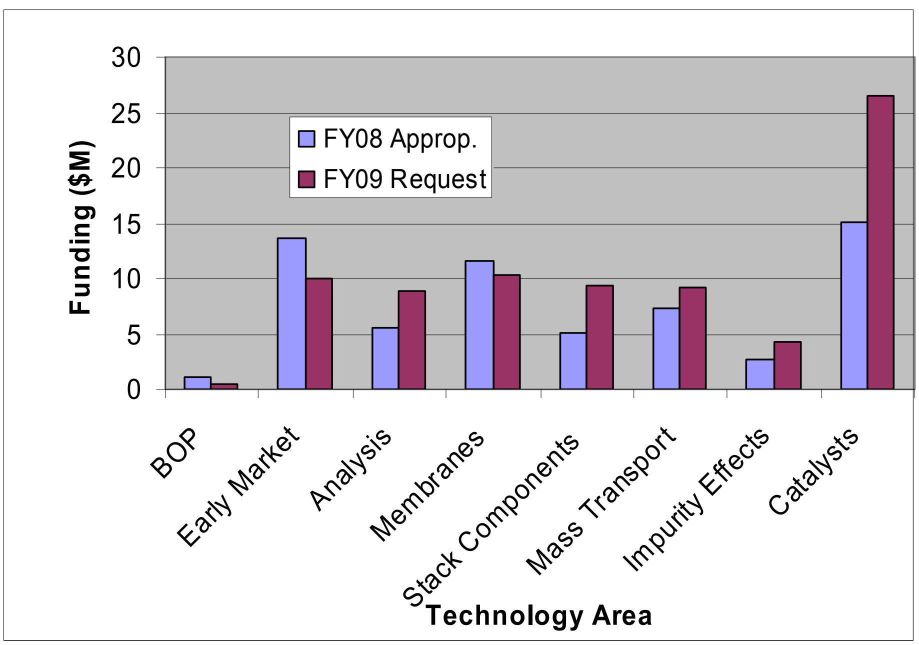
2008
Fuel Cells
Summary of Annual Merit Review Fuel Cells Subprogram

Summary of Reviewer Comments on Fuel Cells Subprogram:

Reviewers consider fuel cell development to be a critical enabling technology for the success of the President's Hydrogen Fuel and Advanced Energy Initiatives. Overall, the research and development portfolio was judged to be well managed, appropriately diverse, and focused on addressing technical barriers and meeting performance targets. Progress was considered outstanding. The continuing focus on partnering (industry, national laboratories, universities, etc.) was applauded and reviewers suggested that some projects might benefit from more interaction with industry, developers, and other program projects to establish a stronger and more technically sound research effort with improved outcomes and deliverables. New projects from the 2006 solicitation were kicked off in February 2007 and were reviewed for the first time this year.

Fuel Cell Funding by Technology:

The Fuel Cell Technology Subprogram continues to concentrate on the critical path technology of stack components (membranes, catalysts, bipolar plates, gas diffusion layers, and analysis and characterization). Cost and durability of stack components continue to be a key focus of the subprogram.



Majority of Reviewer Comments and Recommendations:

This year 56 fuel cell projects were reviewed of the 64 projects presented. In general, the reviewer scores for the fuel cell projects were average to high, with scores ranging from 3.8 to 1.9 for the highest and lowest scores, respectively. The average score of fuel cell subprogram scores was 3.0. The range of scores and the average score were higher than those of the 2007 review. The majority of the projects were reviewed by six to seven reviewers each. Project scores reflect the technical progress made over the past year; relevance to the DOE Hydrogen Program; technical approach; extent of technical transfer; and proposed future plans. While reviewers tend to award those projects closer to commercial application with higher scores, their comments reveal that they also appreciate and support more fundamental work attacking key barriers to commercialization. Key recommendations and weaknesses are summarized below. DOE will respond to reviewer recommendations as appropriate for the scope and coherency of the overall fuel cell research effort.

Catalysts: The six catalyst projects reviewed received an overall rating of average, but they were rated above average in the categories of relevance to the DOE Hydrogen Program and technical approach. The demonstration of more than 7,300 hour life for a 3M nanostructured thin film electrode on a mechanically-stabilized 3M membrane, with voltage cycling, was particularly notable. This particular project was rated second highest in the entire subprogram. The required total platinum content continues to fall as a result of subprogram research, and Brookhaven National Laboratory has demonstrated ternary alloy catalysts with significantly higher mass activity than conventional platinum catalysts. Reviewers again expressed concern about approaches that replace platinum with other platinum group metals (PGM). Some durability results from the non-precious metal catalyst projects are promising, but performance generally needs to be at least an order-of-magnitude higher before this durability matters. The reviewers commented that these efforts in alternative electrocatalysts, though high risk, represent a potential high pay-off option and should be supported in the future. Reviewers suggest conducting in situ testing on promising materials as soon as practical.

Membranes: The fifteen membrane projects reviewed were ranked from below average to well above average. The 3M project ranked the highest among membrane projects, and received the fourth highest score in the subprogram. A membrane based on sulfonated poly(arylene ether sulfone) nanocapillaries in an inert polymer resin from Case Western Reserve University meets the DOE interim proton conductivity milestone and exceeds Nafion performance at the prescribed conditions. A cost of production study of most promising membranes was recommended for many of the projects. Reviewers expressed concern about the ongoing disagreements among membrane researchers about the validity of the proposed standardized conductivity test procedures. In several projects, reviewers commented that membrane principal investigators would benefit from closer collaboration with fuel cell researchers and developers.

Impurities: Three projects on the effects of impurities were rated average. Reviewers note the scope of the projects exceeds what can be reasonably accomplished with resources available. Although the researchers are sharing information and working on coordination, several reviewers recommended increased coordination to avoid duplication of effort and to accelerate the development of engineering models for use in standards development. Researchers are encouraged to move to lower, more representative catalyst loadings as soon as practical.

Water Transport: Three water transport projects were rated above average, with the Rochester Institute of Technology visualization and characterization project receiving the fourth highest score in the subprogram (along with the 3M project mentioned above). The increasing resolution of neutron imaging is helping to validate water transport computational fluid dynamics models. Reviewers recommend that all transport mechanisms for all pertinent phases and species should be accounted for, and that unsteady and transient effects be included as soon as possible.

Water Management: Two projects in water management received average scores. Reviewers questioned the ability of the microchannel humidifier approach to work with realistic automotive fuel cell operating conditions and recommend appropriate transient testing with changing conditions. Reviewers also note that the Nuvera cold-start tests did not account for the heat introduced into the stack by room temperature reactant gases.

Recycling: Two recycling projects were evaluated and each received an overall rating of average. Reviewers generally consider PGM recovery an important aspect of the overall fuel cell life cycle, because it addresses both environmental issues and cost issues that impact the cost of fuel cell systems. BASF has made significant progress toward identification of the most efficient processes to recycle both catalyst-coated membranes and membrane electrode assemblies. Significant progress has been made by Ion Power in economic analysis and prototype process demonstration, including demonstration of performance of recycled ionomer and catalysts in fuel cells.

Distributed Energy: The six distributed energy projects reviewed were ranked overall as average, while the Plug Power international stationary fuel cell demonstration received the third highest score in the subprogram. Reviewers suggest that projects should work with U.S.-based home energy suppliers to determine if options exist in the U.S. for the proposed technology. They also suggest that a collaboration with stack component and materials researchers supported by the Program would help resolve issues with the demonstration systems.

Analysis and Characterization: The nine projects in this category included both the lowest ranked and highest ranked projects in the fuel cell subprogram, with the overall category score above average. These diverse projects were noted to strongly support the fuel cell program objectives and goals. The National Institute of Standards and Technology Neutron Imaging Project again received the highest score throughout the entire fuel cell subprogram. The Oak Ridge National Laboratory transmission electron microscopy characterization effort again ranked high, with reviewers continuing to comment that correlating the microstructure of membrane electrode assemblies revealed in these images with performance data would increase the value of the effort. Components such as membranes, gas diffusion layers, and catalysts more representative of those being used by stack developers and original equipment manufacturers should be considered for study. The reviewers again encouraged the modelers in the fuel cell program to validate their models with real world data, and to move to transient modeling as soon as practical. Fuel cell manufacturers need to supply more experimental data to the modelers. The cost of an 80-kW automotive polymer electrolyte membrane fuel cell system operating on direct hydrogen and projected to a manufacturing volume of 500,000 units per year continues to fall, currently estimated at $94/kW. The market opportunity assessment methodology is thought to have merit.

Portable Power, Auxiliary Power, Special Applications, and Innovative Concepts: Two portable power projects, one auxiliary power project, one special application project, and one innovative concepts project were reviewed this year. These projects received average scores with the exception of the portable power projects, which ranked below average. Some reviewers question the relevance of the portable power projects to the President's Hydrogen Fuel Initiative. The auxiliary power projects received good scores for the focused applications being investigated and for teaming. The special application project developing a fuel cell-powered golf course maintenance vehicle received mixed reviews based on the lack of end-user involvement and the belief that this type of vehicle is not a particularly robust nor compelling application. The reviewed innovative concept project received good scores for objectives and relevance, but lower scores for approach and progress.

