M2FCT) consortium and impact on multiple projects. The current approach appears to have four main facets: (1) determining total cost of ownership (TCO) and the system's analysis with requirements, (2) setting standard protocols and baselines for comparison to new material/process development, (3) providing characterization and modeling support services to all DOE-funded projects, and (4) conducting independent research toward Hydrogen Program goals. In this regard, the approach is solid and meeting expectations; however, to meet the Hydrogen Program's goal of advancing commercialization, a fifth goal is recommended. Something lacking from most project summaries is an objective gap and risk analysis to advance the technology to higher technology readiness levels (TRLs) and hopefully reach a commercial readiness level. With the cumulative brainpower and experience level of the M2FCT, this would be an invaluable service to help project principal investigators (PIs) advance their projects in the right directions, strengthen their future plans, and if need be, pivot in strategy to make the most of DOE funds. This may not be the current mandate of the M2FCT, but it would be invaluable.
- Targets are clear and disseminated well to the community through the consortium site and other venues.
- Integrating with relevant partnerships and performing actual work for the partnerships are at the highest levels. The approach to report partners' achievements is duplicative and excessively detailed. Many approaches are presented as equally significant, which may not be true respective to risks and achieving the targets.
- Using a system analysis to determine what parameters have the biggest impacts on truck customer operating costs is an excellent approach. This helps guide what are the most relevant issues. The only negative was that some of the project work seems to be unrelated tangent projects in which the motivation was not so clear (i.e., studying exotic three-dimensional (3D) array membranes and zeolitic imidazolate frameworks [ZIF]-supported catalysts from constant voltage drop [CVD] methods).
- The technical approach based on the key issues of durability and cost is sound and reasonable.
- The proposed approach is well aligned with the scope and targets of the project.

- There are too many ASTs to rely on to understand whether 25,000 hours of durability can be achieved. There needs to a single model that is prioritized that can aggregate the different ASTs and deliver real-life durability estimates.

Question 2: Accomplishments and progress

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

- The project helps advance the industry with at least three key accomplishments: disseminating HD cost models from the complex systems analysis; conducting detailed characterization of HD MEA degradation mechanisms; and establishing detailed ASTs for the industry and explaining how the group derived these ASTs.
- Significant progress has been achieved in the review period. The system modeling and analysis results were especially impressive and instrumental for the whole community.
- Great progress was reported in many areas of the presentation. It was great to see the breadth of work, ranging from material development to system strategy. It was great to see the systems analysis, TCO, and requirements/status spider plot set the stage for the rest of the presentation. It would be a challenge, but if there is any way to show the impact of these other projects, or the summation thereof, on the spider plot, it would be great to see. The following questions/comments highlight areas for greater clarity and potential recommendations for more hypotheses, gaps/risk analysis, and establishing a data quality metric for all concept evaluations.
    - Slide 21: It was unclear whether the number of cations in this evaluation was quantified. The effect was unexpected, as usually the inclusion of cations and heat treatment reduce water uptake and therefore reduce polymer swelling. It was unclear whether the team has a hypothesis for this. Further, it was unclear why the different dispersions were giving different conductivity when the chemistry and solvent composition are similar.
    - Slides 31/42: The project should state any expected challenges with the array electrode and co-axial nanowire electrode (CANE) concepts in keeping the structure intact after MEA processing and compression. It was unclear what the expected challenges are in scaling up this concept to high-volume manufacturing. It would be good to know what, if any, risks there are to membrane degradation with this kind of patterning. It was unclear if the team played with different aspect ratios to optimize the structure for performance and durability. It would be great to complete a gap and risk analysis for all concepts, taking into account TRL and key challenges to commercialization.
    - Slide 37: It is great the baseline evaluation was done, as many concepts will be compared against this data set. It was mentioned in the presentation that the data was repeated. For this particular data set, it is recommended that error bars be used to show the variation and data confidence so the value of other concepts can be clearly seen. Further, this would provide a good performance set so other labs could compare their own data sets in line with the new MEA AST. It is recommended that the project provide the same baseline set for the component ASTs.
    - Slide 58: Stabilizing antioxidants is an important challenge for achieving the HD durability targets. Based on this Ce retention, it is unclear if modeling will be done to understand the impact over longer time scales to show the crown ether is stable. Open-circuit voltage testing showed improvement over membrane durability; it was not clear whether any impact on performance is expected as Ce dissolves.
- As for the previous years, the results presented are numerous and of high quality. There is a good balance between prospective research for new materials, deep evaluation of existing materials, and development of relevant testing procedures. Regarding modeling, as there are several stack producers offering high-power stacks (+200 kW), it is unclear what the impact of using them would be, as it may lead to different BOP components and simplified architectures. It is surprising to see that operations and maintenance (O&M) costs are the same for diesel engines and fuel cells. Some bus operators claim that fuel cell O&M costs are much higher. Array electrode and CANE seem very promising. Evaluating industrial production and performing testing with increased surface areas (single cell of 50 cm^2) are encouraged. All the lab tests are performed using a classical serpentine design. As it differs significantly from current flow designs, it

should be investigated if the lab results reflect the performance/degradation in current stack designs. If not, a new design should be adopted, even if comparison with many years of data may be lost.

- Fuel Cell System Sizing Analysis: One of the remarkable accomplishments is system sizing analysis for capital expense and TCO benefit. It is expected that outcomes could update the design target for each project. Particularly, sizing is critical for air management projects. Ink Formation and Electrode Structure: Implications of catalyst layer cracks with performance and durability are unclear (no explanation of Method 1–5), and it is unclear whether it is specific for high-oxygen-permeable ionomer. Durability Analysis: Mechanism analysis on the resolution of Pt and PtCo alloy (or intermetallic) would be needed in order to understand the durability of the MEA, which can eliminate voltage clipping and improve the efficiency (high potential operation enabler).
- Progress to achieve targets through enhanced ionomers, membrane stabilization, and catalyst/electrode structure research is very good; however, a multiplicity of approaches to every MEA component brings chaos rather than structure and makes the roadmap confusing. Justification of new AST protocol is weak, and the degradation results in H_2–N_2 dominating over H_2–air are controversial and contradicting past experience by academia and industry. Monotonic degradation in AST justifies a shorter end of test than 500 hours using respective metrics. It is recommended that intermetallics be held at higher than 1 A/cm^2 current density for longer time and confirm they are not increasing electrode resistance. While the targets are specified at ~1 A/cm^2, the economics would be more attractive at higher-rated power densities.
- Excellent fundamental work is being conducted. Though the biphenyl sulphone: H Form (BPSH) work for membranes was a bit confusing because it is known BPSH will not last under truck operating conditions. It was difficult to understand how the PIs believe the 25,000-hour durability was met (Slide 19, spider chart).

Question 3: Collaboration and coordination

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

- The structure of the project ensures an outstanding collaboration between the partners and with any additional relevant entity.
- The consortium has extensive and effective collaboration within the core lab teams and with a variety of external teams.
- The project has a strong and proper balance of members, industry, academia, and national labs.
- A top-notch set of collaborators are on this project.
- M2FCT is partnering with a broad group of national labs, universities, and industry.
- It was unclear which parts of the presentation were coordinated with which project, so it is difficult to assess the strength of coordination on each DOE project. Based on the data presented, it appears there was great support of several projects. It would create more value if M2FCT could have the mandate for a greater guidance role to drive technologies forward. This could be a voluntary ask from the various project PIs to audit their projects and strengthen their plans.
- Relation management with funded and non-funded parties is well organized and well presented. A consortium is an excellent tool for the industry and academia. Access to the specific consortium's unique capabilities related to diagnostics, modeling, and the infrastructure could be enhanced and more transparent to the industry.

Question 4: Potential impact

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

- From a fuel cell perspective, M2FCT is helping to address technology needs for fuel cell truck implementation, which is likely the first step toward wide-scale adoption of fuel cell vehicles. If wide-scale deployment of hydrogen refueling can be achieved in parallel, this project will have significant impact.
- HD fuel cell trucks are the first market entry point for large-scale renewable hydrogen. Developing highly efficient and affordable HD fuel cell trucks is the critical battle that the community has to win.

- The outcomes of this project have significant impact in achieving the cost, performance, and durability—ambitious targets.
- Hydrogen fuel cells for HD commercial vehicles are one of the most important areas for the Hydrogen Program. The consortium focuses on efficiency and durability of fuel cell systems and TCO benefits.
- M2FCT represents significant expertise and has broad impact on the hydrogen industry. This presentation highlights the current status and key challenges toward broader commercialization of fuel cells into the HD transport sector, and all work is relevant and working toward meeting these challenges. It would be good to provide an evaluation of the TRL and analysis of the gaps and risk on each concept to highlight the relative impact and value. This would have the added benefit of strengthening the path forward and where future DOE money would best be spent.
- The project is highly synergistic with the DOE objectives and has a high potential impact, advancing the project toward the DOE goals. However, there is still risk of concluding exotic and not scalable MEA structure that may not be accepted for the industry to scale up.
- Many good results and excellent fundamental approaches are included. To show achievement of key metrics, the project needs to think through how to aggregate those results to come up with something practical for the industry.

Question 5: Proposed future work

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

- The project's future work is reasonable, detailed, and well structured. It is also well aligned with the mid-term and final goals.
- Great detail was shown on the path forward for each segment. It would be valuable to understand the priority and importance of each area to better understand the impact and spread of resources toward low- vs. high-TRL concepts. Even a high, medium, or low ranking would help indicate where M2FCT sees the best bang for the buck.
- Very detailed plans for future work are outlined in the presentation and project plan. A better explanation is needed to justify further development of technologies that do not seem necessary or applicable for HD truck implementation, such as 3D array membranes and ZIF-supported catalysts from CVD methods.
- The project should prioritize a combination of practical concepts to achieve durability and cost targets.
- The future works presented (slides 62 and 63) are strongly supported. Here are some suggestions to consider for additional study to reinforce the consortium.
    - Test Protocol Development for Stack Development: As mentioned, durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define ASTs at MEA level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack condition is different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be proper for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation.
    - Other BOP Component Development: It is very good to have air management projects in the consortium. The air compressor is the largest peripheral power in the HD fuel cell system, and efficiency of the air compressor is critical. The hydrogen blower in the anode loop is also an important component, and the domestic supply is poor for HD application. Active recirculation of the anode loop is important for containing the hydrogen purge and improving the efficiency. It is highly recommended that projects be created for hydrogen blowers for HD application.
- The project should further focus on integrating the leading concepts in ionomers, catalysts, and structures on the MEA level and verify performance and degradation results as presented by the consortium through

industry testing and not only by the consortium. Short rainbow stack verification by the National Renewable Energy Laboratory could be duplicated by the industry partners.

- The project is encouraged to include real-life evaluation of aged components to develop robust AST protocols and assess the relevance of continuing to use conventional serpentine flow fields.

Project strengths:

- There has been great progress in the areas of (1) determining TCO and the system's analysis with requirements, (2) setting standard protocols and baselines for comparison to new material/process development, (3) providing characterization and modeling support services to all DOE-funded projects, and (4) conducting independent research toward Hydrogen Program goals. There is progress at varying TRLs, and some novel concepts are being explored. Further, it is excellent to see the support of diversity, equity, inclusion, and accountability goals into the various projects.
- The consortium project has clear objectives, excellent organization, strong teams, and effective communication and collaboration among the many lab teams. The project also shows a clear pathway to achieving DOE goals for HD fuel cell truck development.
- Access to the advanced and high-risk concept materials, implementing concept components into MEAs and electrodes by standard benchmarking techniques, is of high value to the industry. The consortium members' expertise is on top of the industry.
- The project leveraged modeling to determine the important factors in HD fuel cell truck system development. The project used detailed characterization and reasoning to develop new industry ASTs.
- The project is very well structured, based on a great team of experts and an excellent coordination of all the activities.
- A strength of the consortium is synergetic collaboration among capable members of industry and academia, including national labs.
- Strengths are teaming and access to tools for fundamental analysis.

Project weaknesses:

- There is great detail on the path forward for each segment. It would be valuable to understand the priority and importance of each area to better understand the impact and spread of resources toward low- versus high-TRL concepts. Even a high, medium, or low ranking would help indicate where the M2FCT sees the best bang for the buck. Further, something lacking from most project summaries is an objective gap and risk analysis to advance the technology to higher TRLs and hopefully reach a commercial readiness level. With the cumulative brainpower and experience level of M2FCT, this would be an invaluable service to help project PIs advance their projects in the right direction, strengthen their future plans, and if need be, pivot in strategy to make the most of DOE funds. This may not be the current mandate of the M2FCT, but it would be invaluable. This could be a voluntary ask from the various project PIs to audit their projects and strengthen their plans. This would be good to see for the M2FCT projects as well.
- The project has a very large scope and many participating PIs. Sometimes it may lose focus just because of the size and scope. Certain targets such as power output and PGM loadings are too safe, which may not be challenging enough to stimulate breakthrough and innovations.
- There is a multiplicity of high-risk concept materials under study. Hybridization approaches for the catalysts are lacking or were dismissed. High-risk electrode structures (CANE, etc.) are not verified for sensitivities to common electrode failure modes, such as flooding.
- Some of the work presented seemed to be unrelated side projects. A better explanation for the motivation or relevance of the advanced materials work would be beneficial.
- There are too many ASTs. There is too much focus on fundamentals and new concepts when the current need is an engineered solution that can compete with diesel trucks.
- Comparison with real-life aged components may be increased.
- No significant weakness has been seen.

Recommendations for additions/deletions to project scope:

- It is suggested that the project team deploy a systematic approach in identifying test protocols for durability validation for components to stack level. Durability is an important attribute for HD application, and a proper validation method is critically imperative. The consortium now has a study to define ASTs at MEA level with a subscale differential cell, which disengages the flow-field/bipolar plate effect. However, there is no test protocol to verify the stack design for durability. Obviously, stack condition is different from subscale cells. For example, change of the membrane's hydration state is quite different between stack-level and subscale cells. A systematic approach to define test protocols for stack-level validation is necessary. This could be proper for national labs and universities to lead. It was shown that a stack project misquoted an MEA-level AST to use for durability validation with an unverified acieration factor (time factor). AST is the accelerated stress factor and not directly tied to chronological acceleration without validation. For the air management project, it is suggested that the consortium define a common metric to measure efficiency. Currently, each project uses different metrics.
- It would be great if the consortium project could conduct a more thorough study on the heat rejection and management of the HD fuel cell system and take a more aggressive approach in improving existing or developing new materials that can increase the operation temperature of proton exchange membrane fuel cells. This is a major issue for HD truck design, which has not been sufficiently addressed in the project.
- In light of the polyfluoroalkyl substance (PFAS) regulatory discussions, it is recommended that the project look into perfluorosulfonic acid (PFSA) ionomer control and recycling strategies. The presented highlighted some work looking at hydrocarbon polymer materials; however, this technology is potentially decades away from being commercially viable. A more realistic approach to the PFAS regulation concerns is addressing control and recycling of these materials.
- It is recommended that the project further develop in-cell characterization highlighting MEA component deficiencies along degradation in ASTs (other than polarization curves, electrochemical surface area, and mass activity), specifically proton conductivity/mass transport in the cathodes. The team should develop explicit structure–property polarization curve relations for cathodes that remain true through the ASTs. Concepts should be weighed prior to disseminating.
- The project should attempt to verify the usefulness of the new ASTs in predicting real-world results. Collecting data from real-world demonstrations, even unsuccessful demonstrations, can help to confirm whether any stressors are present that the ASTs do not cover.

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

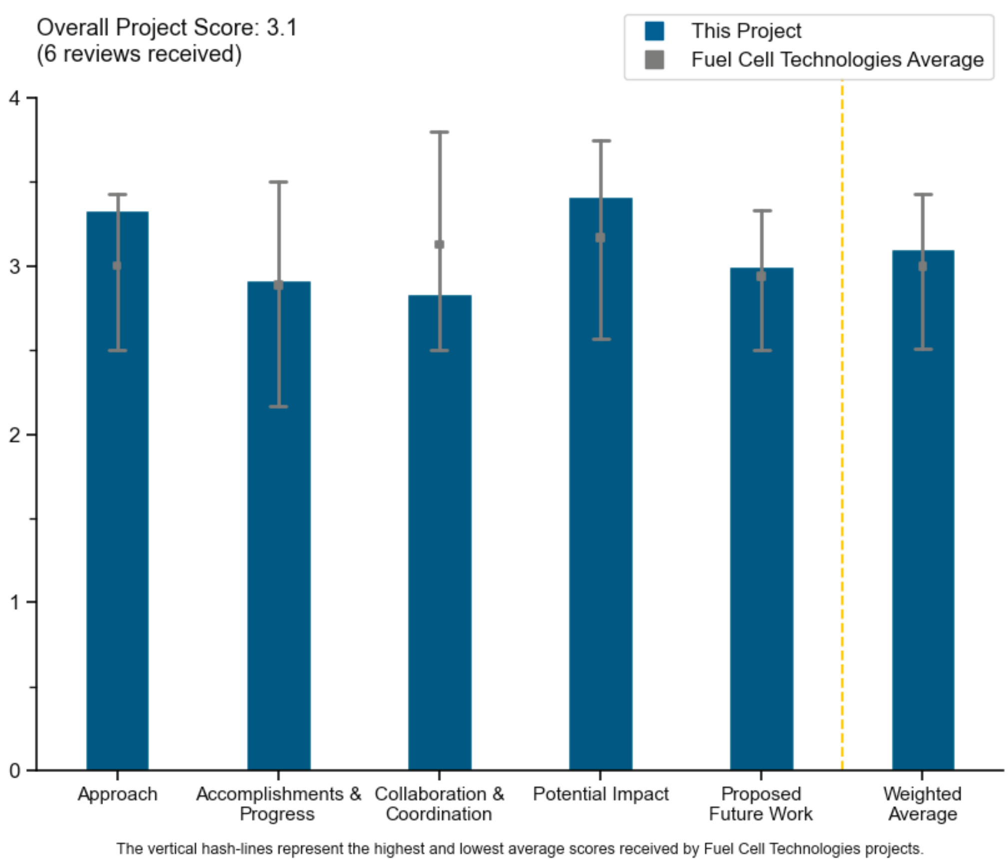
Tianli Zhu, Raytheon Technologies Research Center

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 • Die design and forming process development for extremely small tolerances and complex geometries • Performance of the bipolar plate

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 and diffusion bonding and is developing a defect-free corrosion-resistant titanium coating, optimizing TreadStone Technologies' DOTS technology using carbon particles or gold to meet performance targets.