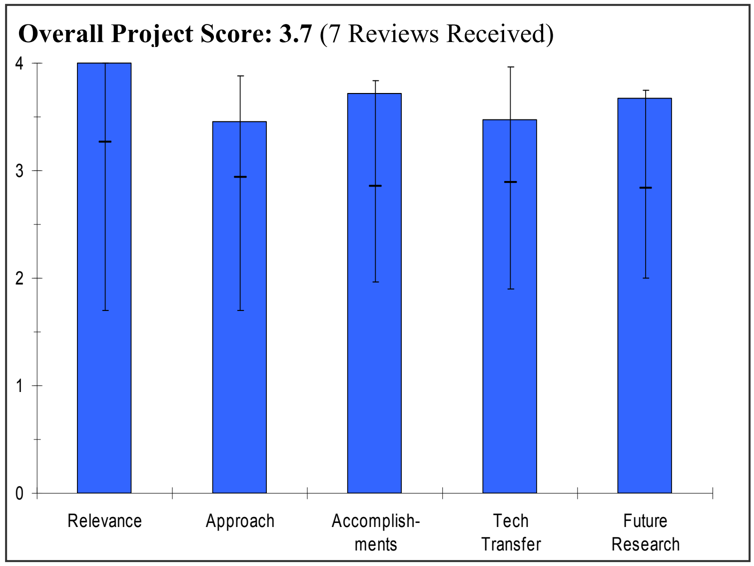
Bipolar Plates: Two bipolar plate projects were reviewed in the Annual Merit Review and Peer Evaluation. Both projects received scores of 3.4, which tie for the fourth highest scores in the subprogram. Reviewers suggest increased collaboration with stack developers and investigating remaining issues of concern, including: metal plate joining, further reductions of processing temperature and cost, and the permeability and durability of expanded graphite/resin plates.

Balance-of-Plant and Integration: One balance-of-plant project and an integration project were reviewed this year. Both projects reviewed were rated well below average. Collaboration with stack developers and original equipment manufacturers will be important to ensure these projects are focused on systems of interest to those working to commercialize automotive fuel cell technology. The integration project on the development of low-cost, durable seals received good scores.

Cross Cutting: The one cross-cutting project from the University of South Carolina received a score well below average. Reviewers generally did not consider the four disparate tasks as a well-defined coordinated project making progress toward targets.

Project # FC-01: Advanced Cathode Catalysts and Supports for PEM Fuel Cells
Mark Debe; 3M Company

Brief Summary of Project



The overall objective is to develop a durable, low cost, high performance cathode electrode (catalyst and support), that is fully integrated into a fuel cell membrane electrode assembly with gas diffusion media, fabricated by high volume capable processes and is able to meet the 2015 DOE targets. The objectives of this project for the past year were to 1) apply DOE specified accelerated durability tests to benchmark the nanostructured thin film catalyst;
2) define and implement multiple strategies for increasing catalyst surface area, activity, and durability with catalyst loadings of <0.25 mg-Pt/cm^2 total per membrane electrode assembly;
3) work closely with collaborators to fabricate and screen new electrocatalysts using high throughput characterization methods, for durability and activity gains; 4) conduct fundamental studies of the nanostructured thin film catalyst activities for oxygen reduction reaction; 5) define and implement multiple strategies to optimize the membrane electrode assembly water management; 6) advance the high volume roll-good nanostructured thin film catalyst /membrane integration.

Question 1: Relevance to overall DOE objectives

This project earned a score of **4.0** for its relevance to DOE objectives.

- This project is fully focused on the DOE research and development objectives.
- Project addresses DOE goals on durability and reducing precious metal loading. Both of these goals are critical to Hydrogen Fuel Initiative.
- This effort is critical as it addresses membranes, electrodes, and manufacturing by a single entity which is known for its technical and manufacturing expertise.
- Addresses key issues of ultimate importance: "durability" and also Pt-reduction.
- Water transport not withstanding, the 3M nanostructured thin film has demonstrated an extraordinary opportunity to meet catalyst cost and durability targets according to data generated using DOE protocols.
- Because 2015 targets have not yet been met, further work is required to achieve performance and durability targets using 2015 target Pt loadings.
- Further work is also required to understand the robustness of the nanostructured thin film over a range of operating conditions.
- Fuel cell durability is key to the Hydrogen Program and industry fuel cell success, and this project is directly aligned with this goal.
- This project fully supports the objectives in developing an automotive-capable membrane electrode assembly design.

Question 2: Approach to performing the research and development

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

- The technical barriers are addressed in a direct, well-defined approach. As a result, most of the DOE targets are met. The exception is Platinum Mass Activity, which should be significantly improved.

- Technical barriers are clearly identified.
- Approach is well thought and focused on overcoming technical barriers.
- Excellent combination of fundamental and applied research.
- This reviewer feels that the appropriate tests and technical aspects of the problem are being addressed.
- Alternative nanoelectrodes or variations should be evaluated in the event that the 3M electrode does not yield.
- The membrane support activity is leading to new potential successes and needs to be better understood.
- Clearly focused.
- Well led and managed; good bottom-up approach.
- Good risk mitigation.
- Sound testing.
- Because 2015 performance criteria have not yet been met, Task 1 (activity improvements) is necessary.
- Given the passing of DOE durability protocols, Task 2 (durability improvements) should not be as critical as other tasks, particularly Tasks 5.1 and 5.2 (gas diffusion layers and interfacial optimization). Although durability is commonly a concern in DOE projects, in the case of the nanostructured thin film, robustness to a wide range of operating conditions is presently a greater concern. That said, attention to anode starvation is a pleasant surprise.
- Tasks 3, 4, and 5.3 (large single cell, durability of advanced structures, and stack testing) are rightfully put aside early in the project.
- The approach is logically laid out, starting from detailed catalyst work and working up to larger media to incrementally validate the progress of the project.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.7** based on accomplishments.

- Remarkable progress has been made during last year. Performances are outstanding. The cost of platinum should be reexamined in defining further research.
- The principal investigator demonstrated steady progress towards 2010/2015 DOE goals; several barriers are already overcome.
- Although some of the 2015 targets are achieved for 50 cm^2 cells, the results have to be confirmed in stacks.
- Excellent progress towards durability and specific activity.
- Accomplishments are significant and insightful. The neutron imaging will yield additional valuable water dynamics data.
- The Gore support has lead to some interesting results, but these results need to be better understood.
- The fluoride data are perplexing. The unsupported membranes fail early; the supported membranes last many hours; yet why are the early membranes failing early when the 3M electrode is carbon support-free? What is the source of the peroxide?
- The Gore supported membrane needs to be looked at carefully for thickness changes vs. time. Is it the catalyst which is leading to the peroxide? Or the stability of the ternary catalyst elements? Or dissolution of the catalyst data?
- Great achievement with respect to durability.
- Huge amount of convincing test results.
- Promising novel Carbon-free catalyst materials
- Passed DOE catalyst accelerated stress tests at sub-2010 loadings.
- Passed DOE polymer electrolyte membrane chemical accelerated stress test at 0.4 mg Pt/cm^2.
- Anode starvation test shows progress in modifying the nanostructured thin film. This was a particularly proactive measure given that investigators do not have access to how this test would relate to realistic on-board cell operation.
- Translation between electrochemically active surface area stability from compositional study and mass activity stability was not reported. 3M also did not report the effect of composition on grain size, lattice spacing and other parameters. Conclusions cannot be drawn upon whether progress has been made from this task to control those parameters.
- 3M did not report voltage in cool start test. More detail regarding gas diffusion layer studies should also be reported.

- Outstanding progress in the last year relative to most of the project targets, most importantly the 7300 h durability which may be longer as it is still on the test stand.
- This project has achieved the gold standard for membrane electrode assembly durability of > 7000 h and should satisfy the DOE durability goals. Catalyst loading appears to have room to decrease further as catalyst support "whiskers" are further optimized.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.5** for technology transfer and collaboration.

- The collaboration with National laboratories and one University is successful.
- Close collaboration with Dalhousie Universities and Argonne National Laboratory.
- Appropriate teaming is in place.
- Excelling consortium.
- The work with Dalhousie is promising in terms of research-level fabrication. More data need to be reported from this activity.
- Results from Argonne National Laboratory appear to suggest competitive alloy compositions. Degree of reproducibility would be good to see.
- Validation of Tafel slope trends from the Jet Propulsion Laboratory cell on conventional rotating disk electrode or from *in situ* fuel cell testing would add to the perceived value of this testing.
- In general, range of collaborators is wide and useful to particular parts of the 3M study.
- Good interactions, not only with the project partners but also with other Federally Funded Research and Development Centers, companies, and system integrators.
- Principal investigator is collaborating with the appropriate national labs and industry partners to develop membrane electrode assemblies. 3M has strong relationships with most original equipment manufacturers and will likely leverage those resources for this project.