Project Scoring



Question 1: Approach to performing the work

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

- The project seeks to develop new technologies for manufacturing aluminum BPPs to improve functionality and reduce cost to meet the DOE target of $5/kW. More specifically, the team takes a different route of using high-temperature diffusion bonding to laminate aluminum substrate with Ti foil, eliminating coating defects and improving corrosion resistance. This strategy is combined with DOTS technology to ensure good electrical contact and electrical conductivity. The technical approaches of this project are appropriate and effective, covering all key aspects of aluminum BPP fabrication.
- The proposed approach is aligned with the scope and objectives of the project.
- The project approach seems reasonable. Adding the following studies is recommended:
    - Formability with thinner aluminum substrate plate: Use of aluminum is effective to the weight reduction of the fuel cell stack. However, thick aluminum plates reduce the effect and make the stack large. Using a thickness similar to state-of-the art stainless steel BPPs, e.g., 0.10 mm, is expected. Thinner plate makes stamping formability difficult. The currently used aluminum substrate with a thickness of 0.25 mm makes the fuel cell stack volume significantly larger. It is highly recommended that the project study formability with a significantly thinner aluminum plate, ideally 0.10 mm.
    - Aluminum leaching out: It is known that an aluminum ion is harmful to the PEM. It is recommended that the project check not only the corrosion current but also identify leaching out of metal ions.
    - Au DOTS: The project intends to use the Au DOTS technology to keep electrical conductivity on the BPP surface. Au is durable enough for normal operating conditions (normal fuel cell potential range) but not durable enough for high-potential conditions such as at the cell reversal condition (more than 1.2 V vs. dynamic hydrogen electrode [DHE]). The team should consider material/coating selection for DOTS technology that is durable enough for anticipated conditions, including abnormal operations. Generally, Au is no longer used for the BPP coating of automotive fuel cells.
- Using Al as the main plate material should allow lower costs than steel- or Ti-based plates and could allow the project to meet cost targets. The use of elevated temperature should improve formability. The focus on formability in Year 1 is appropriate. The 25 µm Ti foil to be used for the coating seems thick, and a thicker coating could provide misleading information when it comes to formability issues and concerns about thinning/cracking of the coating during forming. The cost estimate uses 7 µm thick Ti (which is not available). Cost modeling should use Ti foil with a thickness that is currently available or show a sensitivity to Ti foil thickness (cost is not always proportional to thickness, especially as thickness decreases).
- The presentation indicates that the go/no-go decision relies on corrosion data from a Ti-coated Al plate without Au DOTS. Corrosion testing on the actual proposed structure/architecture should be repeated. Cost per kilowatt cannot be properly assessed without performance data, channel depth/width, landing fraction, etc. Capabilities should be assessed against metrics for optimum design/state of the art to ensure no performance is lost due to stamping capabilities.
- The team has established the proof of concept for the diffusion-bonded Al-Ti coupons and shown lower corrosion currents compared to Ti-Al and SS316. However, real-time application as a PEM fuel cell BPP is necessary to consider this technology to be a viable alternative for making BPPs in high volume.

Question 2: Accomplishments and progress

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

- The team has made some progress in making diffusion-bonded coupons and carried out tests to evaluate their mechanical stability. It will be good to see how these diffusion-bonded bipolar plates work in 25 cm^2 and/or 50 cm^2 single cells.
- During the current period (Year 1), the project is planned to focus on elevated temperature forming and diffusion-bonded optimization to minimize forming time, die wear, and geometry reproducibility, as well

as the adhesion strength of diffusion bonding. Optimization efforts via design and modeling have been reported; however, experimental studies were delayed because of supply chain issues. Toward budget period 1 milestones, it is good to see the team has clarified a future path (thinner Ti foil, stacking, and reduced cycle time) to reach the $5/kW goal via techno-economic analysis. However, it is concerning that:

  - Samples for tensile tests were prepared with 25 µm Ti foil, not the 10 µm that was studied in the techno-economic analysis.
  - The flexural strength test result (one of the two important key performance indicators for mechanical strength) was not from this project (but rather from Pacific Northwest National Laboratory's [PNNL's] previous study), and a much thicker aluminum substrate (0.5 mm) was used in that study.

It could be difficult for the project to reach go/no-go milestones.

- The presented accomplishments are correct in terms of modeling the feasibility of different features of Al-based BPPs and the performance and cost. Some questions arise as to what the minimum thickness of the foils is and whether the diffusion-bonded process is acceptable for the high rates of production needed. Using only one Ti-coated side leads to lower cost, but it is unclear how the Al/Al welding and the long-term durability are affected. It is unclear how the stamped edges look. It is unclear whether Ti covered the Al foil, and if not, what the impact on the corrosion resistance would be. Carrying out evaluations of the BPPs in a real fuel cell is highly expected.
- With the use of finite element analysis simulation, it is good to achieve proper elongation with an aluminum plate. A thinner plate is expected to be used to contain the stack volume. It is expected that the formability study would be extended with a thinner plate, ideally similar in thickness to the state-of-the-art stainless steel BPP, e.g., 0.10 mm.
- The project should examine a cross-section of formed material to see whether there are any issues with Ti thinning or cracking during forming.
- Emphasis was made on strength and forming without showing adequate corrosion data.

Question 3: Collaboration and coordination

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

- The team has established collaboration with a national lab and a small business.
- It is good to involve the national lab's capabilities in the project.
- Collaboration appears to be correct.
- All work in Year 1 was performed by the PNNL team, and there was no clear evidence showing how other research leads have been contributing to the project so far. Although this is likely just how the project was planned, it would be great to see closer collaboration between the project teams.
- There is good collaboration within the project team. The team should collaborate with the Million Mile Fuel Cell Truck (M2FCT) consortium for BPP testing. Collaboration with a stack manufacturer to ensure the forming is acceptable with the project BPP design would be beneficial.
- It would be useful to have an additional industrial partner with real-world experience designing metal plate geometries and fabricating metal plates that have been used in commercial products.

Question 4: Potential impact

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

- The proposed work will have great impact if the team successfully shows promising results in larger-area single cells and short stacks.
- The project is potentially high-impact work. The lower cost and weight of Ti-coated Al plates would provide significant benefits.
- Achieving low-cost and durable BPPs will contribute to lowering the stack cost to the targets.

- Metallic BPP technology is critical for heavy-duty (HD) fuel cell stacks, and domestic sources ensure stable supply chains for HD applications. Use of aluminum enables potentially reducing the stack weight compared with state-of-the-art metallic BPP technology, such as coated stainless steel plates (0.1 mm thickness). However, the project currently uses thick substrate plates (0.25 mm), which makes stack volume significantly larger, probably too large for HD applications. It is highly recommended that the project revise the approach and focus on substrate thickness and formability to make it more effective for the applications.
- The project seems to focus on cost at the substrate material level: forming the sheet. Forming plate halves and bonding them and the cost of that at production-level scale needs to be included. This is where costs could skyrocket and the project will become unfeasible, and this is where the project may not be completely aligned with DOE objectives. Risks seem to be weighted toward the negative side (the pareto chart indicates a higher chance of increasing costs) and a high risk of not meeting the DOE target.
- The project addresses an important challenge for PEM fuel cell development and the DOE target to reduce the cost of fuel cell stacks for HD vehicle applications. While Ti BPPs (the current state of the art) have superior advantages of light weight, good mechanical strength, and corrosion resistance, they are not economically feasible because of the high price and limited supply. Enabling low-cost, defect-free aluminum BPP manufacturing would be a game changer and significant breakthrough.

Question 5: Proposed future work

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

- The proposed future plan is reasonable for catching up some of the delays. Some testing may not need to be full-scale, such as corrosion and resistance tests, which may be pulled ahead in parallel. This may also help promote collaborations between the teams.
- Not enough emphasis was placed on material compatibility with fuel cells. Titanium is a well-known membrane poison; the possibility of titanium contamination of the membrane from the coating should be investigated as a potential showstopper early on, in case the lifetime requirement cannot be met.
- The project should look at joining, welding, and bonding in future work and include these in cost estimates. High temperatures used in elevated-temperature forming may increase oxide layer thickness and make joining more difficult.
- In addition to the proposed future work, it would be interesting for the overall evaluation of BPPs to include a life cycle assessment (LCA) and an assessment of recycling these coated BPPs.
- The team has proposed a significant amount of work to be carried out to meet the go/no-go criteria.

Project strengths:

- The project has a good concept and technical approach for obtaining defect-free aluminum BPPs. The project has a strong team, with strong leads and complementary expertise to achieve the goal.
- Finite element analysis has been used for stamping formability. This model-based engineering is one of the project strengths. Validation of the model is expected.
- This is a good project team. Al plates have high potential to meet cost targets if a defect-free corrosion-resistant coating can be applied.
- This project relies on an experienced team of experts.
- Strengths are an interesting concept and a well-rounded team.
- Involvement of a national lab is a strength.

Project weaknesses:

- The coating technology should be reconsidered. It is highly concerned with use of Au DOTS for automotive fuel cell conditions. Au is durable for normal operating conditions (normal fuel cell potential range) but does not have enough durability for high-potential conditions such as at the cell reversal condition (more than 1.2 V vs. DHE). The team should reconsider the material/coating selection for DOTS technology to make enough durability for anticipated conditions, including abnormal operations. Generally, Au is no longer used for the BPP coating of an automotive fuel cell.

- The focus is on detail; a high-level view of the impact in a commercial fuel cell is missing too many manufacturing steps and uses inherently expensive materials. There is no cost analysis beyond one for plate substrate material, and there is no early evaluation of fuel cell compatibility (particularly with the membrane).
- Progress was substantially slower than originally planned. Synergy among the project teams has not been demonstrated yet.
- The first validation of the new BPPs in a real fuel cell should be evaluated earlier in the project. LCA and recycling are not considered.
- The project needs fuel cell testing, at least in 50 cm^2 cells.
- The project needs to look at joining.

Recommendations for additions/deletions to project scope:

- This project is highly relevant to the goal of HD fuel cell development. Aluminum is a lightweight metal, and it potentially enables reduction of the stack weight. It is an important benefit for not only current HD applications but also aviation applications, in the future. Currently, the project uses a 0.25-mm-thick substrate, which reduces the benefit of weight reduction and makes the stack size significantly larger. State-of-the-art automotive fuel cell stacks use stainless steel or titanium substrate. Their substrate thickness is 0.10 mm, and the unit cell thickness is around 1.1–1.3 mm. If the substrate thickness was increased 0.10–0.25 mm, the unit cell thickness would be around 0.3 mm thicker. Usually, a stack consists of around 500 unit cells, which would make the stack 150 mm longer. It is highly recommended that the project focus on the substrate thickness and improve stamping formability with a thinner substrate. The second recommendation is to reconsider the Au DOTS technology on the surface. Au is stable for normal operation conditions (potential) but not durable at high potentials, which may happen at cell reversal conditions.
- Techno-economic analysis identified that reducing Ti foil thickness to 7 µm was necessary to meet the cost target. As such a thin foil is not commercially available, the model study needs to consider re-tooling cost for a Ti foil supplier to make this new product. The fuel cell stack market is typically too small for commodity manufacturers to change production lines; additional cost may be expected.
- The project should add additional in situ durability and performance testing and complete manufacturing cost (including stamping and welding, at high volume rates).
- LCA and recycling of these new BPPs could be considered, as it appears less obvious than stainless-steel-based BPPs.
- The project should collaborate with M2FCT consortium members to independently evaluate the BPPs in 50 cm^2 cells.
- The project should look at joining/welding of plates.

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

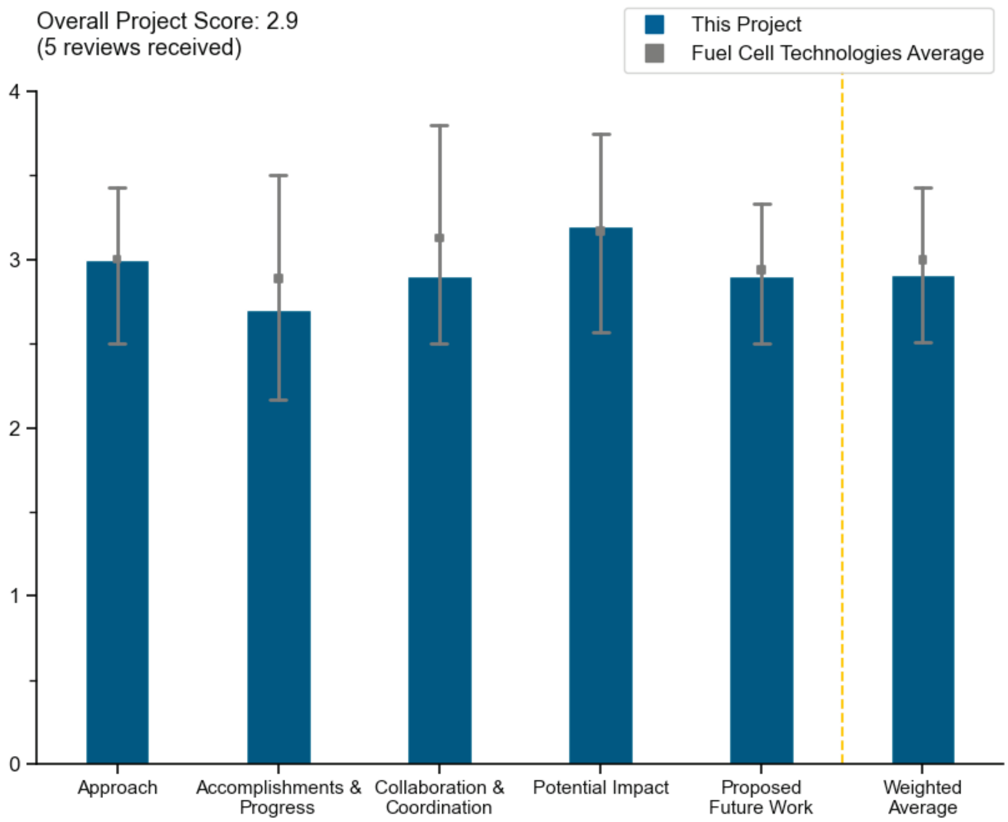
CH Wang, Treadstone Technologies, Inc.

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 x10-6 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 **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project aims to develop manufacturable precious-metal-free BPPs for fuel cells, and it is halfway to its completion. The approach is utilizing Ti-based coating of SS to gain both the reduced manufacturing cost and improved durability. The approach seems to be relying on a well-thought-out process that built on the legacy established by participating partners in this project. The approach is well defined, well executed, and most importantly, well-grounded to the fundamentals that enable its feasibility.
- Combining low-cost substrate, diffusion bonding, and chemically inert particulate oxide coating is an adventurous but smart approach to reach multiple technical targets.
- The approach is a little confusing. The first slide addresses SS as substrate, while the rest of the presentation talks about aluminum. The approach is too focused on plate performance and cost without understanding the performance and cost in a complete fuel cell or system (for example, it is unclear whether the targeted performance is achievable with this kind of plate or whether more cells will need to be added to meet the required power). To avoid spending money on a dead-end path, the risk of using titanium in a fuel cell environment (which is a known membrane poison) needs to be addressed earlier.
- The main concern is that the approach of coating after stamping leads to coating cracking, which will expose the base metal surface (low-grade SS or aluminum), which subsequently leads to corrosion. Another significant concern is titanium stability during fuel cell operation. Platinum-group-metal-free coating is the right approach but is not unique to this project. Measuring Fe release during corrosion testing using inductively coupled plasma mass spectrometry (ICP-MS) is good; Treadstone Technologies, Inc.

(Treadstone) should also measure Al release for the Al plates and Ti release for all samples. The rough surface approach seems to help reduce contact resistance.

- Diffusion bonding of titanium to aluminum or SS substrates seem to be the only path investigated in this project. Although this project is focused on SS substrates, the approach is limited to using dibutyl phthalate (DBP). It would be better for the project to investigate other options for Ti bonding to SS to minimize risks and understand the techno-economic challenges better. Although the approach in this project uses Treadstone's DOTS technology for the TiOx surface coating, there is no effort to compare with other coating technologies. The recommendation is to do a techno-economic analysis of other state-of-the-art TiOx coating technologies, including mixed metal oxide coatings from thermal curing of appropriate precursors.

Question 2: Accomplishments and progress

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

- Although the current progress toward the overall project goals is on track, a few gaps in the data need to be addressed to provide more clarity for the performance indicators.
    - The scale of the Ti layer on the Al substrate is not mentioned (on slide 7). This needs to be a key performance indicator (KPI) for the DBP cycle time and cost.
        - The cost or technical benefits for diffusion bonding at higher pressure and temperature need to be included in the cost analysis for feasibility (on slides 7 and 10).
    - It is not clear whether the corrosion current measurement procedure (on slide 8) is an American Society for Testing and Materials (ASTM)- or DOE-prescribed AST test method for this application. The corrosion current of <1 uA/cm^2 after approximately 90 hours is promising, but this test needs to be run for longer duration under relevant use case cycles, for example, under HD fuel cell truck load cycling conditions.
        - Cost analysis assumptions in slides 9 and 10 need clarification. Slide 9 suggests an 80 kW net fuel cell system, while slide 10 refers to 80 kW stacks. Moreover, slide 9 notes 1,150 mW/cm^2 at 0.663 V, 378 cells, and 328 cm^2 BPP, which works out to a 142 kW stack. At that size, an 80 kW_{net} system would mean that the stack is oversized for the system needs. However, in slide 10, an 80 kW stack is called out at the same power density and cell count. Clarification is requested.
        - The thickness of the BPP, 75 um SS409, should be confirmed for adequacy with a fuel cell original equipment manufacturer (OEM), as 75 um seems too thin. Cost analysis should be based on practical BPP thickness for the application.
    - It seems that the I_{corr} (corrosion current) in slide 12 may be for a 1 cm^2 active area. The I_{corr} needs to be reported at units relevant to the targets. Also, the E_{corr} (corrosion potential) is against the Ag/AgCl reference electrode. Hence, it will be ~200 mV higher against a standard hydrogen electrode.
    - There is a very nice effort to characterize the surface oxide by etching the substrate. For future efforts, a focused ion beam (FIB) analysis, followed by a cross-sectional analysis using transmission electron microscopy (TEM) and/or scanning electron microscopy (SEM) coupled with an energy-dispersive X-ray analysis (EDAX), might be an efficient way to characterize the surface oxides.
- The project is 50% on the way to its completion, and the comments here reflect reported outcomes. The SS and aluminum BPP coated by TiO_x and Nb-TiO_x were evaluated for corrosion, which showed an increase in corrosion rate by number of applied cycles (triangular cycles between 1 and 1.5 V, 80°C, 0.1 M sulfuric acid). While corrosion anodic tests are valuable input, it is expected that more accurate in-depth measurements would have also been accomplished. The project lists ICP-MS as an anticipated method for qualitative and quantitative measuring of corrosion rates. However, that remains to be accomplished, despite the advanced phase of this project. The usual turnaround of ICP-MS analyses is rather fast, and those results should be reported along with anodic corrosion tests. The microscopic structure was done by TEM, while surface composition was probed by x-ray photoelectron spectroscopy (XPS). Provided conclusions were aligned with well-known facts about techniques instead of data analysis, which cannot be

claimed under accomplishments and progress. A new method for surface–oxide analysis, the surface lift-off, is proposed. This method cannot be claimed as new; the project should be focused on method development, and hence, this outcome should not be reported under accomplishments and progress. The overall outcomes at 50% project completion should be at a more advanced stage. Rather simple, well-established analyses must be applied. These are rather simple systems to characterize.