Question 5: Approach to and relevance of proposed future research

This project was rated **3.7** for proposed future work.

- Plans are well-defined, realistic and based on previous successful work.
- Future work is focused on significant improvement of a current baseline and sounds very challenging.
- Future plans may need to focus more on fuel cell stack tests.
- Neutron imaging will be helpful.
- Study leaching and catalyst stability earlier rather than later.
- Why is the supported membrane performing as it is?
- Start-stops electrochemical behavior of the membrane electrode assembly?
- Continuation of the project is straightforward, and the future plans are well justified and promising.
- The answer to nanostructured thin film issues with robustness is likely greater than gas diffusion layer optimization; therefore, the brief note about optimizing interfacial characteristics mentioned in the approach slide should be taken to heart.
- 3M indicates that anode starvation studies will continue, as they should.
- Very specific and understandable future proposed research.
- Future research sounds promising toward improving mass activity, improving durability, and improving water management, which are the appropriate areas on which to focus.

Strengths and weaknesses

Strengths
- Project has considerable strengths in the in-house catalysts production, and its scalability, which eliminates a part of the problem of technology transfer.
- Strong management has resulted in significant progress towards durability and activity goals.
- Strong team combines knowledge and experience in technology and fundamental science.

- Willing to work and collaborate in new areas (Gore support).
- Only a few key players with complementary expertise.
- 3M has paid rigorous and disciplined attention to all deficiencies of nanostructured thin film and has developed a plan of action to address them.
- 3M has developed collaborative efforts in areas where it .may need help (e.g., combinatorial thin film formulations).
- For *in situ* testing, data are thoroughly reported.
- 3M shows excellent progress on durability using sub-2010 target Pt loadings.
- Attention is given to manufacturing process improvements.
- Pushing the envelope of high tech research in the important application area for fuel cells.
- Absolute clarity (no questions!) about the status of the project relative to targets and where the shortfalls still lie.
- It is nice to have such a concise explanation of the durability tests on the same slide as the results.

Weaknesses

- Basic insights into the origin of the activity and stability are lacking and these insights would be useful for further projects' plans and for other projects in general.
- Unclear if there is any scientific approach towards making new catalyst composition.
- Project needs greater emphasis on *in situ* operational robustness, particularly with respect to water transport.
- Collaborative efforts should deliver more tangible results.
- More information is needed regarding certain tasks, such as cool start testing and the compositional testing at Dalhousie.
- Iron content in catalyst might be of concern due to Fenton effect of causing peroxide formation.
- No major weaknesses.

Specific recommendations and additions or deletions to the work scope

- Explore possibilities of reducing Pt loadings.
- Project needs to be more focused on fundamental understanding of oxygen reduction reaction on proposed catalysts.
- Water transport and gas diffusion layer optimization efforts should be prioritized higher.
- In Task 3, the design of the large single cell should be reviewed with DOE. It is unclear whether this work is most appropriate for this project or for eventual nanostructured thin film customers (e.g., original equipment manufacturers) to perform.
- The above comment about cell design should be applied to cool start efforts at stack level.
- Accelerate progress so that this wonderful technology gets into the hands of the system integrators and automotive original equipment manufacturers so that the hydrogen fuel cell automobile can continue to move toward the marketplace!

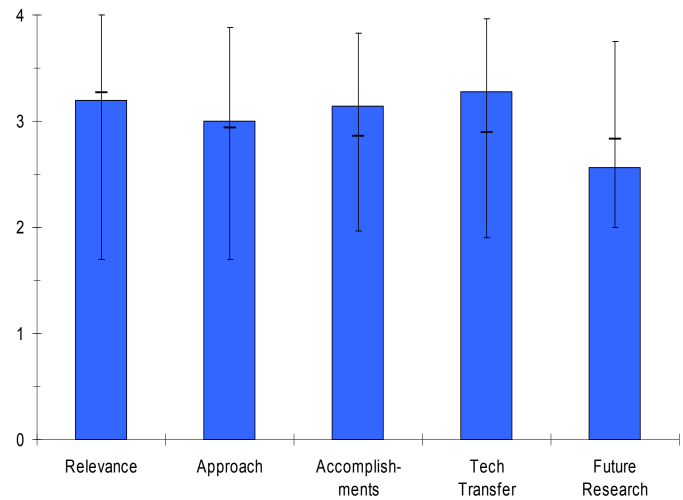
Project # FC-02: Non-Platinum Bimetallic Cathode Electrocatalysts

Debbie Myers; Argonne National Laboratory

Brief Summary of Project

The overall objective is to develop a non-platinum cathode electrocatalyst for polymer electrolyte fuel cells to meet Department of Energy targets that 1) promote the direct four-electron oxygen reduction reaction with high electrocatalytic activity; 2) is chemically compatible with the acidic electrolyte and resistant to dissolution; and 3) is low cost. The objective for the past year was to synthesize and evaluate the oxygen reduction activity, stability, and electronic structure of nanoparticles of three palladium alloy systems (PdCu, PdNi, and PdFe).

Overall Project Score: 3.1 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.2** for its relevance to DOE objectives.

- The principal investigator's justifications for how the project addresses durability and performance (technical barriers A and C) with the binary transition metal catalysts are not convincing. The cost barrier addressed by the research is very clear however.
- The project objectives are relevant to the DOE objectives.
- Insofar as the project is set up to address electrocatalyst targets for performance, durability and cost, there are few projects that are more relevant to DOE objectives for the eventual commercialization of fuel cell vehicles.
- Relevance should also be predicated upon the catalyst composition being considered here. Thankfully, this project's compositions are intended to displace PGMs.
- Bimetallic core/shell and alloy compositions can be well-tread ground unless a systematic, thorough approach is taken.
- The project addresses key elements for the replacement of platinum catalyst for the anode.
- Success of this project will further DOE's goals for developing better/cheaper catalysts.

Question 2: Approach to performing the research and development

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

- The proposed approach is logical for reducing the amount of Pt and extendable to metal systems other than the Pd-Transition metal binaries currently the focus of the research. The effect on durability in a working fuel cell may not be fully addressed by the project plans since factors other than the oxophilicity of the catalyst can be important for stability of surface area and specific oxygen reduction reaction activity. The cost savings by replacing Pt may not be realized unless the full performance equivalence to Pt is obtained since the added cost of extra cells, bipolar plates, etc. will offset the cost savings of the Pt replacement. The project's research is definitely breaking new ground and appears to be well executed. Using carbon as a support is both limiting in its process methods and fundamental corrosion limitations, but the concepts may be extendable to other process methods and supports.
- Use of Norskov-inspired d-band shift approach helps to prevent an exercise in the random selection of elements. Unclear, however, if this approach directed investigators towards PdNi, PdFe and PdCo the same way it did toward PdCu.
- Possible use of fourth period metals (Cu, Ni, Fe) as cores enable a pathway towards meeting cost targets.

- Approach assumes that the same measures taken to enhance activity will also enhance durability. Given the range of surface reactions possible in oxygen reduction reaction-intended environments, the probability that this will be true is low.
- The project incorporates copper as an alloy with palladium to enhance the oxygen reduction activity. Copper is a poison for the anode reaction and plates out onto the surface of platinum. While the project uses copper in the cathode, the prospects for cross contamination to the anode could be high and lead to failure of the anode.
- The project uses iron as an alloying addition to platinum. The use of Fe can promote the failure of the membrane and iron should be avoided.
- It is not clear what alloy is used in the graph on slide 20. Performance is very low.
- Project shows high relevance to DOE's barriers for durability, cost, and electrode performance.
- Approach lays out very specific means to address these barriers.
- Project includes good mix of theoretical and experimental work.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.1** based on accomplishments.

- Impressive results to date on oxygen reduction reaction activity with PdCu and "tricking" oxygen to think it is Pt. Good progress rather than outstanding just because it is a tremendous challenge to replace Pt and even these impressive results are just a start on a long path. Durability has not really been addressed and probably cannot until fuel cell testing begins in earnest. It is not clear why adequate catalysts were not made for at least a few membrane electrode assembly tests, as getting some insight sooner rather than later as to how the rotating disk electrode activities translate to fuel cell performance could be important for helping direct the project to success. Good use of fundamental modeling, state-of-the art characterization and understanding.
- Progress was made to fabricate a PdCu alloy (by colloidal methods) that in terms of activity and valence band energy approximates Pt. Particle size is still a few nm high.
- Very low activity shown for PdNi and PdFe despite best efforts to change impregnation and fabrication parameters.
- PtCo by strong electrostatic adsorption had low activity; not reported whether other eligible core/shells could be made this way.
- In general, a very thorough job has been done of showing – by rotating disk electrode – that catalyst particles will not directly meet DOE objectives.
- The progress made is impressive. If the progress can be moved toward palladium cobalt alloys then the possibility exists for a replacement of platinum.
- The issue of palladium as a precious metal was discussed at the presentation. It is not clear that palladium price will not escalate should it be a replacement for platinum.
- Colloidal technique appears to be effective mechanism to produce smaller particles in a narrower distribution.
- Achieved Pd-based catalysts similar to that of Pt (40% of the cost for the same activity).

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.3** for technology transfer and collaboration.

- Appears to be good in some respects, but could be improved by more focus on fewer material systems and processes.
- Collaboration with others is visible.
- Collaboration with the California Institute of Technology motivated the study of PdCu.
- Collaboration with University of Illinois at Chicago produced PdCo core/shell particles.
- Collaboration with University of Nevada at Las Vegas uncovered the valence band resemblance of PdCu to Pt.
- A larger breadth of collaboration was expected for this project and appears to have been executed.
- A strong team was established for this program. There is a good mix of modeling and experimental effort.
- Appears as though adequate collaborations are in place to move the project forward.

Question 5: Approach to and relevance of proposed future research

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

- The likelihood of finding a non-Pt core-shell structure having a specific activity 2x better than current state-of-the art Pt (the target in a working membrane electrode assembly) would seem to be extremely low. So at this time, rather than trying to screen many different binary combinations, the project should focus on trying to obtain a more fundamental understanding of what the source of oxygen reduction reaction is on one material system considered representative of the class.
- Try to determine what the entitlement activity for this model catalyst system would be if it could be made perfectly, and see how close the measurements come to the theoretical values.
- The second focus should be to put the representative catalyst system into a working membrane electrode assembly as soon as possible and determine durability issues (or benefits) again with the objective of determining whether there is any chance of meeting the targets for durability.
- Unless path forward for how PdCu will meet targets is in sight, PdCu computational analysis should be deleted.
- Modeling should be carried out before preparing more model systems. Justification should be provided for Pd/M and M/Pd systems.
- Only the most active Pd alloys should be considered for membrane electrode assembly testing. *Ex situ* stability testing will not provide appropriate fuel cell validation.
- Pd on Pd-containing core work should either be avoided (for high-PGM cost reasons) or should be merged somehow with Los Alamos National Laboratory/UTC Power projects.
- This project has showed that Pd-containing particles do not meet DOE objectives. Remaining tasks must be focused.
- The project emphasizes copper and iron alloys for future work. An immediate test of the stability of these alloys is necessary to demonstrate they will not poison the anode or promote the degradation of the membrane.
- Detailed plans are in place for future computational, modeling, and experimental work.

Strengths and weaknesses

Strengths
- Experienced and high quality collaborators.
- The principal investigators have done an excellent job experimenting with catalyst synthesis parameters to find whether Pd/M non-Pt catalyst particles can be as active as Pt.
- Investigators applied "apples-to-apples" *ex situ* electrochemical comparisons to find whether synthesized particles could meet DOE objectives.
- Mastery of experimental techniques was evident throughout data presentation.
- Strong list of collaborators were included.
- Systematic approach was followed. No unnecessary durability tests were done.
- The project is developing a strong modeling – predictive understanding of catalysis based on the alloy compositions under test.
- Focused on critical fuel cell barriers.
- Good project team assembled making steady progress.

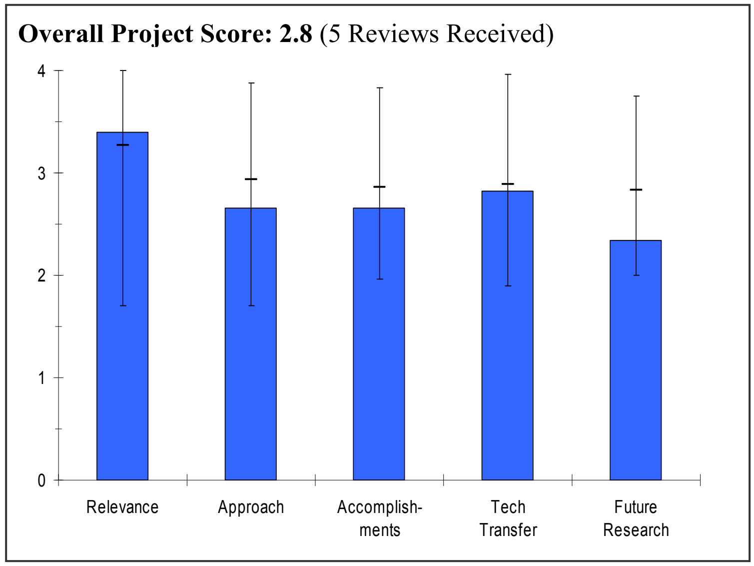
Weaknesses
- Trying to meet difficult practical targets with a basic research effort.
- Materials synthesized were not as active as Pt and do not meet DOE objectives.
- The principal investigator needs to reconsider whether bimetallic species on conventional supports, in general, will meet DOE objectives. Justifications need to be provided, whether by modeling or through literature, to say that a particular composition has a real chance of achieving 0.44 A/mg PGM, given a conventional particle-on-C-support structure.
- The use of copper and iron as alloying agents needs to be evaluated for their impact on fuel cell stability.

Specific recommendations and additions or deletions to the work scope

- Focus on gaining a more in-depth understanding of a model catalyst system representative of their approach, and refrain from trying to screen many materials to see what is obtained.
- Suggest keeping the project.
- If there is no theoretical justification to continue with bimetallic particles, the entire project should refocus on other chemistries. Because catalyst work is critical for the commercialization of fuel cells, academic interest cannot be the reason to continue any of the tasks described in the future work. Future work must have impact.
- Pd on PGM-containing core work should be given to or merged with Los Alamos National Laboratory/UTC Power projects, if carried out at all (latter decision should depend on expected cost, given high use of selected PGM).
- Future work should strongly emphasize improving palladium nickel alloys and cobalt alloys.
- The effort on nanostructures should continue, but not on copper or nickel until their stability is proven.
- Rhodium should only be considered for expanding the understanding of alloy interactions with the oxygen reduction reaction. Rhodium is considered too costly for use in oxygen reduction reaction catalysis.
- Look for opportunities to accelerate sharing of learnings with potential industry partners and systems integrators.

Project # FC-03: Advanced Cathode Catalysts
Piotr Zelenay; Los Alamos National Laboratory

Brief Summary of Project



The overall objective is to develop an oxygen reduction reaction catalyst, other than pure platinum, capable of fulfilling cost, performance, and durability requirements established by the Department of Energy for the polymer electrolyte fuel cell cathode. Other objectives of this project are to 1) design, synthesize and characterize new catalyst supports and electrode structures for new-generation oxygen reduction reaction catalysts; 2) determine the oxygen reduction reaction mechanism on newly developed catalysts via extensive physicochemical and electrochemical characterization and fuel cell testing; 3) optimize electrode with new catalysts and structures for maximum performance and catalyst utilization; 4) evaluate catalyst stability and minimize performance loss over time; 5) assure path forward for fabrication and scale-up of viable catalysts.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.4** for its relevance to DOE objectives.

- The project clearly addresses the major technical barrier, C. for cost reduction by replacing Pt with lower cost materials. But it is not clear that any of the approaches solve any of the durability or performance issues facing even state-of-the-art Pt based catalysts today.
- Improvement of the oxygen reduction reaction efficiency is vital.
- Ultra-low loading of Pt is needed.
- Non-Pt catalysts are the ultimate goal.
- All aspects will improve the cost competitiveness of polymer electrolyte membrane and are highly necessary.
- Project goals directly focused on addressing oxygen reduction reaction performance and durability issues while keeping cost considerations in mind.
- The results of this research have the potential for broad impact in the industry for enabling commercialization of fuel cell technologies.
- Cathode catalyst technology is one of the most critical areas for performance, durability, and cost.
- Particularly, lower PGM loading or alternative novel catalyst technology is highly demanded to develop commercially viable fuel cell technology.
- This project is dedicated to meeting DOE objectives for electrocatalysts by synthesizing new materials, which is highly relevant.
- The project is committed to minimizing PGM content.
- The project is committed to looking at novel structures.
- Too much of the ultra-low Pt task uses PGMs to displace Pt. Although high activities are shown, in principle, non-PGMs should be used to displace PGM since all PGM prices will increase at commercialization.