- Treadstone has shown low contact resistance with the Ti alloy particle coatings. The project should report a direct comparison between the resistance with rough and smooth coatings on SS. Interface contact resistance (ICR) of Nb-TiO_x is impressive. Cost projections show potential to meet the DOE target. There is still no evidence that a 409SS plate that is coated with Ti before stamping will be durable. Details of the materials for the AST test results shown were not provided.
- The cost analysis is well justified and convincing. The approach is well articulated and partially proven on aluminum substrate. Demonstrated technical achievements decrease the risk of this project. The feasibility of forming a flow field structure is still to be demonstrated. The project lacks a physical and analytical explanation of the interfaces, i.e., "why it is working."
- Accomplishments are confusing. Corrosion and ICR results refer to aluminum base material, but the cost analysis is for SS. Ex situ ASTs are not enough to demonstrate durability. Interactions with other fuel cell components must be considered.

Question 3: Collaboration and coordination

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

- The team is working with Los Alamos National Laboratory (LANL) on BPP ASTs. It is suggested that the researchers try to correlate AST results with in situ plate ICR loss and corrosion/iron release. Austin Power is doing cost analysis. There is nice collaboration with Pacific Northwest National Laboratory (PNNL) on Al BBPs, as well as nice collaboration with the University of Tennessee (UT), Knoxville, on developing methods to analyze plate surface.
- There is good contribution on the cost analysis and the original diffusion-bonding technology. However, there is a lack of contribution on the surface analysis and characterization.
- Collaborations and interactions with UT Knoxville are not very clear. LANL is better suited to work on the degradation mechanism based on AST protocols. The degradation/corrosion mechanism of TiO_x is relatively well understood; understanding the kinetics of corrosion under application-specific cycles should be the project focus. The project is based on the expertise and technologies of Treadstone (DOTS technology) and PNNL (DBP technology). However, it is not clear whether this is the right technology path to meet DOE targets. Austin Power should do a comparative cost analysis of current state-of-the-art BPP technology with the project approach/goals.
- Considering the partners involved in this project, the expected outcome should resonate well with the project goals, which would be challenging to claim here. Better coordination among participants is needed, which would enable maximal utilization of their own capabilities as well as execution of trivial structural, morphological, and chemical analyses.
- An industrial partner with real-world application experience would round out this project better.

Question 4: Potential impact

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

- If successful, this project has great potential in addressing the second-most expensive component in fuel cells manufacturing.
- While there are significant concerns over the durability of the project approach, it does show strong potential to meet cost and performance targets.
- There are good indicators for meeting DOE goals for reduced cost and durable metal plate; some barriers (e.g., fuel cell durability) are not addressed adequately.

- The progress toward BPP targets is significant. The feasibility of in-cell integration is still to be proven.
- Project cost analysis done by Austin Power should include the lifetime of the capital, equipment, and tooling costs needed to implement this technology for rapid manufacturing and the rate of depreciation assumption for overall $/cell or $/kW calculations.

Question 5: Proposed future work

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

- The proposed future work will address some of the noted barriers.
- Future work includes single-cell fuel cell evaluation of the TiO_x-coated BPPs in PEMFCs, including operation under AST conditions. Using conditions other than start/stop ASTs is recommended. More details should be provided on plans to investigate performance degradation mechanisms of the TiO_x coating under PEMFC application conditions.
- Future work is logical. However, it is missing a backup plan in case formed flow fields show different corrosion currents or ICRs.
- Future work must address the missing analyses, and a more thorough list is needed. The three bullet points fail to comply with all complexities and associated uncertainties, which are directly related to material properties. More focused and precise work is necessary to provide answers to straightforward questions: actual morphology of films, Nb-TiO_x vs TiO_x, surface composition, microstructure, passivation mechanism, change of electrical conductivity, homogeneity and uniformity of coatings, chemical degradation based on ICP analysis, etc.
- Optimization of the TiO_x formation process and cost analysis should include other state-of-the-art methods of forming TiO_x. The reporting metric for corrosion and resistivity targets needs to be consistent with industry specifications for BPPs, at a realistic BPP thickness, high frequency resistance, contact resistance, or flatness as KPIs.

Project strengths:

- The primary strength is targeting cost-effective base material (SS409) that has previously been considered unsuitable. The mechanism of correlation between coating roughness and contact resistance is interesting. There is an opportunity for fundamental learning here.
- Strengths include the demonstration of very low ICR, inclusion of a cost analysis, and a plan to measure Fe release during corrosion testing and set an Fe release target.
- The approach, selection of materials, project goals, and team members should be recognized as strong.
- The project strength is in the approach, showing achieving baseline targets on the material level.
- There is good collaborations with PNNL and LANL. LANL expertise with BPP ASTs and the degradation mechanism needs to be leveraged more. The Austin Power cost analysis should be improved to consider all realistic design conditions for fuel cell system applications. Perhaps the project should use the Argonne National Laboratory’s model for fuel cell system sizing and cost analysis comparison.

Project weaknesses:

- The dependence of coating before stamping is a weakness, as it will lead to coating cracking. At the very least, Treadstone must provide evidence to the contrary. Ti coatings are expected to be unstable in a fuel cell environment. Start/stop ASTs are not relevant for OEMs that will use system mitigation to keep voltages low enough to prevent cathode carbo support corrosion.
- The collaboration with UT Knoxville is not clear. LANL is better suited to work on understanding degradation mechanisms along with the AST protocols. Cost analysis should be based on a realistic fuel cell system design for light-, medium-, and heavy-duty vehicles because the system size and lifetime vary with application.
- The concept remains on the flat coupons without mechanical forming. Surface analysis is lacking. ICR testing of half-cells would add value to the project.

- Weaknesses include the use of titanium, which is a known membrane poison, and the lack of a second industrial partner with real-world application experience (e.g., a truck OEM).
- The project does not deliver in-depth analysis of materials, aging, and processing conditions.

Recommendations for additions/deletions to project scope:

- The following are recommendations:
    - Report the thickness of Ti foils on all samples.
    - Include hydrofluoric acid in ex situ corrosion tests.
    - Conduct corrosion testing stamped sheets.
    - Report the ratio of solution volume to BPP area on corrosion tests. Clarify how the cut edges of the metal samples are protected.
    - Check for Nb oxidation.
    - Include measurements of Ti and Al, along with Fe, in corrosion solutions.
- It is recommended that UT Knoxville be deleted from the project partners. An addition would be to establish a project technical baseline for BPPs (with or without coating) and include current state-of-the-art TiO_x coatings to the cost analysis models. The project should include techno-economic analysis of Ti substrates or Ti on SS or Al based on other bonding technologies.
- ICR testing of half-cells would add value to the project. The team should focus on testing the flow fields and not flat coupons.
- The project scope is fine, while execution is falling behind.
- No additions or deletions are recommended.

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

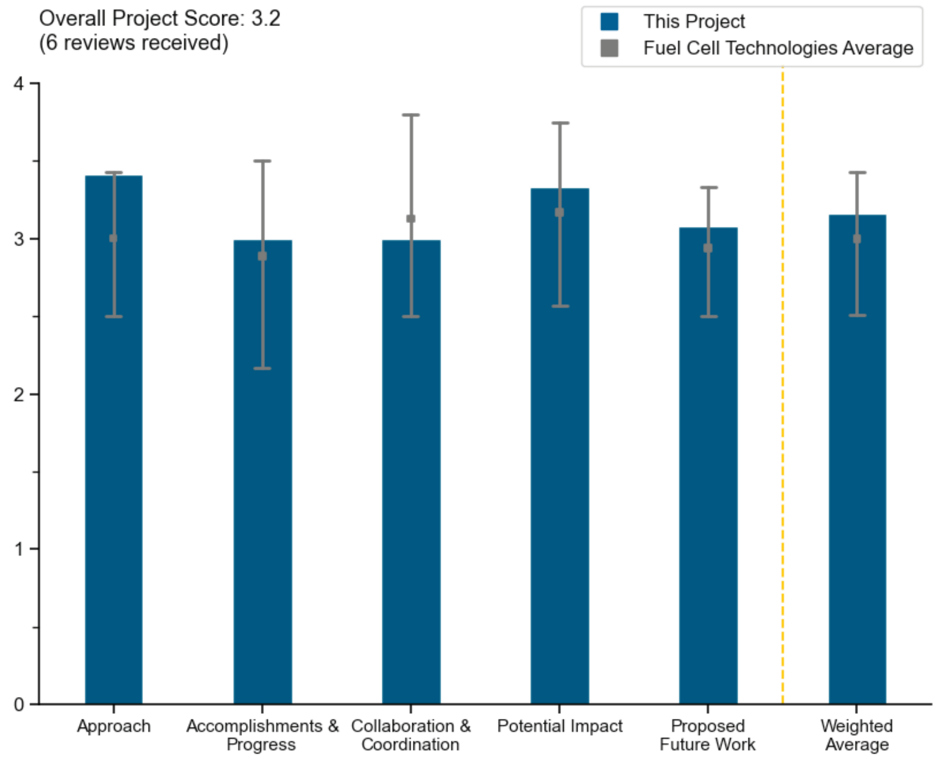
Jon Owejan, Plug Power Inc.

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 • Bipolar plate mass • Bipolar plate manufacturability

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 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 <$4/kW, a plate mass of <0.15 kg/kW, and durability of 25,000+ hours. Progress has been made in various areas, including the development of a wireless cell voltage monitor prototype, trials for coating development and characterization, and investigation of porous rib flow field geometries to enhance performance and reduce pressure loss. Additionally, techno-economic analysis (TEA) has been conducted, estimating BPP cost at $7.69/kW for stamped heavy-duty vehicle BPPs and $3.85/kW for the laminated concept, with part cycle time identified as the most influential cost parameter. The use of low-risk material (stainless steel foils) shows promise with an estimated mass of 0.16 kg/kW.

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 concept overall is very innovative, including several potentially valuable advancements: flat plate flow design, high-throughput manufacturing, a wireless cell voltage monitor (CVM), and new coating approaches. The project may be considered high-risk, but with the high level of innovation involved, this is ideal for a publicly funded project. The project includes a strong scope of activities that are well chosen to meet the project goals, including a TEA.
- The project is focused on reducing cost and time to manufacture BPPs. There is proper selection of materials and coatings to complement the proposed R2R manufacturing method. Associated modeling suggests benefits to the proposed design vs. conventional BPPs.
- This is a well-thought-out and innovative approach to solving cost and manufacturing targets. Barriers are addressed at all integration levels (not just ex situ testing of single components but also in situ testing of integrated components).
- The project has an interesting out-of-the-box approach to fabricating unitized plates. The following are questions about the viability:
  - How the coolant mesh is held in place between the foils (i.e., the adhesion process).
  - What sealing mechanism is between the foils to prevent coolant leak.
  - Where the coolant inlet and outlet locations are on the plates when stacked together.
  - Whether the TiN coating on the plate is stable, i.e., protected from oxidization (recognizing that this is not a plate coating project).
  - What the limitations of channel flow geometry are—for example, how low channel and land width can be made using laser welding and what the effects on performance are.

- What the sources are of the elevated high-frequency resistance (HFR) on slide 14.
- Whether there is any fiber intrusion in the carbon fiber flow field.

- This project address barriers to high-speed, potentially low-cost plate/cell production, while introducing several new challenges. Whether these newly introduced challenges will be outweighed by the potential benefits remains to be seen. These challenges include:
  - Finding a supply for a grooved gas diffusion layer (GDL) at a reasonable cost.
  - Overcoming expected additional contact resistances between the metal films at the mesh for the coolant flow. It is unclear by what method Plug Power Inc. (Plug) will ensure robust film–mesh–film contact in the continuous R2R process.
  - Designing header ports to enable coolant flow into the metal mesh.
  - Maintaining seal and active area compression requirements with flat foil plates.
- Overall, this is a very good approach for meeting 10 million BPPs per year. The techno-economics to meet DOE cost and weight targets are dependent on the manufacturing feasibility and cycle time of the unitized BPP design. This should be the focus for budget period (BP) 2 to get an early understanding of the probability of success and cost of quality. Also, the number of 80 kW systems targeted per year should also be included in the TEA. From the TEA on slide 16, 10 million BPPs per year at a cost of $3.85/kW amounts to ~720,000 units per year.

Question 2: Accomplishments and progress

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

- Good initial results have been demonstrated for most project tasks. Initial results look good for demonstrating the feasibility of the approach and down-selecting details. The project is still in an early phase, but planning and vision seem strong going forward.
- Accomplishments and progress are good, given the complexity of the concept.
- It is early in the project, but progress toward the first go/no-go decision is good.
- The project is on time to complete milestones going into the first go/no-go decision.
- The following points are unclear:
  - On slide 7, from the BPP requirements and material selection table, which key performance indicator (KPI) drives the down-selection process. There is no explanation of the definition of "+", "-", "0", etc. used to rank the materials and their characteristics.
  - On slide 8, what the parasitic loss is for the wireless CVM down the stack, as well as its requirements.
  - On slide 9, what the base material is for the "stamped channels" for cost comparison.
  - On slide10, what the scalability and feasibility is of open-air plasma treatment for BPP.
  - On slide 11, what the TiN paint thickness is and what the standard deviation at that scale is.
  - On slide 12, what the operating conditions were during the pressure drop measured between the two BPP channel depths. The sensitivity to operating conditions of temperature, relative humidity, and stoichiometry should be compared to understand boundary conditions for heavy-duty vehicle (HDV) and other applications.
  - On slide 16, whether a feasibility analysis been done for the R2R unitized BPP design to achieve 1 sec/BPP cycle time, as well as what the cost is of quality for the various cycle times. It would be good to understand or include it in the TEA.

  On slide 13, based on the downward trend of differential pressure for the porous rib vs. channel depth, it is suggested that the project try a porous rib with a 1.0 x 0.5 mm channel. The manufacturing feasibility of porous ribs also needs further clarification. Technical and cost barriers to the manufacturing of porous ribs need to be addressed early, before additional project funds are spent on the development of this concept. On slide 15, the University of Tennessee (UT) performance model is very detailed and provides a very good indication of the benefits of the porous ribs. Modeling the O_2 mass fraction as a function of channel dimensions should be focused in BP 2 prior to manufacturing pilot trials for this concept.

- N_2 plasma has been demonstrated to be capable of coating Ti-painted stainless films. There is no data for contact or corrosion resistance as of yet. Performance in porous rub cells shows benefits over solid cells at low oxygen stoichiometry results. The HFR is slightly higher than in the solid cell. Plug has demonstrated the project can meet the cathode pressure drop with GDLs with laser cut grooves, which is not representative of the final product. GDL channel prototypes have not been delivered.
- A wireless CVM has been produced, but accurate voltage reading has not yet been demonstrated.

Question 3: Collaboration and coordination

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

- The collaboration and coordination are at an appropriate level. Having an industrial partner with real-world application experience as the principal investigator (PI) for this project is extremely valuable, ensuring that research and development value is also practical and targeted toward solving real problems.
- Collaboration between the partners is good. The contribution from Oak Ridge National Laboratory (ORNL) and UT is sufficient. External companies such as Smith Engineering and Limitless Design have been engaged well.
- All funded collaborators are contributing individual expertise to critical aspects of project. A number of non-funded collaborators were also mentioned in the presentation. In the next Annual Merit Review, it would be helpful to see, specifically, more information on options for manufacturing the grooved GDLs and the robustness of said GDLs when exposed to stressors experienced during fuel cell operation.
- The team members overall appear to be coordinated well to address the complex project goals. Tasks or project partners are well defined and clearly oriented toward the project goal. It is suggested that more iteration be conducted on the results from different team members in the coming budget periods.
- The collaboration with Smith Engineering, Limitless Design, and non-funded collaborators is unclear. The presentation did not mention whether Smith Engineering and Limitless Design are cost-sharing partners or vendors in the project. It would be helpful to know whether other CVM vendors were considered. If so, the PI should provide additional details on what the requirements were for this component and the supplier selection process. ORNL is developing the open-air plasma treatment and performing the interfacial contact resistance (ICR) and corrosion tests. However, it is not clear that these tests will be performed at the single-cell size for validation. The TiN-coated BPPs need to be tested for defects at beginning-of-life and at end-of-life (EOL)/end-of-transmission as well.
- This project really needs a GDL supplier as a partner capable of making grooved GDLs. UT has done some modeling, but it is unclear how it is driving the design. The model polarization curves are much lower than the data. ORNL did plate coating and surface analysis. The reviewer is looking forward to seeing the contact resistance and corrosion results. It was unclear who did the cost analysis (Plug or Smith Engineering).

Question 4: Potential impact

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

- The project appears very innovative, including several technologies that would all have significant impacts on advancing the DOE fuel cell program objectives. This type of high-risk but potentially high-impact work is ideal for publicly funded projects at the stack level. The flat plate BPP approach has high potential impact, as it can address manufacturing throughput challenges with BPP forming, as well as addressing issues with coating formed plates, simplifying manufacturing, and lowering stack weight and cost. Wireless CVMs and new coating approaches included in the project also have good potential impact.
- There are so many valuable aspects to this project (manufacturing, cost, diagnostic methods, materials development, performance, system efficiency) that this project has enormous potential to meet DOE goals.
- TEA projects that propose material selection and manufacturing methods will meet DOE targets for weight and cost when performed at scale. However, the proposed process is high-risk–high-reward, and the

proposed components need to be shown to be durable when exposed to fuel cell stressors, which is planned for after the first go/no-go decision.

- The impact of cost and manufacturing will be significant, if the project is successful.
- High-speed plate manufacturing is a key enabler to meeting fuel cell cost targets.
- It is unclear whether this is a new stack design or an incremental change to an existing design. Also, more information is requested on the current baseline cost, mass, or technical barrier that Plug is attempting to overcome in this project. It is hard to assess the approach and impact without understanding the current state-of-the-art challenges faced by Plug. Also, although ORNL is testing ICR and corrosion properties, the main technical barriers and the project objectives list only durability and mass targets. An EOL resistivity target needs to be specified to get full value from the development work and assess the long-term impact of the pursued technologies.