Question 2: Approach to performing the research and development

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

- The project has many, unrelated approaches, all with significant challenges.
- Approach is strong with excellent team but there are some weaknesses that need to be addressed.
- Fe is a known accelerant for membrane degradation – what will be ultimate price in durability for this cost saving?
- Is Fe in electrodes even a worthwhile material to investigate or is it already a known dead-end?
- *In situ* fuel cell experiments are poorly run and understood.
- Appears to be a 4-year program of parallel efforts, each with their own independent goals. Need to address specific overall project metrics and plans for downselect/direct comparison between different catalyst approaches before the end of the project.
- Individual approaches are generally strong, and in particular, the microemulsion approach is innovative.
- It is good to cover various approaches in a project.
- It is necessary to develop a common set of metrics to screen the technical approaches. It is not appropriate to set different metrics and target criteria between PGM catalyst and non-PGM catalyst.
- A common set of metrics and criteria should be developed from fuel cell requirements.
- The overall sequence of the approach – synthesize, understand oxygen reduction reaction mechanism, durability / membrane electrode assembly testing – is appropriate.
- The motivations for particular materials (e.g., chalcogenides) are not clear (other than to eliminate Pt).
- Go/no-go decisions should be applied for each material even before fuel cell testing. Criteria could include open circuit voltage, %H_2O_2, ability to be fabricated into a membrane electrode assembly, thickness of catalyst layer (which should be reported each time a fuel cell test is performed).
- Wide diversity of materials is commendable, since each material has a low probability of succeeding.
- Polarization curves should be broken into kinetic / ohmic / mass transport losses. Particularly for $PtAuNi_5/C$.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.7** based on accomplishments.

- The first year's progress has been good in demonstrating or advancing the concepts for several different new catalyst approaches. But none of them show significant progress in overcoming the DOE technical barriers A, B, and C. The highly experienced principal investigator and collaborators' work is excellent but fragmented due to the very broad nature of the project.
- High degree of fundamental electrode preparation and analysis has already been accomplished.
- *In situ* fuel cell experiments, which are the ultimate indicator of feasibility, are poorly run and understood based upon the results shown at this review meeting.
- Scanning Electron Microscope / Transmission Electron Microscope images are vital to understand phenomena and are well used.
- Microemulsion approach is very innovative and will likely lead to significant results in terms of practical catalyst fabrication and performance.
- Good progress being made in each of the parallel catalyst development efforts, with improvements of state-of-the-art demonstrated in most cases.
- Some good performance is shown with core-shell catalyst.
- Potential of Ru replacement with Fe is good but performance is still too low.
- High activity shown for $PtAuNi_5/C$, along with compositional confirmation – not stable under fuel cell conditions.
- Throughout ultra-low Pt section, activity numbers need to be re-normalized based on mg PGM, not mg Pt (inconsistency between 1.5 A/mg Pt for $PtML/Pd_3Fe$ on milestones slides and bar plot showing activity later).
- Need to show actual current densities as well for RuSe/C and better indication of core/shell character than compositional analysis.
- Use of polypyrrole nanotube to improve *ex situ* durability is good. Investigators need to show path towards *in situ* testing, particularly how catalyst layer will interact with polymer electrolyte membrane, gas diffusion media.
- CoFe complexes show low open circuit voltage, which lowers the probability for good performance.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- The project has all the right kinds of collaborators for effective technology transfer.
- Work between National Labs and Universities is high and clear.
- Unclear what the level of interaction between National Labs/Universities and Cabot.
- Membrane electrode assembly developer / stack developer should be considered to be added to the program to validate feasibility of materials, membrane electrode assembly preparation and fuel cell testing.
- Not really addressed. Doesn't even appear to be much interaction between members of the team, much less other projects/programs.
- Many collaborations.
- Collaboration is with at least two proven institutions (Brookhaven National Laboratory, Los Alamos National Laboratory on fuel cell catalysis.
- Collaboration is perhaps the most wide-ranging in the fuel cell subprogram.
- Collaboration is evident in the presented data, particularly with Brookhaven National Laboratory and University of Illinois Urbana-Champaign.
- Contributions of University of New Mexico, University of California-Riverside and others are not clear at present.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.3** for proposed future work.

- The project still appears to be trying to do too much and cover too much ground.
- For the second year, it would be advised to start downselecting the various approaches to one or two at most and focus on just those for achieving the performance target.
- The next focus should be on taking the best candidate and begin to study the durability issues.
- Fundamental approach is strong and should continue.
- Re-evaluation of Fe-based electrodes is necessary to determine end-use feasibility.
- Improvement of membrane electrode assembly and fuel cell testing is desperately needed and is not addressed sufficiently.
- In some cases, the principal investigator did not show data to support issues identified/future plans (i.e., how do they know there is a need for improved uniformity of Au on Ni core in the $PtAuNi_5/C$ catalyst?).
- What is approach to prevent Fe dissolution in Pt_3F_3 catalysts?
- It would be more beneficial to focus on the characterization work. For instance, it would be valuable to identify critical materials/design parameters to synthesize core/shell catalyst, rather than just aiming for better performance by trying various approaches.
- Screening milestone is necessary to sort out approaches. There are too many approaches on-going.
- Open circuit voltage for polyaniline-based and N-free catalysts should be improved before fuel cell testing ("performance") is done.
- System for direct electrochemical detection of H_2O_2 in polymer electrolyte membrane fuel cells should be mostly developed, or else this could be a considerable task.
- Hierarchical catalyst study should immediately address durability in some form since the probability of an activity / durability tradeoff is very high (high surface area, but low stability).

Strengths and weaknesses

Strengths
- Excellent and experienced collaborators.
- Core strength of various National Laboratories/Universities for fundamental work is exceptional.
- Strong team with very complementary expertise and clear lead roles in program.
- Variety of technical approaches.
- Diversity of materials.

- Well-executed electrochemical and analytical analyses.
- Challenges for each material clearly identified.
- Novelty of materials.
- Attention given to both support and active species.

Weaknesses
- Too many diverse approaches.
- Lack of membrane electrode assembly developer / stack developer for research direction and high level fuel cell testing hurts the program and causes unneeded diversions.
- Use of Fe in electrode is known drawback and should be avoided from day 1.
- Lots of parallel approaches here. Would like to know plan for future direct comparison of the catalysts being developed and whether any downselects will be made during the 4-year. Lack of a direct comparison (apples-to-apples) during the program will prevent identification of best catalysts to implement.
- Would benefit from spending more time on a few key highlights in depth in next year's brief rather than trying to cover everything in the program.
- Project management, since this project seems to be just collecting data for each task.
- Project should be conducted with a common set of metric and criteria.
- Reliance upon PGM-containing cores for some of the low-Pt work.
- Even greater attention to "red flags" (e.g., low open circuit voltage) needed in earlier stages of testing.

Specific recommendations and additions or deletions to the work scope

- Select one or two catalyst approaches and discard the others for next year.
- Reassessment of Fe in electrodes.
- Addition of membrane electrode assembly/stack developer.
- Project could benefit from putting together its own list of criteria that each catalyst / catalyst layer has to achieve. Attributes could include open circuit voltage, mass activity at 0.9 V, thickness of layer (may be dependent upon gas permeability, electrical conductivity, support stability), H_2O_2 evolution, etc. Although improvements are identified, this process could be more systematic.
- Greater emphasis upon performance loss breakdown when polarization curves are taken.
- More reported detail about catalyst layer ionomers and polymer electrolyte membranes used in testing.

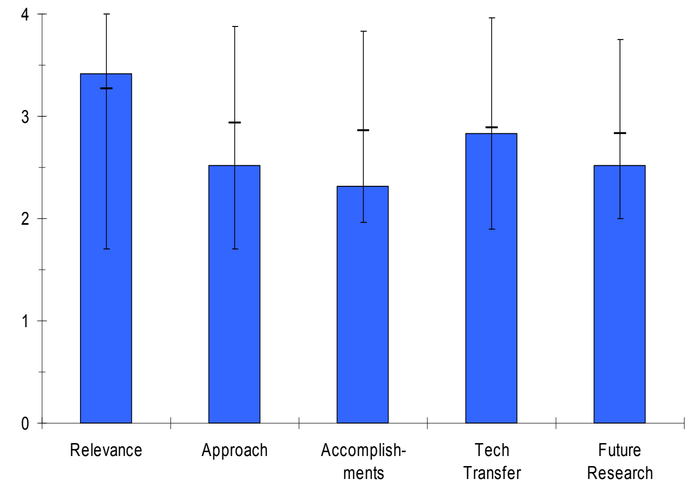
Project # FC-04: Development of Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells

Yong Wang; Pacific Northwest National Laboratory

Brief Summary of Project

The overall object is to develop and evaluate new classes of alternative and durable high-performance cathode supports. The objective for 2008 was to identify leading cathode compositions with better durability than carbon black supported Pt cathode.

Overall Project Score: 2.6 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.4** for its relevance to DOE objectives.

- Improvement of catalyst support is highly needed to meet durability targets.
- Improvement of catalyst utilization is highly needed to meet cost targets.
- Both improvements will aid fuel cell commercialization.
- Project is relevant to DOE objectives.
- The goal of the project – improving durability of the catalyst supports – is critical for the Hydrogen Fuel Initiative.
- Project is relevant to DOE targets although it is not properly focused.
- This project has the potential to yield valuable insight into the stability of the electrode supports leading to new guidance in durable electrodes.
- The testing of new materials as a support is critical to understanding and yielding a new stable electrode composition.
- The project objectives are relevant to the DOE objectives.
- Corrosion of conventional carbon supports is known to be a threat to automotive fuel cell durability targets. This project attempts to make more durable catalyst supports.
- Work that shows loss of Pt on Pt/ highly ordered pyrolytic graphite with electrochemical cycling (and not thermal stress) should be related to realistic *in situ* stresses (if necessary beyond providing answers about Pt deposition). Sulfuric acid anion has an unrepresentative interaction with Pt. The relationship of highly ordered pyrolytic graphite to realistic support in terms of contact angle, strength of Pt anchoring, and surface morphology is not established. This part of the work is not relevant to DOE objectives without all of the above.

Question 2: Approach to performing the research and development

This project was rated **2.5** on its approach.

- Exploration of new supports is good.
- Unclear why carbon nanotubes are used due to cost.
- Residual Chlorine in catalyst layer will cause significant issues if not completely removed.
- Project management needs improvement.
- In general, approach is effective. However, it can be improved by more careful characterization of synthesized supports.
- Catalyst support projects should focus on un-catalyzed supports and not on supported catalyst.
- Pacific Northwest National Laboratory is not using DOE-defined accelerated test protocols so the data cannot be directly compared to data from other approaches/researchers.

- The protocols being used by Pacific Northwest National Laboratory probably cause multiple degradation effects (i.e., not isolated effects), rendering the data and conclusions suspect.
- Pacific Northwest National Laboratory needs to monitor mass activity as well as electrochemical area.
- An overall sound approach and good use of microscopy and electrochemistry.
- Pacific Northwest National Laboratory should not only evaluate the materials, but also evaluate them in an electrode structure and configuration that might represent what will be utilized in the fuel cell. It is not apparent that the tests included ionomer in the electrode or other components.
- Using E-TEK as a reference is understandable, yet the composition of E-TEK is proprietary; therefore, industry might not use it.
- The Pt/WC system was developed and studied by General Electric in the 1960s and 1970s.
- Good approach of utilizing different catalyst supports. Down selection criteria is suggested to relate to *in situ* testing as well.
- Even though the corrosion of carbon is well-known, the project does not seek to entirely eliminate carbon-containing structures. Catalysts that are entirely supported by alternative structures (e.g., WC, ITO) should be studied.
- Beyond the Pt/WC durability data, quantitative justification for the proposed supports is lacking. It would be interesting to see "downselection criteria" for supports such as electrical conductivity, thermal/hydrolytic stability, strength of Pt interactions, etc.
- Catalyst durability testing should seek to isolate failure modes (e.g., agglomeration and support loss).
- E-TEK should only be used as a baseline if the carbon structure or graphitization level is well-known.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.3** based on accomplishments.

- Accelerated protocol which is different than accepted industry protocol could be providing data which is not useful.
- These protocols make the progress difficult to assess.
- Limited/unclear durability data at this point.
- Going directly to new catalyst support with platinum jumps over the first ideal step of catalyst support durability alone.
- Technical accomplishments are not convincing. Quality of rotating disk electrode data is poor in order to claim higher catalytic activity of the synthesized catalysts compared to Pt/WC.
- The statement on higher surface area on synthesized supports is not supported by experimental surface area measurements.
- The statement on improved activity of Pt-TiO_2-WC catalyst over E-TEK is not supported by experimental data given on the chart on P.14.
- The inappropriate protocols make the progress difficult to assess.
- It was not made clear that the TiO_2 system is more stable than the XC72 (slide 14).
- WC is as old as the early General Electric work of the 1970s.
- The testing should include negative voltages as well.
- Electrode stability is critical; yet it is the electrode that generates hydrogen peroxide which then destroys the ionomer in the electrode and the membrane. Can the team incorporate a peroxide generation test?
- What is the phase of WC as there are many sub-stoichiometric phases; same question for TiO_2?
- Will the mesoporous carbon generate peroxide species?
- Pacific Northwest National Laboratory should spend more time on alternative supports and stability.
- The surface area from both Brunauer, Emmett, and Teller theory and electrochemical active Pt sites should be evaluated for each catalyst support system as well as Pt loss following cyclic voltammetry (CV) under both higher and lower potential conditions.
- *In situ* testing is suggested to be included in comparing and down selecting the supports.
- Although it has been observed that Pt/WC is more stable than WC, there is no clear indication why.
- Fundamental understanding of other Pt/support model systems (support = ITO, SnO_2, TiO_2, oxycarbides, SiO_2) has not been shown.
- Scaffold structure has still not been selected, contrary to scheduled deadline in 2007.

- Pt/ ordered mesoporous carbon activity should be shown in comparison to Pt/XC72. Currents should be normalized by area.
- A considerable matrix of materials still needs to be synthesized by the end of 2008. The investigators have not shown the ability to quickly move through a large quantity of experimentation.
- TiO_2-XC72 stability has not been clearly established over XC72 stability, given limited data set.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- Good collaboration with existing partners seems to be appropriate for this program.
- Close collaboration between National Laboratories and the University; presence of industry is not indicated yet.
- The project needs more participation by industrial partners who build and operate stacks.
- Appropriate at this stage.
- Collaboration with others is not visible; Pacific Northwest National Laboratory should clarify the interactions amongst the group.
- There is no evidence of an Automotive Fuel Cell Cooperation contribution thus far.
- Oak Ridge National Laboratory has successfully been used to provide mesoporous carbon materials.
- The role of the University of Delaware is not clear. It is unknown if "model materials" refers to highly ordered pyrolytic graphite.
- Without evidence to the contrary, the project appears to be firmly led by Pacific Northwest National Laboratory with only material inputs from other organizations.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.5** for proposed future work.

- Using different accelerated protocol is a concern and should be reevaluated.
- Analysis of catalyst support alone would be a worthwhile intermediate step.
- In-depth cost analysis of the different catalyst supports would be useful before experiments begin.
- Future work is based on the previous progress.
- Priorities should be shifted towards identification of the reasons for low catalytic activity of the synthesized catalysts.
- Pacific Northwest National Laboratory needs to focus on supports before studying supported catalysts.
- Further work is as planned in the original scope.
- Additional detail on future work would be helpful – more specificity on what is going to be done (i.e., how does the work on interfacial interactions compare with prior work?).
- Better understanding of stability of such systems.
- Regarding the plan to test under potential sweep between 1.4-0.6 V, it is suggested to quantify electrochemically active surface area losses for each support system.
- It is suggested to consider including *in situ* testing following down selection of the support systems.
- Clarify path forward towards obtaining the 2X better stability than carbon black supports.
- Data to justify replacing XC72 with ordered mesoporous carbon and carbon nanotubes in future work has not been shown.
- Both potentiostatic and potentiodynamic testing should be considered for *in situ* future work if different failure modes are to be decoupled.
- Emphasis on *in situ* fuel cell work must be accelerated.
- Process for membrane electrode assembly fabrication will need to be validated, including ink formulation, ink application and gas diffusion layer selection.

Strengths and weaknesses

Strengths

- Analytical work is high.

- *Ex situ* materials characterization clearly demonstrated interaction between Pt and WC.
- Novel approach to synthesize carbon materials.
- Strong synthetic background.
- Solid team that understands the key stability issues.
- Team is not biased with respect to testing of new materials.
- Appropriate testing capability.
- This project is uniquely positioned to address catalyst support corrosion, a failure mode that is critical to meet DOE objectives.
- The project is linked to competent fuel cell research organizations (Pacific Northwest National Laboratory, Oak Ridge National Laboratory, Automotive Fuel Cell Cooperative, and the University of Delaware).
- The researchers demonstrate proficiency with the required test techniques.

Weaknesses

- Use of chlorine is a potential downfall.
- Use of different accelerated protocol.
- Not investigating durability/cost of catalyst support only.
- Project management.
- Quality of rotating disk electrode data needs to be improved starting from Pt/WC as a standard.
- Since the rotating disk electrode curve and mass activity for Pt/WC are not presented on P.14, it is unclear if poor catalytic activity of the synthesized catalysts is due to support of poor quality of rotating disk electrode data.
- In order to demonstrate better catalytic activity/durability, both surface areas and mass activities should be presented in absolute and relative numbers.
- Incorrect focus.
- Incorrect test protocols.
- Would like to see the team evaluate other potential support materials such as mixed metal oxides, sub-stoichiometric oxides, and not just use the same materials such as carbon nanotubes.
- Should understand other degradation issues such as dissolution, agglomeration, as well.
- Collaboration with others not visible.
- Several groups seem to be included; however, roles are not very clear.
- Fabrication of materials has not proceeded quickly enough.
- Researchers have not justified present scope of materials nor have they considered higher risk/reward possibilities that eliminate carbon.
- There has not yet been enough *in situ* fuel cell testing.
- Researchers need to carefully consider parameters used in test techniques, which metrics to report and how data are reported versus baselines.