Question 5: Proposed future work

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

- Remaining milestones going into the first go/no-go decision, the proposed deliverables working toward the second go/no-go decision, and the finalization of the project are all clear and well-constructed—going from single-small-cell development, to full-size cell development, to short stack assembly and testing.
- Overall, the plan for the remainder of the project seems sound and well designed to achieve the goals for the full stack deliverable and durability testing. The project plans down-selects materials and steps up scale in a reasonable way. It is somewhat unclear whether all the proposed technologies will be integrated into the final stack or if alternative back-ups are being considered for risk mitigation.
- The proposed future work is well explained and laid out in enough detail (in the timeline slide). One area that might be overlooked (unclear) is whether development of materials requirements for the GDL will be done early enough. An open question is whether the GDL will suffer compression set over life, affecting geometry of the flow path and therefore performance and pressure drop.
- Overall proposed future work is good. However, prior to prototyping and demonstrating manufacturing at any large scale, a manufacturing feasibility study with all cost parameters need to be reviewed with DOE. It is recommended that a BPP accelerated stress test (AST) or unitized cell durability test be performed and EOL BPP properties (ICR, corrosion, etc.) be reviewed prior to scale-up or pilot stack manufacturing.
- Cost models should include GDL cost with supplier feedback. The project needs some focus on header design. It is unclear how the reactants and coolant will get into the cells. This project does not work without the grooved GDL. This needs to be a top priority. Plug should not make a stack with the dual GDL approach used in single cells. The plans for cell unitization and seal addition are unclear.
- Proposed future work has been identified, but demonstration of the idea as a stack will be crucial.

Project strengths:

- Overall, the project has a good approach and timeline, with appropriate go/no-go targets. Adding a resistivity target will only strengthen the project and help with understanding the risks to meeting manufacturing feasibility. Collaborations between Plug, UT, and ORNL are good. However, collaboration with Smith Engineering, Limitless Design, and non-funded collaborators is unclear. There has been good progress on porous rib design, and proposed future work to optimize the channel profile is good. Overall, progress is good, and the presentation by the PI was good. Plug has the right team assembled for the project.
- This is highly innovative work advancing fuel cell stack and BPP technology in several directions. The project appears to be well designed, and the team is generally well integrated to achieve project goals. Successful completion of all project goals would represent a major advancement in fuel cell stack technology that clearly supports the DOE objectives.
- The innovativeness and out-of-the-box thinking is a primary strength of this project, as well as the large assembled team. Projects driven by industrial partners (as this one is) can help ensure that research money is targeted toward current and actual problems.

- The project is exploring novel approaches to BPP manufacturing that, if proven successful, look to be game changers for making BPPs at scale.
- The project has an interesting concept and out-of-the-box thinking, as well as good collaborators. It is good to see Plug allowing room for such new ideas.
- This is a creative approach to high-speed plate manufacturing. The focus on wireless CVM is a strength.

Project weaknesses:

- R2R manufacturing limits compatible materials and specifications. The porous carbon-based GDL/gas channel must be shown to be durable compared to current graphite or stainless steel plates/channels. The project must show that water management does not become an issue as the stack ages and becomes more hydrophilic. The project also needs to show that the proposed corrosion-resistant nitride metal foils for Al (i.e., TiN) are stable in an oxidizing atmosphere and do not convert to an insulating TiO_2 layer.
- It is not clear whether the CVM and porous rib approaches are the only path investigated in this topic. If there is a down-selection process identified for these components, that needs to be published as well. Stack requirements for HDV systems, the KPIs that drive the down-selection process for the BPP material selection and processing, are not clear. The definitions of +, -, 0, etc. used to rank the materials and their characteristics need to be clarified.
- The project has no GDL supplier. For the coating, there is no evidence that the oxide layer has been effectively removed from the stainless in a continuous process. There is concern that the Ti will oxidize in an open-air plasma process. The plans for cell unitization and seal addition are unclear. The coolant mesh approach is expected to add resistive losses.
- The BPP coating technologies seem relatively early-stage and high-risk compared to the rest of the work. R2R application of BPP coatings does not seem to have a clear advantage over high-throughput batch processes. A potential risk of the thin flat plate design is the propagation of alignment or thickness errors through the stack, which should be carefully considered in the upcoming budget periods.
- This is an all-encompassing project, which can be seen as a strength but also might be a weakness if focus is diluted by trying to do everything all at once.
- Viability of the concept in a stack is yet to be demonstrated.

Recommendations for additions/deletions to project scope:

- It is recommended that a BPP AST or a unitized cell durability test be performed and that EOL BPP properties (ICR, corrosion, etc.) be reviewed prior to scale-up or pilot stack manufacturing. Also, short stack size for final performance and durability validation needs to be published. In addition, the final BPP deliverable to the Million Mile Fuel Cell Truck (M2FCT) should be at the beginning of BP 3 so that M2FCT labs can perform appropriate ASTs in parallel while Plug builds and tests the short stack. Finally, the duty cycle for the ≥1,000-hour durability test is not clear. It is recommended that Plug try to work with an HDV original equipment manufacturer to obtain an appropriate duty cycle for the durability tests and to project 25,000-hour durability feasibility.
- The project should report oxygen energy dispersive spectroscopy (EDS) or x-ray photoelectron spectroscopy (XPS) results of the plate surface after plasma treating. Plug may need a back-up plate-coating approach. Also, Plug needs to define the maximum anode overpressure requirement. The project needs to report how the seal is being introduced to the plate and how the membrane electrode assembly is being unitized with the plate. It needs to be determined whether the coolant mesh requires conductive coating. Compression effects on grooved GDLs need to be measured or modeled.
- The BPP coating approaches appear high-risk, and it would be good for the project to consider alternatives as a back-up plan for the final stack deliverable. The project should ensure that any concerns about the mechanical robustness of the alternative stack design are addressed.
- More detail is recommended around understanding the GDL material requirements for this concept.

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

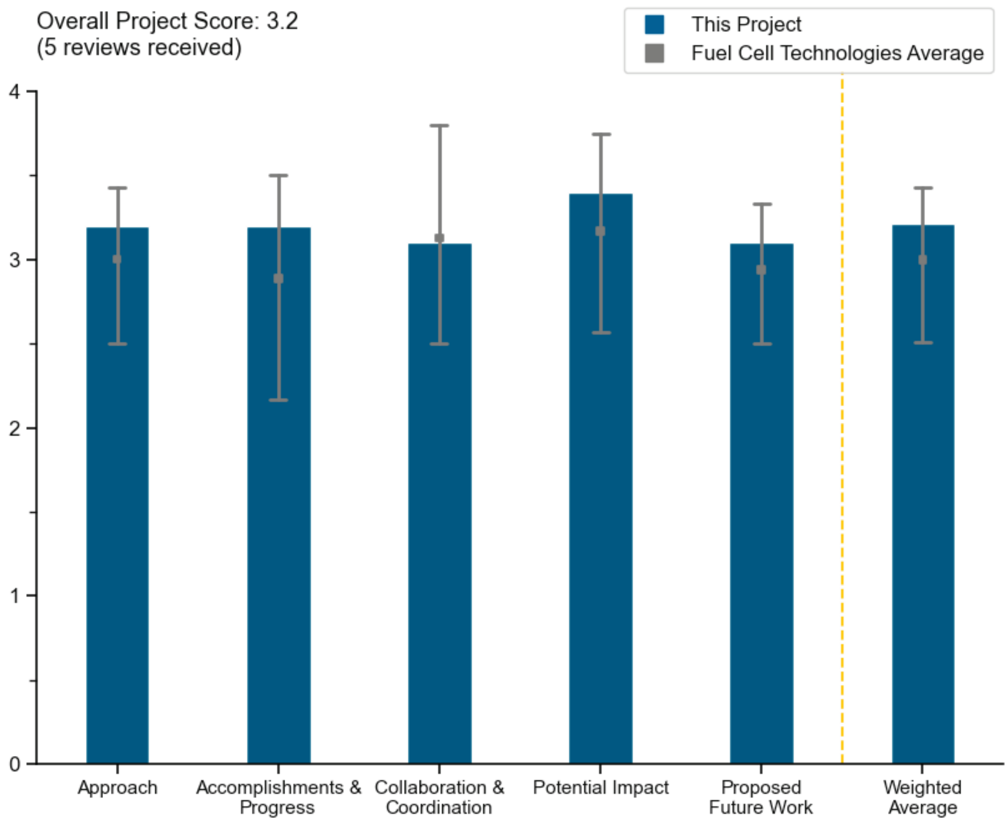
David Chadderdon, NeoGraf Solutions, LLC

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.

- This project uses a simple but effective approach. It uses a proven technology for the production of bipolar plates (BPPs) and targets reducing the amount of material that is used by decreasing plate thickness. The challenge that this pathway creates is the inclusion of foreign particles in the plate. For certain particle size to plate thickness ratios, defective plates may be manufactured. The challenges seem to be understood and are being addressed through improvement of the production process.
- A proposed approach is based on modification and cleaning of natural graphite flakes, which is very viable, scalable, and controllable. Proposed methods for the removal of natural and/or artificial impurities are well described and sound reasonable.
- A metric reflecting ash content was shown, including removing particles >200 microns and bringing down the ash content to a range of 6–22 parts per million (ppm). More information is needed on this metric and the confidence level that reducing ash to this level will be sufficient related to cation/impurity release and BPP gas leakage. Also, it seems this metric is important to the final limitations related to how thin the plates can be. It seems part of this metric should include what the ash content is. For example, SiO_x is probably completely inert, whereas FeO_x could be problematic. It would be nice if the approach would include a comparison of theoretical power density between composite plates and metal plates. In addition, as some original equipment manufacturer (OEM)/stack developers are working on relatively high-temperature operation, the project should examine the plate/resin materials to evaluate higher-temperature operation, such as 100° to 105°C, and the durability. The resin materials might have to be specifically chosen depending upon the OEM operating temperature. Furthermore, Advent presented a new membrane

electrode assembly (MEA) manufacturing line with an operating temperature of 180° to 200°C. Finally, the stated goal seems to be reducing the plate thickness from 1.7 mm to 1.4 mm. It is not clear that this reaches power density and volumetric density goals of most OEMs.

- The project is addressing the cost of the bipolar plates for heavy-duty fuel cell systems. The project is not addressing either the durability (25,000 hours) or the efficiency (68%) target. The material choice for bipolar plate may not have a significant impact on the fuel cell system's peak efficiency. However, the stack durability could be significantly affected by the bipolar plate-to-membrane interactions. To improve membrane durability, it would be good to understand the level of iron contamination for these expanded graphite materials and add some tasks to reduce iron contamination if preliminary analysis shows >5 ppm of iron.
- In general, the approach is good. It is recommended that the project assess whether process or material is the more significant source of inclusions. Then the approach could be more targeted.

Question 2: Accomplishments and progress

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

- The project is only 10% spent to date, so accomplishments reflect that amount of spending. A Design for Manufacture and Assembly (DFMA) analysis reading of $4.5/kW is a positive result for the potential of these materials. Additional information on the prior plates, which operated for millions of miles—the operating conditions and overall results of those plates—and the differences between those materials and the project materials would be valuable.
- Accomplishments demonstrated to date are in good agreement with proposed work scope. Planned milestones were achieved.
- Significant progress has been made toward demonstrating lower-basis-weight plates. Achieving <5% rejection of thin plates is a key criterion that needs to be demonstrated quickly, per Milestone 14.
- The project is in early stages, but a significant amount of progress has been made.
- According to the plan, the project is on schedule. Foreign particles in the BPPs have been significantly reduced, showing that progress is being made. However, given that a larger-than-Six-Sigma production environment is required for the production of BPPs, stacks can be built adhering to Six Sigma principles, as Six Sigma translates into 3.4 errors in one million parts. With a base failure rate of 17% in the team's assessment, the target should essentially be much better than 0.00034%.
- It is somewhat unclear whether inline quality control is available that can prevent faulty BPP from being assembled in a stack. It is also unclear if a certain number of faulty parts (i.e., the yield of usable BPPs) is considered in the cost analysis.

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.

- Ballard Power Systems and Strategic Analysis, Inc., are valuable partners for this project, and the project team covers the materials, plate formation, cost analysis, and an OEM. The Cummins project (not part of this project) presented machined graphite plates. This project should initiate an additional collaboration with projects like that one (as obviously using machined graphite plates is not a long-term approach, and that is currently the rate-limiting step for that project).
- This is a good mix of industry (customer, manufacturer, and material supplier) and research and cost engineering. All project partners seem to be effectively engaged and contributing.
- The team has shown good collaborative effort, including a coordination with the Million Mile Fuel Cell Truck (M2FCT) consortium.
- All project partners are collaborating well. However, there is no interaction with any university or national lab. While the plate leak check is a good way to catch issues before stack build, it may not translate to 100% leak-free plates in the stack after testing and during 25,000-hour durability. Therefore, it is critical to

develop methods for detecting any inclusions and particles >100 microns in the graphite roll before the plates are formed/pressed. Perhaps the project can leverage the M2FCT consortium or other entities to estimate iron contamination and develop a nondestructive plate quality check to detect inclusions in the plate.

- The team includes industry, analysis, and national laboratories (through M2FCT).

Question 4: Potential impact

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

- This project addresses the cost reduction of bipolar plate assemblies to meet the DOE target of $5/kW. Graphite is the largest cost driver for high production volumes of BPPs. This project targets the reduction of graphite material used while maintaining all other requirements on the BPPs. The challenge of material inclusions that cause leaks and weak points in the plates is addressed. The project is well structured in logical and sensible tasks. The overall approach is well described and makes a good deal of sense.
- A direct comparison between these composite graphite plates and metal plates is inevitable. There should be OEM input on mass manufacturing and evaluation on the Strategic Analysis, Inc., cost analysis; it seems only a few OEMs are exploring graphite plates. Most OEMs seem to be exploring metal/coated metal BPPs. Assuming these materials can reach the cost target (as modeled) and can have similar volumetric and mass power densities, this is a valuable technology to pursue.
- It is important to continue developing cost models and manufacturing improvements for carbon-based plate materials, as they have a better potential for meeting all DOE research goals (including durability).
- This project can have a significant impact on stack durability and cost, if executed per the plan and additional quality control methods for particle detection are implemented.
- If successful, the project will substantially effect a price decrease of BPPs for fuel cells and potentially other applications.

Question 5: Proposed future work

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

- The team proposed future work based on the project milestones and go/no-go design points, which correlates with a final deliverable.
- Future work is planned in a logical manner, and milestones are appropriate.
- Future work seems to be laid out relatively well. Discussions with other OEMs (beyond Ballard Power Systems) to verify that applicability of the materials is widespread could be valuable.
- Future work is reasonable. The team should have some interaction with a university, a national lab, or the M2FCT consortium for iron-level analysis and defect detection.
- The project focuses on the BPP production part entirely. The team is talking about reduction of leak rates, but in terms of plates leaking, the question is what the effect of leaking BPPs is on the durability of the MEAs in the stack. Several questions need to be answered: how much H_2 or O_2 is leaking, what efficiency is lost through these leaks, what the implications are of leaks on durability—in other words, what these leaks mean.

Project strengths:

- The project builds upon working BPPs that are employed in the field. Cost analysis is used to show that cost targets can be reached at target production volume.
- The project has a well-defined and well-thought-out approach on making expanded graphite particles (“worms”), followed by carbon sheet manufacturing.
- This is a good team that covers the needed technical areas. This is the only DOE-funded BPP project exploring carbon composite plates. It seems like that is the minimum that should occur (the number of projects should not be zero).

- The project has good collaboration and materials for development. The topic is important.
- The project has a good team and a good approach.

Project weaknesses:

- One weakness is the potential omission of supply chain evaluation for new sources of feedstock material. It would be helpful to know where the sources are located, whether the supply is limited, and whether there are any logistical or price issues.
- The understanding of what particle inclusion can be tolerated is based solely on leak rates. The actual impacts on performance, efficiency, and degradation are missing. This information is required to understand what type of particle inclusions may be acceptable and which ones should result in rejection of a plate.
- The project could use more work on understanding where some of the metrics originate and whether those metrics are appropriate.
- There should be more collaboration with national labs to better characterize the nature and origin of impurities.
- Lack of coordination with M2FCT is a weakness.

Recommendations for additions/deletions to project scope:

- Some studies should be added on (1) the efficiency and durability effects of the leaks (e.g., tolerated leak rates) and (2) on-line quality control that allows separation of plates with particle inclusions prior to stack assembly.
- The project should add (1) quantification of iron levels and (2) in-line/roll-to-roll defect detection for finding >100-micron particles in the graphite roll.
- There should be outreach to other OEMs to make the technology as widely applicable as possible.
- It would be good to add some supply chain analysis.

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

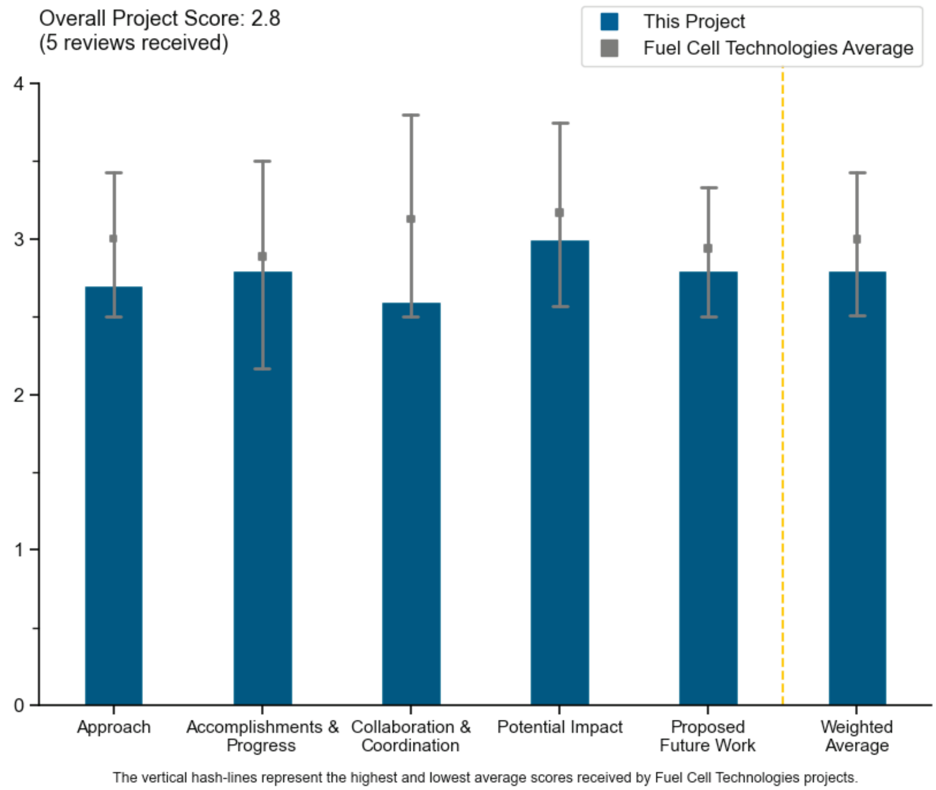
Siguang Xu, General Motors LLC

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 through-put with 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. The project has attained the target for equivalent elongation in low-cost ferritic stainless steel through channel-forming trials, developed microgrid technology for thin-sheet formability testing, identified humping as a major defect in high-speed BPP laser welding, and made progress in coating optimization trials. Future work includes completing material characterization and failure strain measurement, additional stamping simulations and testing, optimization trials for coating, further laser weld testing, and improving numerical simulation capabilities.

Project Scoring



Question 1: Approach to performing the work

This project was rated **2.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project aims to develop a stamping technology that enables the production of BPPs from low-cost ferritic steel. Part one is looking at various production approaches, such as single-step versus multi-step; part two is looking at the development of required coatings for use as BPPs in fuel cell systems; and part three is enhancing laser welding technology for the assembly of these plates into BPP assemblies (BPAs). The approach is sound and logical with regard to fundamental aspects and the development of a method to create such plates. Understanding how well the coatings may hold up in the harsh conditions of a fuel cell stack and how this could result in contamination processes is not yet addressed.
- Emphasis appears to be on the forming/stamping/manufacturing of the BPPs. Material and coating development is coming later. The comparison between atomic layer deposition (ALD) and physical vapor deposition (PVD) coatings will be interesting. ALD will likely be the cheaper long-term alternative. The project will develop stamping/laser welding and coating methods for ferritic BPPs. This should be a substantial cost savings over Ti plates.
- The approach is generally good—in particular, the fundamental understanding for forming and welding failures and the replication of those failures in simulation and modeling. However, the approach for coating seems weak or was not given enough attention. It does not look like the coatings are on track to meet the conductivity performance target, no corrosion data is available yet, and more details around the cost–manufacturing assessment are expected.
- The approach to the work is to form BPPs at high speed and then coat and weld them. There seems to be a disconnect between the project approach and the project goals, which are focused around making 100,000 units/year, and also a disconnect with the broader DOE goals to make 20,000 fuel cells per year, which requires on the order of 6 million BPPs per year. There is little explanation of how the project will

meet the go/no-go goals. It is not clear how electrical conductivity and iron release will be measured. Coatings work is shown, but the resistance reported in this presentation (the lowest is 0.015 ohm cm^{-2}) exceeds the project goals. It is not clear how the resistance will be lowered.

- The proposed approach was neither well described nor well presented. The approach workflow was unclear and not structured. The challenges to address were not stressed.

Question 2: Accomplishments and progress

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

- According to the plan laid out, the project is on schedule, and very good progress has been made with regard to understanding various stamping, coating, and welding processes. The project has well-communicated basic research elements whose results are useful to the entire industry. Some results, such as the reason one laser power strategy works better than another, should be looked at from a theoretical direction in addition to the empirical approach that was presented. This may save time in optimizing the process and making it available for other materials and/or plate thicknesses.
- This project is in its early stages, so progress is reasonable, especially given significant delays in material procurement, etc.
- The project is only 3% to 4% spent to date, so it is just starting, with limited accomplishments at this point. It seems like the project needs to ramp up. Two-step forming seems like a more expensive methodology. ICR appears to need improvement, especially considering this is beginning-of-life.
- Progress is difficult to evaluate for this project. The spending is somewhat low, so it appears to be early in the project. It would have been helpful if the presentation had worked through the technoeconomic analysis and required manufacturing speed; the reviewer had to go through the numbers in the presentation and calculate the required welding speeds, etc. One challenge with this project is that it was awarded with the goal of 100,000 units per year, but DOE has already moved on to a goal of 2,400 units per hour (see Funding Opportunity Announcement 2922), or approximately 6 to 10 million units per year. The resistance of the plates is presently too high to meet the go/no-go criteria. Clarification is needed on how it will be lowered to meet the goals. There was no mention of Fe emissions from the plates, particularly over time toward the 25,000-hour goal for the Million Mile Fuel Cell Truck (M2FCT) consortium. For the project review next year, the presentation should be more explicit about the DOE M2FCT goals and project goals and how the research is progressing toward those goals.
- Despite several accomplishments presented, it was not emphasized how they effect the achievements of the project's final goals.

Question 3: Collaboration and coordination

This project was rated **2.6** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to be a good level of collaboration between partners.
- Penn State is doing the imaging of the laser welding at Argonne National Laboratory (ANL), presumably using the Advanced Photon Source (APS), but the APS is closed for a significant time. It is not clear where future imagining will take place. The project includes General Motors (GM, a primary original equipment manufacturer), plus two universities (Penn State and Northern Illinois University).
- The team has industry and university contributions. It is unclear whether this project is collaborating with the M2FCT consortium. With regard to basic understanding of the degradation of the coatings that are developed here, this may be beneficial.
- The presentation was not very clear about how GM was coordinating with the partners. The Penn State logo was included on several slides, but specific accomplishments were not clear. The accomplishments of Northern Illinois University are also not clear. GM appears to be collaborating with ANL, on imaging and it would be helpful to clarify the lab's role on the collaboration slide.
- There was no collaboration with external institutions, especially coordination with M2FCT consortium.

Question 4: Potential impact

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

- This project addresses the cost reduction of BPAs to meet the DOE target of $5/kW. Graphite is the largest cost driver for high production volumes of BPPs. This project aims to create thin-sheet BPAs that are welded together and use low-cost steel coated with a protective layer.
- In particular, the understanding and simulation of high-speed welding defects are very important and have large potential (positive) impacts.
- The project is aimed at lower-cost materials and processes to meet the DOE BPP targets. The project is examining the stamping processes, which few other DOE projects have done.
- If successful, the project can result in decreasing the price of BPPs and increasing the fabrication rate.
- The progress on rapid welding is very good and could have a high impact. The impact of this project is not clear, as its goal is 100,000 plates per year, while a more realistic goal should have been 6 million per year. While the contract was likely negotiated at 100,000 per year, GM and DOE need to figure out whether they should change the goals for this project. If the goals do not change, it seems like much of the work will be low-impact because it will not be able to meet the speed requirements for modern fuel cell manufacturing. The cost impact of the methods chosen is also not clear in terms of the M2FCT goals of $80/kW per system.

Question 5: Proposed future work

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

- The project just started, so the majority of the project is the future work. Coating development (TiC by ALD and/or PVD) appears not to have started yet. This is listed as trials being complete by the end of Fiscal Year 2023, which seems like an important portion of the project. The material evaluation plan related to corrosion testing seems undefined at this time. The project should include a cost comparison between ALD and PVD coatings. The overall cost analysis of the BPPs, other than the DOE cost target, does not seem to be mentioned. This project should include a cost analysis.
- Risks were not identified; mitigations were not proposed. The decision point comes almost at the end of the project. Given that the coating includes Ti (a known membrane poison), future work should include not only an understanding of the durability of the coating but also the durability of other fuel cell components in the presence of that coating.
- Future work is included on slide 8. The activities are relevant to meeting the Phase I goals for the project, but there is no specific mention around meeting the go/no-go criteria for durability measurements (i.e., Fe dissolution) and plate resistivity. There is also no mention of meeting goals for speed (100,000 plates per year) or scrap rate.
- Future work should include studies on the lifetime of the plate coatings, potential contamination of cell components, and quality control (QC) aspects, such as surface roughness and flatness of the created BPPs.
- The team presented future work based on the project milestones and go/no-go plan.

Project strengths:

- High-speed welding of BPPs is a tremendous challenge for the fuel cell industry. Others seem to have met the required speed goals by using adhesives, but a welded BPP would clearly be superior. Also, it would be highly beneficial to have BPPs made from lower-grade steel. GM and the team are doing a nice job using advanced imaging methods to evaluate welding work. ALD and PVD seem like promising methods to make robust coatings.
- The project covers the entire stamping/welding processes, plus different coating processes to meet the DOE cost target.
- The project has a sound approach and development concept that creates basic knowledge that may be useful in other fields and industries.

- The team has significant plate and simulation expertise. Welding investigation is important.
- The project offers a potential increase in welding and production rates.

Project weaknesses:

- The project goals seem out of alignment with DOE goals to make 6 to 10 million BPPs per year. There is little techno-economic analysis showing how the innovations in this presentation lead to the project goals, for instance, whether ALD and PVD coatings meet cost and speed requirements. The principal investigator should correlate the welding speed (m/sec) and coating method speeds to BPP manufacturing rate and cost.
- Coating investigation seems to be given lesser priority; the impact of coating on durability of other fuel cell components has not been considered.
- If the coatings do not last, then the whole development will not be useful for fuel cell systems. The lifetime of coatings, contamination in cells, and QC are missing.
- It is unclear whether the processes defined in this project will be made available to the wider community or if this is going to be available only to GM.
- The workflow lacks structure.

Recommendations for additions/deletions to project scope:

- This project is still in early stages. For next year, the team should consider evaluating a more rigorous techno-economic analysis showing how the path that GM has chosen will meet DOE cost and speed goals. At a broader level, DOE and GM need to consider whether it is worthwhile to pursue a method for 100,000 BPPs per year (enough to make 167 stacks with 300 cells and 600 BPPs per stack). It seems that 167 stacks per year is far from the volume needed for a successful product.
- A presentation or report should clearly state challenges and how the project approach will resolve these challenges. The results and accomplishments should be clearly structured, correlated with milestones, and represent progress toward final goals.
- Earlier in situ evaluation of coating performance and durability in a fuel cell environment is recommended.
- Inclusion of a material vendor related to the plate materials and stamping process could be valuable.
- Studies should be added on lifetime of coatings, contamination in cells, and QC of plates.

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

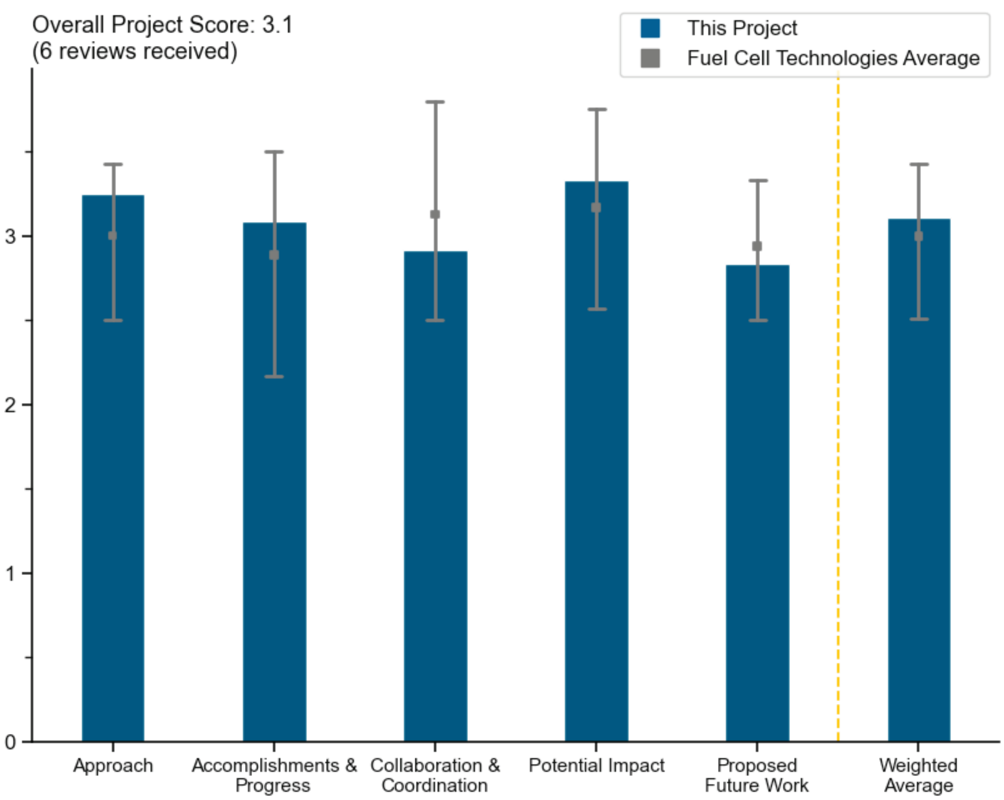
Giri Agrawal, R&D Dynamics Corporation

DOE Contract #	DE-EE0009617
Start and End Dates	5/1/2022–11/1/2024
Partners/Collaborators	Loop Energy, University of Texas – 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 **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- R&D Dynamics Corporation highlighted the company's partnership with Loop Energy in helping to address the critical barriers of efficiency, mass, and cost in fuel cell system CE expander development. The project team has demonstrated excellent progress toward meeting or exceeding the stated efficiency goals for CE, turbine, motor, and drive efficiency. The project also has an excellent pathway toward meeting weight and volume targets. However, the team is waiting for quotes to state the projected CE cost. An estimate on projected CE costs should be known, as the project is close to 50% completion. There was also a question on noise from the reviewer panel that may not have been fully addressed. CE cost and noise could be addressed during the next Hydrogen Program review.

- The approach of the team is good and has identified critical enabling capabilities for the air-handling system for a fuel cell system. Targets on efficiency, cost, and durability have been identified. Performance was substantially discussed. Cost and durability received less communication at this early stage but could have been addressed a bit more in the discussion of the design stage to ensure targets are met.
- This work demonstrated the technology enablers to meet DOE air machine efficiency, package, and weight targets, including high-speed centrifugal wheel design, air foil bearing, motor driver with SiC, etc. More supporting evidence to demonstrate 25,000-hour durability is needed.
- The project focuses on efficiency and durability. These attributes are the most important for the fuel cell system for HD applications.
- A trade study to understand the engineering balance of cost, efficiency, and reliability, which are the three primary project objectives, would be appreciated. Going into what decisions have been made with the planned prototype hardware would be appreciated. For example, slide 4 lists advantages, but nowhere else were the disadvantages or challenges of the selected sub-components and designs readily apparent.
- It is unclear whether the minimum rotation will be sufficient to ensure that an air lift will be achieved to minimize friction and maximize efficiency at the anticipated fuel cell idle flow.

Question 2: Accomplishments and progress

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

- Achievements include a planned air machine using compact aerodynamics that enables package volume and weight that appears to be competitive. Company experience with air bearings is a plus. Regarding opportunities, the project would benefit from aero maps for the compressor and turbine. Aero efficiency is not quite reaching the project target, and it appears there is an external air feed that should be called out, as it leads to overall air machine efficiency impact. Also, it would be good to see a more detailed validation test plan that includes water injection testing of the expander. Perhaps accelerated testing could be conducted to look into damage modes to this air machine. It would also be good to test at module level with Loop Energy once component tests are completed (or in parallel, if time is an issue); it was not clear whether such a test was planned.
- The project largely completed design in the period, as per the plan. This work is progressing well. Several critical design elements were identified as having been complete but were not addressed in the Annual Merit Review (AMR) materials; two that may be expected to be difficult to resolve are (1) balancing of thrust forces and (2) internal motor heating due to integrated power electronic switching at high speeds. One of the stated critical capabilities was the need for air foil bearings to eliminate oil contamination. This was not addressed with detail in the AMR material, so it is difficult to understand progress on this with respect to expected capability and durability.
- R&D Dynamics Corporation has shown excellent progress toward addressing the critical barriers of efficiency, mass, and cost in fuel cell system CE development. The project is exceeding many of the performance targets in CE efficiency, mass, and volume. Cost metrics are pending. Also, the total power of the fuel cell system air CE does not seem to be noted.
- There has been good progress in meeting or showing evidence in meeting air machine efficiency, package, and weight targets. Supporting data or testing plans to meet the 25,000-hour durability target are requested.
- The basic design has been completed. It would be helpful to see the model of efficiency and the performance diagram and intended operation points for HD fuel cell system applications, as well as the design verification test plan.
- Three milestones originally scheduled for January and May 2023 were not completed. An explanation for the delay and a mitigation strategy to either avoid a reoccurrence or accelerate progress were not provided.

Question 3: Collaboration and coordination

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

- R&D Dynamics Corporation seems to be in good engagement with project partners. Discussion with Loop Energy on addressing CE efficiency was highlighted during the review. Discussions with the University of Texas – Dallas (UT Dallas) on CE drive and control software design were highlighted in the presentation. R&D Dynamics Corporation is encouraged to summarize specific accomplishments from each partner in future presentations.
- The project demonstrated good collaboration between the fuel cell system developer, component developer, and academic partner.
- While it is still early in the project, it would be good to know how much collaboration has been done at this point. System mechanization of the air delivery system should be included because that plays a foundational role in how the component is selected. The inverter–controller with high-frequency SiC metal–oxide–semiconductor field-effect transistors (MOSFETs) and the algorithm/software comprise a large portion of the component cost; therefore, more detail should be provided.
- Preliminary design and fabrication of drive electronics and software were completed (perhaps by UT Dallas, although that was not clear), but results were not presented.
- Project collaboration is being clearly and effectively leveraged.

Question 4: Potential impact

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

- The project being led by R&D Dynamics Corporation is providing excellent support toward advancing DOE objectives in fuel cell air delivery systems. If successful, R&D Dynamics Corporation will have developed a fuel cell system air CE expander that could transition to industry. The total impact of a fuel cell system air CE expander on the overall DOE fuel cell system is more challenging to address at this point of the project.
- A highly efficient, durable, small, and low-cost air machine is one of the key enablers for fuel cell technology adoption and commercialization to reduce CO_2 emissions. This project demonstrated the potential path to meet DOE research, development, and demonstration goals and objectives.
- Outcomes (particularly the proper size of an air compressor for HD fuel cell systems) would be highly impactful on the domestic supply chain for HD fuel cell system development.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- Efficiency is close to the target. However, understanding accurate volume production costs and long-term durability, especially with liquid and vapor water exposure, will be critical.
- Several performance targets appear to have been achieved, and several others are yet to be defined. These targets are yet to be demonstrated with a prototype. Anticipated system weight and volume are significantly below targets. It would have been useful to show performance maps for both the compressor and expander.

Question 5: Proposed future work

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

- R&D Dynamics Corporation's presented milestones provide good effectiveness to address project management. The project has one go/no-go decision point in November 2023, which will allow DOE monitors to appropriately address project risk. A point of clarification to address is how much of the CE will be manufactured and tested by the November 2023 go/no-go decision point. CE testing should be completed before November; the presentation summary states "end of the year."
- The proposed work is a logical sequence. However, it is unclear how durability over 25,000 hours will be assessed. An accelerated stress test is perceived as necessary. R&D Dynamics Corporation is a foil bearing

pioneer. However, performance data for other applications were not reported, which could support an assessment of the risk level of the proposed work.

- It is suggested that the project provide more detailed plans in durability protocol developments, including accelerated durability testing protocols with various failure mode stressors.
- It is suggested that the project clarify test protocols for design verification, particularly efficiency and durability.
- The plan by which durability will be validated in 2024 was not clear. It is not clear whether there is an accelerated test procedure that can extrapolate to the required end of expected life for the application.
- Future work is not well outlined, nor are any potential headwinds.