Specific recommendations and additions or deletions to the work scope

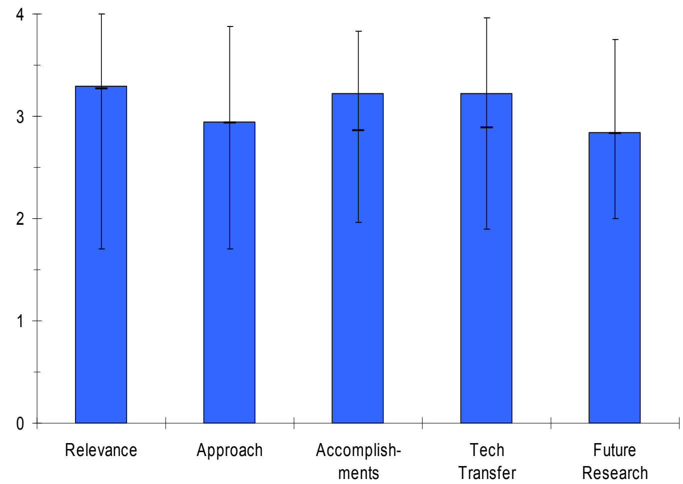
- Use of accepted accelerated protocol.
- Investigation of durability/cost of catalyst support only.
- Complement rotating disk electrode experiments with fuel cell testing.
- Suggest keeping the project; however suggest testing several types of catalyst-coated membranes other than Pt/Nafion-based and creating mitigation strategies as the effects of each impurity are investigated
- Collaborators, such as Oak Ridge National Laboratory, could be more valuable if involved at a level greater than merely material input.
- Attempt to synthesize Pt/WC or Pt/TiO_2 without carbon nanotubes, ordered mesoporous carbon or XC72.
- Delete *ex situ* testing if it interferes with time needed for more valuable *in situ* testing and post-mortem analyses.

Project # FC-05: Highly Dispersed Alloy Cathode Catalyst for Durability
Sathya Motupally; UTC Power

Brief Summary of Project

The objective of this project is to develop a structurally and compositionally advanced cathode catalyst that will meet the Department of Energy 2010 targets for performance and durability. The impact of oxygen on Pt dissolution and structural stability for various core/shell systems has been qualified. A number of elemental and alloy cores have been evaluated; Pd_3Co and Ir cores lead to the highest improvement in oxygen reduction reaction. Various PtIrX alloys have been synthesized and tested to understand activity and durability trade-off. Objectives for the past year were the bench-scale demonstration of appropriate dispersed alloy catalyst formulations and downselection and verification of a dispersed alloy catalyst.

Overall Project Score: 3.1 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Strong rationale for improving performance by 2.5X to achieve lowered catalyst loading while simultaneously focusing on durability to achieve 2010 goals.
- Addresses both fundamental understanding and pathway(s) for scaling catalysts and transitioning to practical systems to address DOE goals.
- Project is relevant to the Hydrogen Fuel Initiative.
- Addresses DOE goals on improved electrocatalytic activity/durability.
- 100 % fit with overall objectives.
- Commercialization of fuel cell vehicles will increase the price of any PGM (spot prices are irrelevant). The catalysts studied in this project all seek to displace Pt with other PGMs. This creates difficulty addressing cost.
- Fundamental knowledge gained from modeling and *ex situ* studies is not applicable toward reducing PGM content.
- There is no plan to investigate compositions that significantly reduce PGM content.
- This project has not addressed the "barriers" sufficiently – little supporting evidence that these catalysts have any advantage over Pt-only.
- COST has not been addressed adequately.
- The systems chosen (Pt-Ir, Pd, Au) do not appear to have any cost, loading, or durability advantages.
- Most of the presentation focused on modeling, but little evidence was presented to justify the investigation of the systems chosen for the research or that supported the fact that a core-shell structure existed.

Question 2: Approach to performing the research and development

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

- Strong approach with coordinated experiment and theory.
- Team roles and synergies are well defined.
- Strong scientific rationale that leverages best of mass activity and durability catalysts known to date to develop catalysts that exhibit both properties.

- Approach is well designed, but combines only fundamental instruments of catalyst investigation such as thermodynamic modeling and rotating disk electrode experiments.
- Approach can be improved by validating rotating disk electrode experiments with single cell testing.
- Results of modeling also need to be validated.
- Lack of microstructural characterization raises questions about core/shell structures.
- Convincing approach.
- Good use of complementary expertise.
- Use of broad background know-how.
- *Ex situ* cyclic voltammetry cycling does not speak to *in situ* durability. Investigators should develop *in situ* path forward immediately.
- Atomic structures (e.g., slabs) used for modeling may not be sufficient to capture nanoscale phenomena. Geometry not reported.
- So far, no consideration has been given to processes needed to obtain *in situ* data (e.g., ink, ink application).
- Again, a proper approach for reducing cost must seek to use non-PGM materials.
- Rationale for choosing bimetallic cores (Pd_3Co and Pd_3Fe) for analysis is unclear.
- There is way too much emphasis on modeling.
- The presenter did not provide sufficient evidence supporting the presence of a core-shell structure, however all modeling efforts assume that the catalysts are core-shell.
- MUST have additional confirmation that the catalyst structure exhibits core-shell (TEM, and X-ray photoelectron spectroscopy (XPS)).

<u>Question 3: Technical accomplishments and progress toward project and DOE goals</u>

This project was rated **3.2** based on accomplishments.

- Theoretical progress in understanding impact of oxygen on Pt segregation and dissolution is an important finding.
- Significant progress in demonstrating improved catalysts, including attempts to scale the technology.
- Good synergy between experimental and theoretical efforts – they are impacting each other beneficially.
- Principal investigator demonstrated promising results on durability and electrocatalytic activity.
- Progress is measured well.
- Interesting modeling activity; seems to be useful for catalyst development.
- Risk minimized by two parallel routes that might ultimately be combined.
- Reproducibility of mass activity data was not reported.
- The principal investigator did not present analysis to verify core/shell structure of Ir/Pt or Pd_3Co/Pt samples.
- Activity / durability tradeoff with dispersed alloy materials was not presented with data.
- Effect of particle size or particle size distribution was not reported for any samples.
- For what was planned, bimetallic PtM modeling analysis was comprehensive.
- It is unclear why the catalyst systems listed in presentation (Ir, Au, Pd) have been chosen – these systems will not help reach cost targets or perform any better than Pt-only catalysts.
- Catalyst systems are more like "model" systems than practical fuel cell cathode catalysts.
- There are not enough comparisons with Pt-only catalysts to justify replacement with these alloy/mono-layer catalysts.

<u>Question 4: Technology transfer/collaborations with industry, universities and other laboratories</u>

This project was rated **3.2** for technology transfer and collaboration.

- Individual projects well coordinated, and results from theory and experiment impacting each other and accelerating the catalyst development effort.
- There is close collaboration between academic institutions and industry
- Small consortium with excelling individual expertise results in efficiency and effectiveness.
- The collaborators assembled (UTC Power, Johnson Matthey, Texas A&M University, and Brookhaven National Laboratory) have an impressive amount of experience and capability.

- There is no direct evidence of Brookhaven National Laboratory collaboration.
- Modeling performed by Texas A&M University directly led to core/shell selections.
- Johnson Matthey provided material input but it is unclear whether they provided additional collaboration.
- The collaborators on this project represent some of the best in fuel cell development, but it is unclear as to the role each is playing in the project and what goals have been reached/targeted by each participant.
- The majority of research presented focuses too much on modeling without supporting data on actual catalyst structure.

Question 5: Approach to and relevance of proposed future research

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

- Future plans clearly derived from most recent results and focus on further advancing the technological successes while addressing the remaining challenges.
- Future plans are based on previous progress and focused on problems identified during the first year of research.
- Natural straightforward continuation as proposed makes sense.
- Future work is confined to PGM catalysts.
- *In situ* durability tests are regarded as a late-project activity, but should be a primary part of the project.
- The project should place more focus on *in situ* durability to achieve DOE objectives.
- The future work should definitely include additional characterization to verify core-shell structure – otherwise, the modeling effort is not representative of actual catalysts being studied.
- A cost analysis comparing Pt-only catalysts to Pt(Ir,Pd) should be conducted to support additional work in this development effort.
- Present more evidence that shows that these catalysts demonstrate enhanced durability and activity. This should be a major focus.

Strengths and weaknesses

Strengths

- Appreciate honesty about scale-up issues and retaining performance. Good to hear about both successes and challenges going forward.
- Project combines both modeling and experimental parts.
- New modeling approach is developed to predict stability and durability of core/shell catalysts
- Small consortium with excelling individual expertise results in efficiency and effectiveness.
- Results of modeling are applied to limit experimentation.
- Researchers are familiar with experimental techniques and correctly use electrolyte with low interaction with samples.
- High mass activities are shown.
- Collaborators with proven experience are involved.
- Clearly, a strength is the modeling effort, but there is too much modeling without supporting data for the catalyst structure.