Project strengths:

- The project strengths include R&D Dynamics Corporation's technical knowledge of turbo machinery. The partnership with Loop Energy, an industry leader in fuel cell system development, is also a strength. The communication between Loop Energy and R&D Dynamics Corporation is appropriate for this effort.
- Strengths include R&D Dynamics Corporation's expertise in foil bearings and air machinery and the inclusion of a fuel cell developer.
- The team has strong expertise and experience in compressor and expander development.
- The solutioning approach, technology experts, and collaboration are all good.
- The project will provide good evidence to meet air machine DOE targets in efficiency, weight, and package.
- Size and mass are strengths.

Project weaknesses:

- There is no significant project weakness at this point of execution. Clarification is needed as to when a fuel cell system CE could be available. If one could be available prior to the November go/no-go, there is no issue. If after the November go/no-go, perhaps the go/no-go decision point should be moved. Per discussions at the AMR, R&D Dynamics Corporation should state the power level, address cost, state the approach to the accelerated stress test, and provide estimates on noise of the fuel cell system CE in future project updates.
- Time in the AMR to address the details of the critical design decisions was limited, so it is difficult to say whether requirements are being met with a robust technology. The team has stated the requirements' importance, so it would appear that they are being addressed. Some concise evidence of completion could have been helpful.
- Weaknesses include a justification for the inclusion of UT Dallas, progress delay, the unknown match between fuel cell idle and foil bearing airlift, and missing relevant information in several areas.
- The project should provide more supporting analysis and/or data to meet the durability target.
- A project plan to demonstrate reliability and estimated costs has yet to be seen.

Recommendations for additions/deletions to project scope:

- The project schedule and scope are appropriate.
- The project team should seek to interact with academia and/or national labs to pursue the modeling; study of materials compatibilities, particularly for durability; development of test protocols; and design verification plan.
- 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

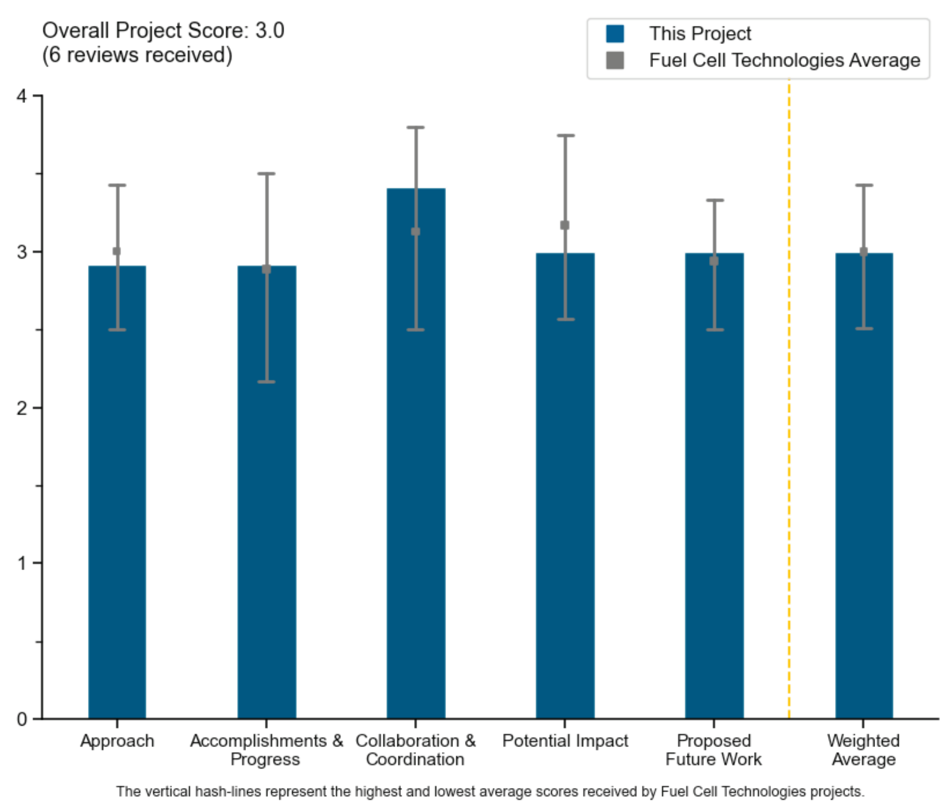
DOE Contract #	DE-EE0009618
Start and End Dates	9/1/2022–11/30/2024
Partners/Collaborators	Ballard Power Systems, National Renewable Energy Laboratory

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 goal of the project 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



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.

- Eaton has clearly identified the critical performance barriers being addressed by its project. The project is well defined and feasible. Teaming with Ballard Power Systems (Ballard) and the National Renewable Energy Laboratory (NREL) makes for a good approach to performing the work. NREL's task on air system modeling and simulation seems to be the most developed task of the project. It was not exactly clear how much work has been completed at Eaton, as approximately 15% of the funds are reported to have been spent and the project is over 40% complete. The execution of the proposed work may need more clarification. It was unclear if a no-cost extension was requested, as it was not easily found in the documentation reviewed.
- The approach of the team is good. It has identified critical enabling capabilities for the air-handling system for a fuel cell system through the application of a Roots machine to deliver performance and efficiency. The project stated targets of 50% improvement in power consumption and a path to improve reliability, durability, and affordability. Performance was substantially discussed. Cost and durability received less communication, and a clear path to address these in the project is needed against the project goals.
- It is good for the project's approach to use model-based engineering to validate the prototype. It is supposed to show the design specification of air flow and pressure—perhaps full and partial power points for heavy-duty (HD) application. A value of 260 g/s at 2.33 bara seems to be too small for HD application (per the Million Mile Fuel Cell Truck [M2FCT] reference fuel cell system). It is suggested that the project reconcile design requirements and specifications.
- The project outline seems to be well communicated. Challenges and mitigation factors have been provided, although some could be unsolvable within this project scope.
- This work used a system modeling approach to define fuel cell system architecture and conducted design studies to establish component requirements to meet system targets. The project should provide more supporting data to address high-risk barriers, including meeting air machine efficiency, package, and durability targets and oil contamination concern.
- The selected compressor type may not achieve the intended efficiency target, and durability is expected to be compromised by the injection of water, leading to corrosion.

Question 2: Accomplishments and progress

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

- The project has made good progress.
- In terms of accomplishments, the potential for reliability seems suited for permanent grease-type roller bearings as long as sealing can be guaranteed. It would be clearer to understand directly what compressor/expander/motor efficiencies are compared to the funding opportunity announcement target, rather than baking everything together as a power number. This could further highlight the strengths and weaknesses of the sub-components that make up the air machine. A testing plan to include water is a plus; however, it is focused on a compressor inlet based on system architecture decisions and not so much on an expander inlet, which is normally the point of concern. In terms of opportunities, cost, mass, and volume are not well covered. Expander inlet water testing is not addressed. Further explanation is needed regarding what can be done to make a Roots expander more feasible. Using a recuperator is interesting from an efficiency perspective but may lose value because of water evaporative cooling upstream, and freeze is a real concern. It is not convincing that adequate humidification is achievable with the water introduction location, plus having two heat exchangers before the stack.
- Eaton has presented current estimates on fuel cell air delivery system power consumption, which are on track to meet the project objectives. The execution of the proposed work may need more clarification. A go/no-go gate is scheduled for November 2023. Some of the estimates for power consumption are expected to be validated with hardware. This might not be possible with the state of effort discussed during the review. This was also not completely clarified during the question-and-answer session at the merit review.
- Good progress was made in system modeling and design studies. The presenter should provide more supporting data to meet air machine efficiency, to meet package and durability targets, and to mitigate oil

contamination risk. For example, it is unclear what the design options are to close the power consumption gap at 50% flow.

- The project largely executed design and analysis tasks in the period, as per plan. From the material presented, it is difficult to assess whether the project is proceeding per schedule. The project stated a go/no-go before November 2023.
- Only progress toward energy consumption targets is mentioned, leaving many other targets undefined, such as weight, volume, and cost.

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.

- Eaton seems to be in good engagement with project partners. It is getting input from Ballard on fuel cell system requirements and working with NREL on modeling. The presentation highlighted the programmatic accomplishments led by NREL.
- The project demonstrates excellent collaboration between industry and academia, particularly in model-based engineering. The project is expected to clarify the design requirements for HD applications from the M2FCT reference fuel cell system for Class 8 HD trucks led by Argonne National Laboratory, rather than Ballard.
- The project demonstrated good collaboration between the fuel cell system developer, component developer, and NREL.
- There appear to be good links with Ballard and NREL, and work has been shown.
- Collaboration with technology partners appears excellent. Several questions during the Annual Merit Review (AMR) were answered by an assumed partner from the audience. It was difficult to track the answers, as they were given off-mic and off-camera.
- Although a fuel cell system duty cycle is useful (M2FCT), it is unclear how such a cycle would be applied to derive a compressor–expander accelerated stress test to rapidly evaluate durability.

Question 4: Potential impact

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

- A highly efficient, durable, small, and low-cost air machine is one of the key enablers for fuel cell technology adoption and commercialization to reduce CO_2 emissions. This project demonstrated the potential to meet DOE research, development, and demonstration goals and objectives; more supporting data are needed to overcome high-risk barriers in meeting air machine efficiency, package, and durability targets and mitigating oil contamination risk.
- Eaton can provide excellent support toward advancing the DOE objectives in fuel cell air delivery systems. If successful, Eaton will have developed a fuel cell air delivery system that is "transitioned to industry," i.e., Eaton can mass manufacture the proposed fuel cell air delivery systems.
- The project is highly expected to impact the domestic supply chain in the air management system for HD fuel cell system applications.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- The power consumption at 50% load is still significantly higher than the target. The lower-speed machinery impact on durability and reliability is compromised by the water injection, which is expected to lead to corrosion. Projections for several important metrics have not yet been quantified (weight, volume, cost). The risk of air contamination by lubrication oil is not discussed.
- Three main pillars of the project are cost, durability, and efficiency. Cost so far is missing. Durability has potential but is yet to be seen, and a productive accelerated durability test would be fruitful. Efficiency for the 50% power point seems far off target.

Question 5: Proposed future work

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

- The project summarized the remaining challenges and action items, which is an excellent approach.
- The project did a good job being forthcoming with challenges on Slide 11.
- The project sequence is reasonable, but significant risks remain, such as the presence of corrosion, air contamination by oil, and operation under subfreezing conditions.
- Eaton presented milestones providing a good effectiveness to address project management. The project has one go/no-go decision point in November 2023, which will allow the DOE monitors to appropriately address project risk. This might need clarification or review.
- The development of the pathway to improved durability and affordability was not clear. An accelerated test procedure that can be extrapolated to the required end of expected life for the application should be performed. It was unclear whether cost vs. payback is being evaluated against a baseline.
- More supporting data is needed to close the efficiency gap, mitigate oil contamination risk, develop a durability protocol, and provide test planning and execution.

Project strengths:

- The project presents a good technology opportunity and has an aggressive performance improvement goal. Good technology expertise and collaborative partners are also strengths.
- The project strength is use of a system modeling approach and design studies to define system architecture and component requirements.
- The project's strengths are leadership: an industry leader in vehicle air machinery and a world leader in fuel cell system design and manufacturing.
- A strength is team composition, with the inclusion of a major original equipment manufacturer and fuel cell system subject matter expert.
- Strengths are strong capabilities in Roots compressor–expander design and development and strong collaboration to pursue model-based engineering to design.
- Durability is a strength.

Project weaknesses:

- Limited time was available in the AMR to address the details of the critical design decisions, so it is difficult to say whether requirements are being met with a robust technology. The team has stated their importance, so it would appear that they are being addressed. Some concise evidence of completion could have been helpful on affordability and durability.
- The main project weakness is in execution as presently reviewed. If the fuel cell air delivery system is not on test by November, a no-cost extension should be considered. Per reviewer comments, understanding the impact of water injection into the fuel cell air delivery system is crucial to assessing viability.
- The project should show more supporting data/analysis to address high-risk barriers in meeting air machine efficiency, durability, and package targets and mitigation of oil contamination risk.
- Weaknesses are undefined machinery accelerated stress test, corrosion, air contamination, and subfreezing risks, as well as missing projections for several important metrics (efficiency, weight, volume, cost).
- Cost (unknown) and size/weight are not addressed.

Recommendations for additions/deletions to project scope:

- This project is to develop an air management system with a positive displacement compressor and expander. It is suggested that the team clarify advantages and disadvantages vs. a centrifugal compressor and expander for HD applications, including effectivity of the Roots expander for partial power. A value of 260 g/s at 2.33 bara seems too small for HD application (per the M2FCT reference fuel cell system). It is suggested that the project reconcile design requirements and specifications.
- Corrosion, subfreezing, and air contamination activities to assess risks should be included.

- The project schedule and scope are appropriate.
- No additions or deletions to the current project scope are recommended.

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

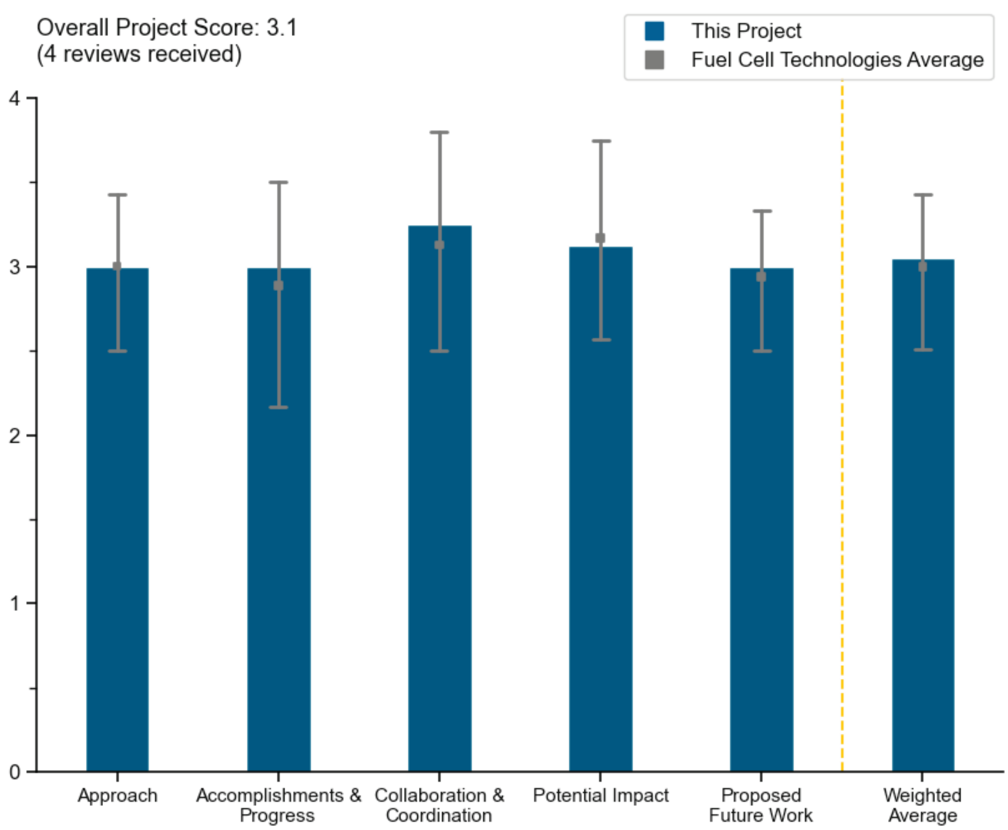
Mike Bunce, MAHLE Powertrain, LLC

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 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 will use 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. Achievements include the completion of the initial model, the selection of compressor and turbine geometry, and the definition of the air cleaner size and geometry. Future work includes individual component design activities, fuel cell system control strategy development, integration with experimental setups, and high-fidelity component performance degradation and stack poisoning modeling.

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

- MAHLE Powertrain, LLC (MAHLE) has clearly identified and addressed the critical performance barriers of the project. The project is well defined and feasible. Teaming with BMTS Technology (BMTS) on compressor–expander design was important on this project. MAHLE has presented a well-designed project to meet the objectives. The company is also integrating the efforts between Oak Ridge National Laboratory (ORNL), BMTS, and General Motors (GM) Global Propulsion Systems well.
- The project objectives are clearly identified:
    - Optimizing the compressor–expander and bearings.
    - Developing primary air filters with adsorption.
    - Incorporating a secondary filter to remove chemical impurities in air.

  The project approach includes an aerodynamically optimized compressor wheel and housing for high efficiency, a coated aluminum variable geometry turbine for a low-enthalpy environment, and a novel “3D” bearing for tighter clearances and faster compressor speeds that is water-lubricated to prevent oil leakage.
- Water-lubricated appears to mean ethylene-glycol–water-lubricated. Ethylene glycol will be problematic for the catalysts if there is any leakage into the fuel cell. It is not clear there would be any advantage to ethylene-glycol–water lubrication over an oil-lubricated bearing, as both ethylene glycol and oil leakage into the fuel cell will cause similar issues. The redundant air filtration system should improve reliability. The presence of Pt in the “catalytic” filter could be problematic from a critical materials and cost perspective. Approaches without precious metals should be prioritized, and cost needs to be considered for the filter. Two of the three systems being investigated contain Pt, but the amount of Pt in the filter is not discussed. The project does not address the motor controller, which is a major cost contributor to the air management system.
- The inclusion of a secondary air filter is expected to increase durability and reliability. However, water–glycol for lubrication is likely to lead to corrosion, even if subfreezing temperatures are averted.

Question 2: Accomplishments and progress

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

- MAHLE is on track to meet project objectives for the development of the catalytic air filter for the fuel cell air system. The company is also on track with BMTS support to meet the DOE fuel cell air system goals stated during the review, and the team is hitting virtually all the stated metrics with an un-optimized system. Programmatic milestones may not have been shared during the Annual Merit Review (AMR). These would have helped give a better picture of project status. As discussed in previous AMRs, funding expenditure seems lower than expected. Clarification on spend rates should be discussed at the next programmatic review.
- The project has made good progress in the first six months. Only the progress made in the first quarter was mentioned. The team has developed an initial simulation model for the air system and component models to project the performance relative to the end-of-project targets. The team has determined the air cleaner size, geometry, and pressure drops. The team has selected catalytic materials for the secondary air filter.
- The project is still early in development. Good progress has been made on compressor designs to date.
- A milestone schedule was not provided, so it was not possible to assess progress against deliverables. Progress includes air compression, system simulation, and primary and secondary filters. Several important weight, volume, and cost targets were not addressed.

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.

- This is a strong team with several original equipment manufacturers (OEMs) that cover all major elements of the proposed air subsystem including powertrain, compressor–expander, and air filters. Contributions from national laboratories and support from other fuel cell manufacturers (e.g., Ballard Power Systems and Hyzon Motors Inc.) are also included.
- The project has a strong team, with BMTS and ORNL as subcontractors and GM as an industry advisor.
- MAHLE has a strong team for addressing fuel cell air subsystems. The contributions from BMTS were well highlighted. The work from GM and ORNL could be better highlighted. Per text and AMR discussion, MAHLE has received input from GM, Hyzon Motors Inc., and Ballard Power Systems. This might be better highlighted or tabulated in future AMRs.
- There appears to be good collaboration to date. Additional collaboration is needed to determine the filter requirements and specs for air coming out of the filter (i.e., acceptable contaminant levels).

Question 4: Potential impact

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

- MAHLE has a strong team that can provide excellent support toward advancing the DOE objectives in fuel cell air delivery systems. The partnership with BMTS provided a good pathway to commercialization of MAHLE's product. There were some reviewer questions regarding corrosion from leakage of the BMTS compressor–expander machinery. This concern should be addressed.
- Air management equipment is very relevant. Air handling is a major cost contributor and can be a significant parasitic loss to system efficiency.
- The project goals are mostly consistent with the funding opportunity announcement targets.
- Several targets (e.g., weight, volume, cost, and durability) cannot be evaluated because they are seemingly not included in planned activities. More specifically, it is unclear whether an accelerated stress test will be used to obtain compressor–expander durability within a relatively short period (<<25,000 hours). Activities are ongoing to establish primary and secondary filter maintenance needs. The impact of a Pt catalyst for the secondary filter on cost has not yet been determined and increases constraints on this element availability for fuel cell manufacturing.

Question 5: Proposed future work

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

- The proposed work follows a reasonable sequence. It is unlikely that stack poisoning relationships will be successfully developed, because a relevant air mixture needs to be defined and realistic concentrations would lead to a slow degradation that will be difficult to separate from other degradation modes. More specifically, the inclusion of only SO_2, H_2S, NO, NO_2, and NH_3 is too limited and does not reflect the presence of other contaminants.
- Plans for Pt-based catalytic filters for the species identified seem misguided. These appear to be more accurately described as chemical traps, and more cost-effective options than Pt should be available.
- The project needs additional collaboration and input to determine filter performance requirements.
- MAHLE may have not included (or adequately discussed) project milestones during the AMR or in the documentation submitted. A go/no-go milestone is discussed, but the date is omitted. Assuming a date of November 2023, MAHLE should be able to demonstrate sufficient progress to clear this go/no-go gate. With respect to work in 2024, more details on fuel cell stack poisoning could be useful.
- The proposed future work is consistent with the barriers and challenges identified to date.

Project strengths:

- Project strengths include an extensive team of OEMs and national laboratories, collaboration activities, and the inclusion of a secondary filter.
- The compressor is based on a known reliable design with relevant previous data and acquired experience. The design would suggest the project can come close to performance targets.
- The project's partnerships are its greatest strength toward meeting the DOE goals for developing an advanced fuel cell air system.
- Project strengths include a strong team and relevant experience.

Project weaknesses:

- There are no glaring weaknesses in the execution of this project as presently reviewed. Per reviewer comments during the AMR, an understanding of glycol leakage from the compressor, an understanding of possible corrosion from the glycol leakage, and an understanding of the impact to the fuel cell catalyst should be presented at the next programmatic review.
- The project's weaknesses involve several targets not being discussed (e.g., weight, volume, cost), the corrosion risk (i.e., water–glycol lubrication), a few unreadable illustrations, an unclear development schedule (i.e., milestone tracking) that makes gauging progress difficult, and difficulty in establishing practical poisoning relationships.
- The project fails to address motor controllers. The use of Pt in the catalytic air filters and the presence of ethylene glycol in the bearing lubricant are also weaknesses.
- The project is not yet addressing the cost and weight targets. It has no plans to develop the motor and motor/controller, even though these components are known to be the most significant contributors to cost.

Recommendations for additions/deletions to project scope:

- Use of noble metals, such as Pt, as coatings for the secondary filter should be discouraged. The project should add a subtask to develop low-cost motor and motor/controller.
- Recommendations include adding activities to quantify the corrosion risk and reconsidering and revising contamination activities.
- Pt-based catalytic filter work should be removed or decreased.
- The reviewer has no additions or deletion to the current project scope.

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

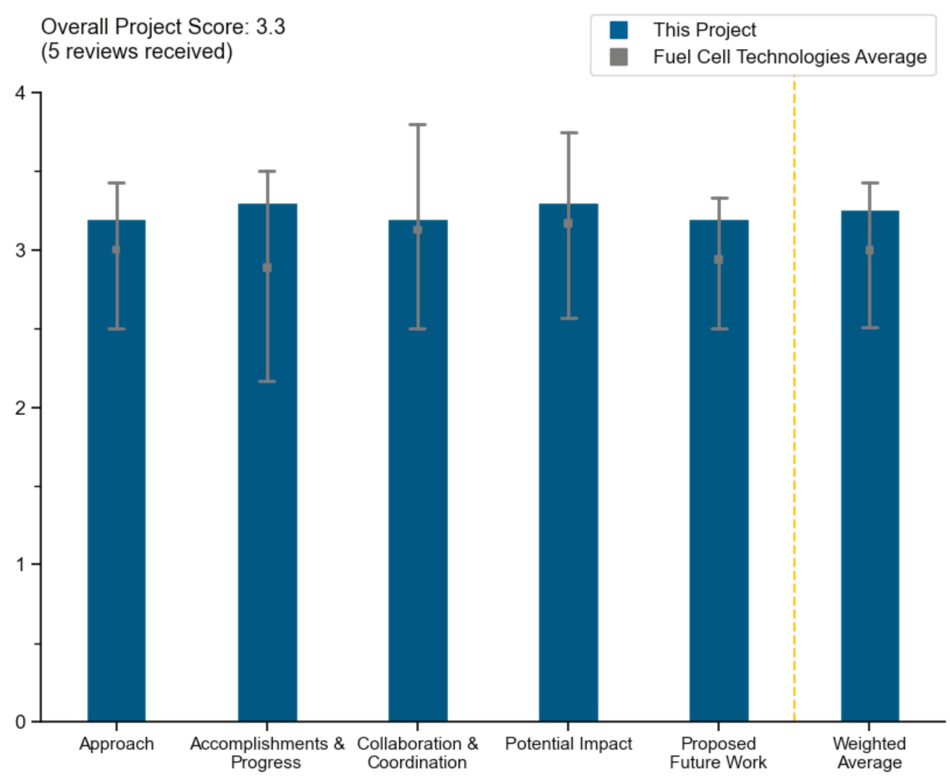
Paul Wang, Caterpillar Inc.

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 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 components, especially air system components, have a significant impact on the performance and reliability of fuel cell systems. The project addresses this 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. Accomplishments and progress include literature review, steady-state system modeling, analysis of candidate technologies, and down-selecting the optimum solution.

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.

- This project goal is clearly stated as developing a high-efficiency air boosting system that will form the basis for larger 350 kW to 1,000 kW fuel cell systems for heavy-duty construction machines. The approach is well laid out but not novel. The project plans to use off-the-shelf compressors and expanders, down-select available bearing options (rolling element, fluid film, and air foil), and design a new electric motor.
- The approach of the team is good and has identified critical enabling capabilities for the air-handling system for a fuel cell system. Stated targets on efficiency, cost, and durability and critical barriers were identified. All were substantially discussed and addressed in the design phase of this project, as appropriate.
- Caterpillar has clearly identified the critical performance barriers being addressed by its project. The project is well defined and feasible. Teaming with BorgWarner Emissions (BorgWarner) and Ballard Power Systems (Ballard) are project strengths. The proposed approach is pragmatic for delivering a fuel cell air system.
- A technology-agnostic and comprehensive approach is used to identify the best option for the air system. An alternate design (oil lubrication) minimizes risks if the main down-selected solution is inappropriate.
- Rolling-element-bearing-type machines are used mainly in screw-type compressors, not e-compressors. Caterpillar lists some disadvantages, but there are more, including:
    - Limited load capacity. In a fuel cell compressor, the impeller rotation and aerodynamic forces generate significant radial and axial force.
    - Sensitivity to contaminants critical to a fuel cell.
    - High start–stop wear.
    - Speed limitation. In a fuel cell application, the rotational speeds can be demanding and lead to heat generation, fatigue, noise, and reduced bearing lifespan.
    - Ball bearings that require more frequent maintenance than other bearing types.

Question 2: Accomplishments and progress

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

- Caterpillar is on track to meet, or ahead of meeting, the programmatic schedule. The status toward addressing the critical barriers to the DOE goals of motor and controller efficiencies, compressor and turbine efficiencies, reliability, noise, packaging, and cost is summarized and on track for success. Accomplishments to date are focused on compressor–expander, bearing selection, and motor. Spending might be low compared to reported milestone progress.
- All milestones scheduled before the Annual Merit Review (AMR) were completed. Additionally, significant progress was achieved for five other milestones spread over the three budget periods (50%–100% completion).
- The project has made good progress in the first year. It has down-selected the compressor, expander, bearings, seals, motor, and power electronics.
- Thorough review of the approach to select critical technologies is mindful of efficiency, durability, and cost.
- Cost and efficiency were reported for the various options considered. No analysis was shared to indicate the potential to meet durability or sealing targets. The team claims a Pugh analysis of candidate technologies was completed, but it was not shared.

Question 3: Collaboration and coordination

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

- The project has a strong team, with Caterpillar as prime; BorgWarner as a subrecipient for air system design, fabrication, and testing; and Ballard as sub-recipient for PEMFC system.
- Caterpillar has a strong team for addressing fuel cell air subsystems. Coordination between the team members seems appropriate for a successful project.
- The project includes an effective team composed of fuel cell and compressor manufacturers led by a heavy-duty vehicle manufacturer.
- The collaboration on the project is being clearly and effectively leveraged.
- There seems to be a good coordination between Caterpillar and Borg Warner on the air machine design, selection, and test plan. Ballard's contributions are unclear. Presumably, it will provide stack/system models to quantify system performance benefits.

Question 4: Potential impact

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

- Caterpillar has proposed a pragmatic approach to addressing the DOE goals for fuel cell air system development. The Caterpillar team comprises partners with strong manufacturing ties. As presented in the AMR summary, the project seems appropriate to the DOE Hydrogen Program goals.
- This is the only funding opportunity announcement project funded by the Hydrogen and Fuel Cell Technologies Office that is targeting air systems for 350–1,000 kW fuel cells for heavy-duty applications.
- Low-cost, high-efficiency, high-power air systems are essential to enabling heavy-duty fuel cell commercialization.
- The stated goals and execution toward those goals are important to the success of fuel cell electric vehicles in application.
- Most targets are projected to be met. Although a durability test is included in the approach, it is unclear how this will be ascertained—for example, whether bearing liftoff will be achieved at fuel cell idle condition to reduce erosion; or whether an accelerated stress test will be used to determine, in a short amount of time, whether the device will last 25,000 hours. It is not clear whether a method been selected or devised to assess oil leakage from the prototype.

Question 5: Proposed future work

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

- The proposed future work is consistent with the barriers and challenges identified to date.
- The proposed future work is appropriate and logical.
- Caterpillar has effectively planned its project to address the DOE fuel cell air system goals. The milestones and go/no-go decision points are well established. Per a reviewer's comment during the AMR, cost may need to be reviewed. The DOE goal for the fuel cell air system is $12/kW; Caterpillar is stating it is at $8.8/kW. This seems better than the DOE goal, but there was a question as to how the cost was calculated. This may need to be reviewed.
- Testing should include start–stop tolerance. The sealing validation plan was not shared. The project should test for turbine robustness to liquid water. It would be great to see Caterpillar work with Argonne National Laboratory (ANL) to run system analysis against a known benchmark.
- The plan by which durability will be validated in 2023 was less clear. It was unclear whether there is an accelerated test procedure that can extrapolate to the required end of expected life for the application.

Project strengths:

- The project's partnerships with industrial partners are its greatest strength toward meeting the DOE goals for developing an advanced fuel cell air system. Another significant strength is the pragmatic approach to keeping the fuel cell air system as simple as possible.
- The project is addressing all the DOE targets for component efficiencies, volume, weight, and cost.

- Strengths include a good solutioning approach, good technology experts, and good collaboration.
- The project has a strong team appropriately focusing on cost and efficiency.
- Strengths are a strong comprehensive approach and team and rapid progress.

Project weaknesses:

- There are no glaring weaknesses in the execution of this project as presently reviewed. There is a concern (not a weakness) about air system costing. Perhaps Caterpillar's estimate of $8.8/kW for the fuel cell air system could be discussed at the next programmatic review.
- No significant weaknesses were detected. Durability evidence against an accelerated protocol is a perceived challenge.
- This has the appearance of a developmental project relying on existing expertise in turbomachinery. The only criticism is that it is not very innovative.
- It is unclear whether/how the selected design can meet sealing and durability requirements. Test plans were not shared.
- Durability demonstration approaches are unclear.

Recommendations for additions/deletions to project scope:

- The project should test against the DOE target of 50,000 start–stops. The project should report the voltage operating range for the selected machine. Compressor–expander performance maps should be shared with ANL (Million Mile Fuel Cell Truck [M2FCT]) to compare system efficiencies with other air machine technology being developed through DOE projects.
- No additions or deletions to the current project scope are recommended.
- Project schedule and scope are appropriate.

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

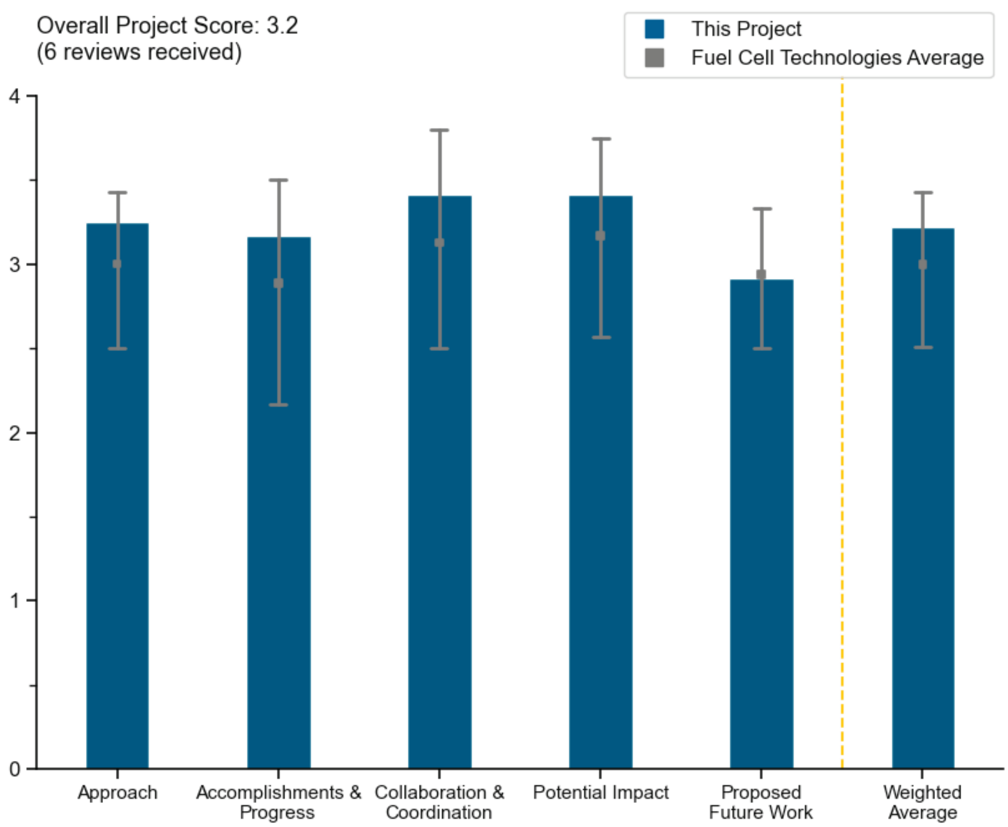
Brian James, Strategic Analysis, Inc.

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	• System cost: Realistic, process-based system costs, need for 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 models based on Design for Manufacture and Assembly (DMFA), 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 lifecycle. This methodology will be employed in an effort to understand the state-of-the-art fuel cell technology for low-, medium-, and high-duty (LD, MD, HD) 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 **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The Strategic Analysis team members use their DFMA approach to set cost targets for MD and HD fuel cell vehicles. They have optimized their model for years and work with vendors to constantly update prices/costs. The work of the Strategic Analysis team is generally well regarded, and they are recognized for setting the key performance indicators for DOE, and effectively the world, in fuel cells.
- It is excellent to keep to a consistent DFMA approach for cost analysis. The collaboration with Argonne National Laboratory (ANL) on system analysis is a good approach to specifying the system architecture and performance as a basic assumption of cost analysis. It seems to be good to expand the cost analysis to other than the HD applications. Clarification is needed on how the fuel cell system information is being obtained to pursue the cost analysis for train and marine applications.
- The proposed approach is well aligned with the scope of the project.
- The project team members have demonstrated that they are very good at cost analysis of fuel cell systems and components. This was very well suited for a research and development (R&D) project focused on LD fuel cell systems where lowering capital costs was the top priority. However, there is concern that this approach is too narrow to provide the most value for HD systems, where capital costs are secondary to total cost of ownership (TCO). It appears that the project is targeted to minimizing capital costs under some semi-arbitrary constraints on durability, efficiency, and other application requirements. This is fine for cost benchmarking, but for strategizing R&D, it would be better for the analysis to look at which HD fuel cell system minimizes TCO and then identify fuel cell R&D priorities based on the answer.
- There is a good approach for LD, MD, and HD systems with prioritized timelines. Rather than application-specific analysis (for example, HD vehicles vs. rail or marine), it may be helpful to have cost as a function of only power level (e.g., the cost for 100 kW, 200 kW, 300 kW) since such fuel cell packages may be interchangeable in different applications with slight packaging variations. Also, it may be helpful to keep the power level of LD and MD vehicles the same to drive some complexity out of cost modeling and allow a focus on underlying cost drivers due to higher durability requirements. Some additional background or references on balance-of-plant (BOP) cost drivers to meet durability would help. It would be helpful to know whether there is any relation between cost and usage (i.e., whether the same MD vehicles with bigger batteries have an impact on fuel cell cost).
- It is difficult to quantify HD vehicle costs when it is not clear whether 25,000-hour durability is possible with the current material set and systems approach. It would be more valuable if the predictions were bounded between a high and low. With the current material set, it is difficult to see stacks lasting 25,000 hours. Perhaps the team should also be looking at a stack replacement in the 2025 numbers. It just seems unrealistic that the numbers being predicted with a single original set are likely.

Question 2: Accomplishments and progress

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

- The Strategic Analysis team responded to original equipment manufacturer (OEM) concerns and decreased the power loss of the stacks over their lifetime by introducing “voltage clipping,” which is a standard method used by controls engineers to not over-oxide platinum and platinum alloy catalysts. The team also looked more carefully at the impact of battery hybridization for sizing the fuel cell, another common practice now, especially as the cost of batteries has decreased. In this way, the project is able to provide guidance on how to lower costs and improve durability.
- There are good outcomes from the new Million Mile Fuel Cell Truck (M2FCT) reference system (275 kW) cost analysis.
- The project progress is clear, with regular accomplishments being reported. Focusing efforts on MD and HD road vehicles (rather than rail) appears to have been a good choice, as the level of application-specific detail required for a systematic analysis is significant. This limits the number of applications that can be effectively investigated with this approach. However, given the wide range of fuel cell applications that are

of interest, it may be worthwhile for the project researchers to consider whether they could apply an alternative "breadth first" approach to provide some useful information on a broader variety of applications quickly without a complete detailed analysis. Specific results of the project are generally well communicated in terms of understanding the reasoning and basis for the analysis, although there could be some improvement in making the high-level results more digestible, especially considering the complex tradeoffs and constraints for HD fuel cells.

- Regarding accomplishments and progress for MD vehicles:
    - On the table for Battery Energy on slide 8, it is not clear whether the peak is in kilowatts or kilowatt-hours. Also, since the battery is a key enabler for MD, it would be helpful to provide some estimate of the cost of this battery.
    - It is not clear why fuel cell "key-on" time is 14.5 hours versus 25,000 vehicle hours, nor is it clear whether the target of 25,000 is for vehicle hours or fuel cell system hours.
    - The project has a good approach for the cost walk between LD and MD. Since the main difference between these applications is durability (not power), a cost walk of associated durability enablers will help readers correlate cost−benefit, or "bang for their buck."
    - The rational for an additional $35 for changes to BOP is unclear, as the size (kilowatts) is similar to LD. It is not clear whether it is for more durable components or whether that is factored into the replacement cost—or whether there is some double-counting.
    - Since BOP cost is a significant cost driver (almost half of the cost increase), a detailed component-by-component breakdown would be helpful. Also, any insights into which components will need to be replaced will help with those designing and packaging the fuel cell systems.
    - It is not clear whether the need for active area-oversizing to meet durability considers the benefits of hybridization to help enable durability in the ANL analysis.

  Clarification is needed on the peak power of the battery in the HD study on slide 13. Insight into the tradeoff between battery size and battery cost for both MD and HD vehicles would be helpful, as would any insight or key references on usage (i.e., battery charge−discharge cycling) of its durability. The reviewer is looking forward to future updates on this side study.
- As usual, accomplishments correspond to the foreseen work plan. It is not clear whether using a cost target for 100,000 systems per year for HD vehicles is relevant, as this number refers to a unique system producer. Perhaps 30,000 systems per year is more appropriate. In the cost breakdown comparing LD and HD vehicles, the impact of the different duty cycles should be taken into account. HD vehicles have fewer dynamic duty cycles, which should have a positive impact on lowering the degradation of some bipolar plate components compared to the corresponding components used in LD vehicles. As some stack suppliers are now providing high-power stacks over 200 kW or even 300 kW, it would be helpful to know the impact of the system modeling and the overall cost.
- It is not clear whether the numbers have been verified with OEMs.

Question 3: Collaboration and coordination

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

- The Strategic Analysis team appears to be effectively integrated with the project partners at ANL and the National Renewable Energy Laboratory (NREL) to improve understanding of fuel cell technologies, model system development, manufacturing considerations, and durability concerns. The feedback and information from industry partners appears to be effectively collected and used by the project.
- The Strategic Analysis team does an outstanding job gathering information from the fuel cell industry to make accurate models. The team also works with ANL on a vehicle model and supports the techno-economic analysis at NREL. The team does an excellent job at not "leaking" information from any of the fuel cell sources to retain the company's trusted status in the industry.
- In addition to collaboration with the systems analysis led by ANL, the project demonstrates good communication with industry partners to obtain the information.

- There is good collaboration with ANL on the performance and durability modeling.
- There might be value in looking at cost savings possible by standardization. Also, OEMs should be involved in validating the approach and numbers.
- The collaboration seems adequate, but close discussions with HD vehicle manufacturers and users could be strengthened.

Question 4: Potential impact

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

- The project provides essential information to the DOE Hydrogen Program (the Program) and fuel cell community to understand fuel cell costs as well as considerations of manufacturing and system integration. Much of this information is typically proprietary and therefore inaccessible to the broader community, but the model systems developed and analyzed within this project, with industry input, effectively convey necessary lessons in a non-proprietary format. This provides key strategic guidance for the Program and broader fuel cell community to maximize the effectiveness of R&D efforts.
- Cost is always an important attribute for commercialization. Analyzing M2FCT reference system design (275 kW) and providing feedback for the next design iteration has high impact potential for HD applications.
- The outcomes of this project may facilitate final investment decisions of several projects and convince new adopters to shift to hydrogen mobility, in particular for HD vehicles.
- Cost reduction is a key enabler for wide acceptance, and this team is helping break down the cost drivers and helping with projections into the future.
- The potential impact of this work is very high.
- It might be worthwhile to relook at carbon plates if SS316 is $3/kW. (Ballard Power Systems is recently claiming a large reduction in costs due to an improved manufacturing process.)

Question 5: Proposed future work

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

- The proposed future work is to add rail and marine system analyses and then return to update the analysis for the various system types. This is a reasonable approach following the project's current focus. However, there is concern that the analysis is not fully embracing a consideration of TCO concerns to the extent required for effective analysis of HD fuel cell systems. It is suggested that the project incorporate this into all of the analysis going forward (or at a minimum, that the project have side studies looking at how system choice affects TCO). For example, the project could consider how stack oversizing, degradation rates, and replacement times affect TCO, or the project could consider what kind of system design maximizes overall efficiency and whether this justifies potentially higher capital costs. The planned future side studies of hybridization, battery and power electronics costs, and comparisons of stack replacement strategies are all good topics.
- The future work appears to be correct, with some additional proposals. The project should assess the sensitivity of the battery costs (which depend not only on their size but also on the type of battery energy/power and the chemistry chosen). The impact of using non-polyfluoroalkyl substance (non-PFAS) membranes should also be assessed. The project should compare the fuel cells with hydrogen combustion engines for HD vehicles. The project should also include a TCO approach, which is an important factor used for selecting HD vehicles.
- The team is planning to conduct cost studies for the battery and its impact on overall system cost. Strategic Analysis should continue to collaborate with the analysis teams (i.e., ANL) to study optimal MD/HD system battery size that minimizes overall TCO for different applications (e.g., MD and HD vehicles vs. rail vs. marine).
- The proposed work by the Strategic Analysis team is fairly incremental, following on existing work. The team does not have any plans for how to capture the changes in hydrogen costs and battery electric vehicles

in the fuel cell industry. The models should also include the impact of platinum group metal (PGM) recycling, even at a minimum of recuperating 20% of the Pt value, and then showing the impact of recovering higher values.
- The priority on rail or marine system cost analysis does not match. The fuel cell system design should be created and agreed upon first. The project should prioritize the HD system analysis, particularly by updating the M2FCT reference system (275 kW net), and provide feedback for the next design iteration (system analysis) to reduce the cost.
- The approach and numbers should be validated before any more applications are modeled.

Project strengths:

- A project strength is the very high-quality work on core cost analysis and model system development. There is good integration between project team members and industry partners. There is high value and potential impact from the project efforts.
- One of the strengths of the project is the accumulated knowledge of DFMA cost analysis approaches, particularly the detailed level of the stack, unit cell, membrane electrode assembly, and bipolar plate. The project shows a strong connection with industries to obtain cost information.
- The Strategic Analysis team members make improvements to their models yearly, and their guidance is used throughout the fuel cell industry to set costs and performance goals.
- There is sound, rigorous analysis from both a technology and a business perspective (e.g., the impact of horizontal integration).
- This project relies on many years of development and on a strong, skilled team of experts.
- A strength is the diligence in collecting cost data.

Project weaknesses:

- The impact of stack parameters on cost and degradation seems to be mature. However, it is unclear whether BOP durability and replacement projections are mature. It is suggested that the project conduct some analysis on transfer functions between vehicle usage to fuel cell system usage (with battery buffer) and then to component usage (with some assumption of underlying controls and operating strategies). Also, references for basic physics of stressors for each of these components would help with understanding cost impacts.
- The models consider a relatively low outdoor maximum temperature of 40°C. U.S. military standard MIL-STD-810 is for 49°C, and this seems like a better, more proven temperature to use. The Strategic Analysis team's models do not reflect major changes in the hydrogen fuel cell market, such as the impact of the decreasing cost of hydrogen on vehicle ownership. The models are not validated because they are based on high-volume manufacturing, which does not exist yet for fuel cells.
- The project consideration of TCO for HD applications is lacking. It seems as though the constraints on the project scope and use of fuel cell specifications from national lab consortium partners may limit the project from providing the best strategic guidance on HD fuel cell R&D priorities.
- A multi-year approach with numerous types of transport vehicles may lead to not being able to deepen enough different potential system architectures.
- The presentation did not provide a detailed level of the DFMA approach for BOP components.
- A project weakness is the unvalidated data/approach.

Recommendations for additions/deletions to project scope:

- The Strategic Analysis team began to examine the impact of PGM recycling on costs in some of the company's prior work, and the team should continue this work. It might make more sense to use higher Pt loadings for higher performance, coupled with recycling, rather than using a lower Pt loading and oversizing the fuel cell stack. The Strategic Analysis team has a "bottoms up" approach with its DFMA model. It would be interesting to compare the cost targets for fuel cells versus projections for battery electric vehicles (and for hydrogen internal combustion engines), especially as the cost of hydrogen is projected to fall. As awards are made by DOE in 2024 for high-volume fuel cell manufacturing, DOE and the Strategic Analysis team should consider how to validate their models with real data.

- It is highly suggested that the project should pursue the TCO analysis for HD applications as a side study. For HD applications, customers are conscious of TCO rather than capital expenditures (system cost). It will be good to identify implications of TCO with system efficiency and durability. In addition, the cost analysis is expected to expand to include the recycling of previous materials in the cost model. Finally, the BOP cost analysis should be updated with ongoing project information, such as the air management system (centrifugal and positive displacement) as a side study.
- The project should expand to incorporate TCO into its cost analysis or begin working closely with other projects focused on TCO analysis to make use of their findings. It would be good for the project to consider alternative system designs, for example, a very high-efficiency system. An investigation into hybridization strategies is a good step in this direction.
- The project should assess the sensitivity of the battery costs (which depends not only on their size but also on the type of battery energy/power and the chemistry chosen). The impact of using non-polyfluoroalkyl substance (non-PFAS) membranes should also be assessed. The project should compare the fuel cells with hydrogen combustion engines for HD vehicles. The project should also include a TCO approach, which is an important factor used for selecting HD vehicles.
- The scope seems correctly prioritized, with initial focus on HD vehicles and then on other applications.
- Validation and consultations with OEMs should be added.

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

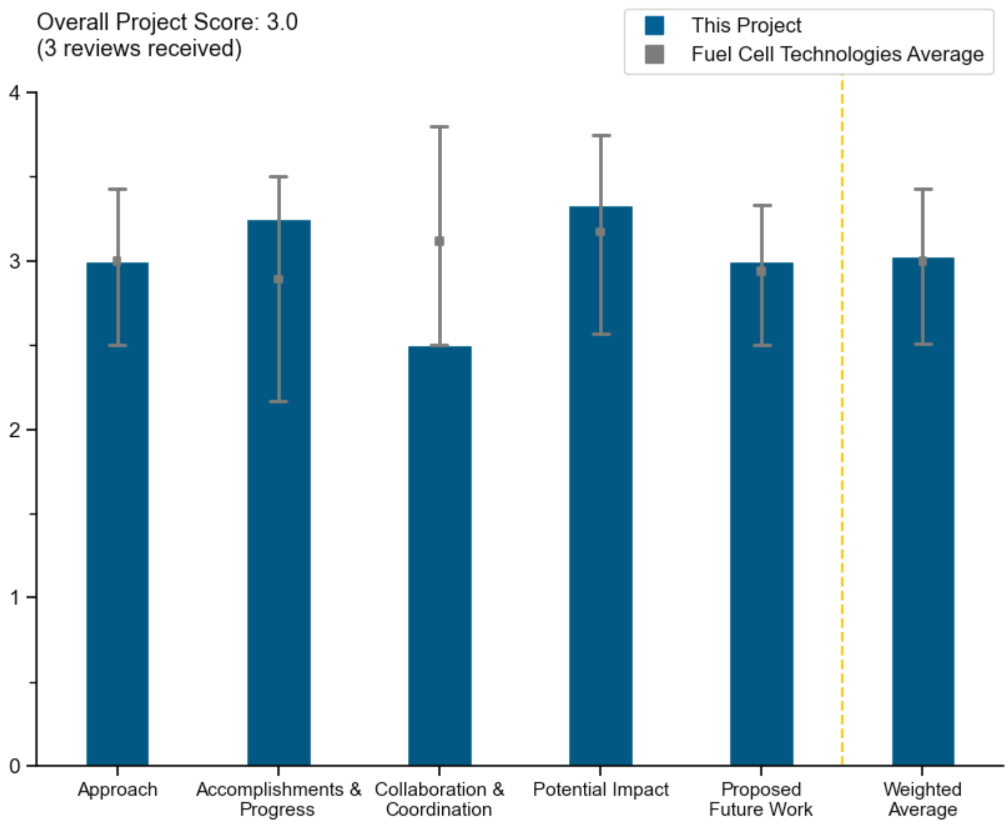
Vivek Sujan, Oak Ridge National Laboratory

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 (FCEVs) 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 (HD) 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



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

Note: This is a new project in 2023. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

Question 1: Approach to performing the work

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

- The project appears to be considering overall system cost and tradeoffs between the fuel cell stack and DC-DC converter in the optimization, not just DC-DC converter costs and efficiency, which is appropriate. Project targets (i.e., cost, efficiency) are not defined, and milestones do not contain DC-DC converter or fuel cell system performance metrics. The approach seems to be trying to cover a broad space and appears to be attempting to design a flexible DC-DC converter architecture that would be applicable to a wide range of architectures, applications, and power levels. The low end of the proposed power range (100 kW) does not match current Hydrogen and Fuel Cell Technology Office (HFTO) priorities. A focus on higher power levels of ~250–400 kW, current fuel cell vehicle system architectures, and HD vehicles would better match current HFTO priorities and allow for quicker identification of requirements and design optimization.
- The approach is clearly spelled out, but there are some holes that need to be filled. There are several approach drawbacks. (1) Cost receives some mention, but it should be a key consideration listed on slide 5. (2) The presentation mentions targets but then fails to list numerical values. Slide 7 lists a target of >94%, but that seems a low and not particularly ambitious target. (3) In terms of clarity, the team speaks of architectures but not of circuit design/material selections. It is not stated what basis material set (metal-oxide semiconductor field-effect transistor [MOSFET] vs. insulated-gate bipolar transistor [IGBT]) is being considered.

- This project seems well organized; barriers are identified, and objectives are clear. More effort should be placed on leveraging existing knowledge. For instance, rather than developing some of the models required for Phase 1 (powertrain resistance and performance models), existing models should be adapted and improved.

Question 2: Accomplishments and progress

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

- This is a brand new project; planning and background material are at an appropriate level for this stage of the project.
- The project has just started, so there are no results yet.
- The project just got started.

Question 3: Collaboration and coordination

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

- Collaboration with M2FCT is good and provides the project with access to a range of companies conducting FCEV development. The project also lists "consultancy" with three companies, one stack/ system/vehicle developer, one stack/system developer, and one coolant fluid developer. This provides the project with good input on the system-level issues. Electronics/DC-DC converter companies are not listed. Oak Ridge National Laboratory (ORNL) has substantial internal knowledge, but consultation with actual companies developing DC-DC converters would strengthen the team.
- Currently, no collaborations exist. The project team expects to collaborate with M2FCT in the future. This project would benefit from collaboration with fuel cell stack and fuel cell truck original equipment manufacturers (OEMs), (Cummins, Plug Power Inc., Nikola Motor, Hyzon Motors Inc., etc.), especially during initial phases when requirements are being defined and in the validation activities.
- Planned collaboration with industry partners and leveraging ORNL power electronic expertise will improve the likelihood of success.

Question 4: Potential impact

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

- The DC-DC converter and the power electronic architecture considerations involved with it have been historically overlooked by the community and DOE. This project will take a large step in correcting this.
- This is an important component in the fuel cell system that drives weight, cost, and efficiency and is under-studied. This project could significantly impact DOE targets and goals for FCEVs.
- The project aligns with DOE objectives to improve efficiency and reduce costs of HD fuel cell vehicles. The DC-DC converter does not appear to be a major contributor to overall system cost, and efficiencies are already fairly high (~95%–98%). While improvements would be beneficial, the expected impact of this project on achieving overall fuel cell system cost or efficiency targets is not expected to be large.

Question 5: Proposed future work

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

- As this project is just starting, all of its work is proposed future work. The approach is good, so the future work is also good.
- Planning and milestones are logical. Targets are very ambitious; the team should make use of existing models wherever possible and lean on industry partners.
- The planned work is logical.

Project strengths:

- Work on power electronics for FCEVs is overdue, and this project is a step in the correct direction. The project starts with architecture studies and ends with a hardware demonstration. That is a good approach. Coordination with M2FCT is a must-have. ORNL is a well-experienced, knowledgeable team appropriate to take on this project.
- ORNL expertise in power electronics and vehicle electrification is a strength.
- Strong collaboration partners are a strength.

Project weaknesses:

- The project does not have numerical metrics for the milestones and go/no-go criteria. The project does not have a collaboration or consultancy with an actual electronics manufacturer for that particular perspective.
- The project lacks existing collaborations with fuel cell vehicle OEMs and defined requirements and performance targets for the DC-DC converter.
- The project might be too ambitious. The range of applications and use cases might prohibit a truly scalable DC-DC.

Recommendations for additions/deletions to project scope:

- Numerical targets should be added to milestones and go/no-go criteria. Cost and total cost of ownership should be incorporated earlier in the project (included in budget period 1). The team should consult with a volume manufacturer of DC-DC converters. Current DOE/M2FCT plans assume only a low of 0.7 V/cell at peak power (at the end of life). But current FCEVs can dip to 0.6 V/cell. This potentially changes the required ratio for the DC-DC converter. This lower voltage should be considered in the project. Mention is made of different coolant fluids and types. In addition, Chemours is included as a consultancy. Specific assessment should be made of the impact of colder refrigeration fluid temperature on the efficiency/performance of the DC-DC converter.
- Collaborations with fuel cell truck OEMs would be beneficial.