Weaknesses

- Lack of materials characterization.
- Activities evaluated by a rotating disk electrode technique are not validated with the fuel cell testing.
- Mass activities are not always accompanied by specific activities, raising questions about the origin of improved mass activities.
- Unclear if baseline Pt/C catalyst employs the same support as core/shell catalysts.
- Too many numbers were presented.
- Reliance only on PGM for all catalyst materials (and cores) with no other plans.
- Low derivation, at present, of fundamental knowledge relating activity to catalyst particle parameters or core/shell compositional analysis.
- No *in situ* durability data reported.
- Not enough emphasis on characterization of catalyst structure.

- Not enough information presented to justify investigating the catalyst systems chosen for study.
- Too much modeling, not enough testing.

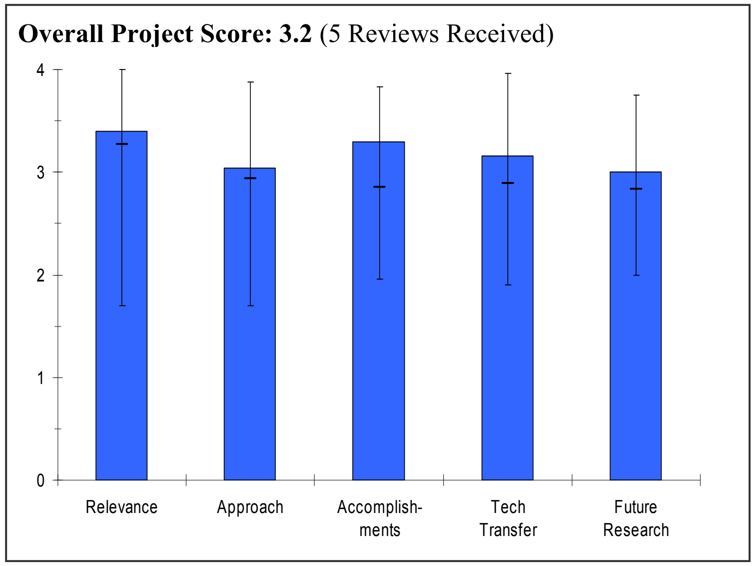
Specific recommendations and additions or deletions to the work scope

- Complement activities evaluated by rotating disk electrode technique by fuel cell testing.
- Validate results of thermodynamic modeling.
- Project should study catalyst particle cores that are non-PGM.
- Immediately begin to study *in situ* degradation phenomena.
- Directly compare of these catalyst systems to Pt-only catalysts to determine whether worth pursuing further.
- Greater evidence should be placed on activity and necessary loading of these catalyst systems compared with Pt-only.

Project # FC-06: Fuel Cell Systems Analysis
Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project

The objective of this project is to develop a validated system model and use it to assess design-point, part-load and dynamic performance of automotive fuel cell systems. This includes supporting the Department of Energy in setting technical targets and directing component development as well as establishing metrics for gauging progress of research and development projects.



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.4** for its relevance to DOE objectives.

- Project elaborates valuable modeling tools to support development of fuel cell systems and components.
- Extremely relevant. Not only does competent modeling allow a more comprehensive screening of technology options, it is also clear that none of the current models accurately account for start-stop, part-load, or transient effects on durability. More and better modeling and simulation, especially those which could provide an indication of performance deterioration, are obviously needed.
- Relevance is compromised by use of only elevated temperature and not a complete range of stack operating temperatures.
- Original equipment manufacturers use of distinct fuel cell systems limits project relevance to its ability to describe system componentry to DOE and DOE-funded projects.
- Impurity modeling covers familiar phenomena and does not add to understanding of impurity effects.
- Project addresses design of a pressurized fuel cell system. Industry is reporting performance similar to pressurized systems at reasonable temperatures using atmospheric pressure. The energy losses associated with transients are not fully addressed while the load cycles for automobiles, stationary power plants, and motive power (e.g., forklifts) are based on rapid transients, even with battery hybrid systems.
- The project appears fully centered on compressors, thermal management, and water management technology associated with Honeywell and does not address a broad base of manufacturers.
- This project fully supports the objectives in developing an automotive-capable membrane electrode assembly design-principal investigator was wise to avoid premature discussion of high temperature systems. These models serve to establish trends and suggest efforts to achieve maximal results in the overall system design. Providing Sensitivity analysis is perhaps the most useful function of such models.

Question 2: Approach to performing the research and development

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

- Clear approach resulted in clear results!
- Collaboration with "real world" manufacturers as e.g., Honeywell is beneficial.
- Generally very good.
- Some of the assumptions appear to require more justification than presented.
- There was no evidence of expected accuracy and no real discussion of limitations.
- The effect of operational turndown ratios (pressure, flow rates, temperatures, humidification) and especially stop/start operation has not been sufficiently explored to determine consequences for system component selection.

- Investigators should consult future Directed Technologies, Inc. system assumptions (2010 and 2015). Enthalpy wheel is unlikely at commercialization due to total weight (including auxiliaries) and reliability.
- Analyzing needed Pt loading with changing operating conditions should be unnecessary since automotive operating conditions should already be assumed to be widely varying over a drive cycle.
- Stack operating conditions (100% relative humidity, outlet temperature vs. inlet temperature) should be verified.
- Consideration should be given to transient operation. Software packages (e.g., Simulink) exist to enable this.
- The project's analytical approach is based on GC-Tools. At one time, GC-Tool was a steady-state model and not capable of addressing transients. If this is still the case, the success of the project will be limited.
- Industry groups are using a version of Aspen which was adapted to address transients. Has Argonne National Laboratory considered using Aspen?
- The approach is strongly tied to Honeywell. Since Argonne National Laboratory is addressing the DOE model for fuel cell systems for more than automotive applications it is recommended the program consider other system component manufacturers.
- These models are only as useful as the information inputted in them. Principal investigator must take care to ensure that all the parameters used compliment each other. Principal investigator must avoid picking and choosing the best parameters from multiple systems.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Important results for deeper understanding of system issues and further optimization of fuel cell systems/components.
- Collaboration with key players is strengthening the effort.
- Very good.
- Especially interesting were the efforts to assist in determination of nozzle area control to improve part-load efficiencies.
- Also very relevant was the inclusion of heat exchanger options to improve overall performance.
- Incorporation of variable area nozzle to facilitate both flow and pressure control is an important new addition to the model.
- Collaborations have allowed progress on modeling air management, water management and thermal management systems, but the deficiencies already mentioned in the "Approach" section prevent this project from delivering results more representative of automotive operation.
- System dynamics and membrane electrode assembly characteristics will have a profound effect on impurity buildup. The impurity calculations are not based upon dynamic assumptions, and therefore, progress here is left without value. Validation will be nearly impossible.
- The discrepancy between the Argonne National Laboratory model and the Japan Automobile Research Institute data appears to be dependent on which isotherm is used in the analysis. The presentation did not provide background information on the Langmuirian isotherm or the Temkin isotherms.
- What is the estimate for 35% high platinum loadings for atmospheric stacks based on? Does the Argonne National Laboratory data predict we have hit a limit for Pt loading? Argonne National Laboratory did not report the platinum utilization in the cell stack, but their prediction would require that information. How did Argonne National Laboratory come to this prediction?
- Rajesh’s work is always thorough and provides a good feel for sensitivity of key parameters in the system design. The model could only be improved to a more realistic scenario if proprietary information is supplied. This is unlikely to occur.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.2** for technology transfer and collaboration.

- Dissemination of results and collaboration in various groups is very good.
- Generally appears to be very good.
- Most actual collaboration seems to be with only one or two groups.

- The project has collaborated moderately well with component-level organizations, such as Honeywell, 3M, Emprise, and PermaPure. In this respect, the project has gathered detailed component parameters and injected these parameters into the model.
- The project fails with respect to collaborations that would provide a more realistic set of assumptions for the overall system, in terms of both components and realistic automotive operating conditions. The proper parties are not listed in the presentation and must be sought out.
- Argonne National Laboratory is limited its system work to Honeywell and system components based on Honeywell compressor expander, Emprise, and PermaPure. It is recommended they include other system component manufacturers in their analysis who are operating at constant near-atmospheric pressure.
- Argonne National Laboratory is working with the North American Hydrogen Quality Team but did not mention the team composition or team's objectives.
- Principal investigator is collaborating with the appropriate national labs. Principal investigator could use more guidance from original equipment manufacturers to further narrow component and performance selection.

Question 5: Approach to and relevance of proposed future research

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

- Convincing.
- Generally good.
- No mention in presentation of plans for further efforts on start-stop, transients, extreme operating conditions, etc., which seem to have huge "real-world" effects on both fuel cell durability and overall efficiencies.
- At present, the work proposed for the future of the project continues with the same assumptions. Instead of attacking the minutia of humidifier operation, and attempting to learn automotive stack operation from a membrane electrode assembly supplier, the project needs to take a "step back" and reconsider many of the assumptions involved.
- The future work information provided was very broad and did not supply sufficient information regarding tasks Argonne National Laboratory would be working on.
- No statement regarding evaluations of transient systems.
- Continued work on the Honeywell compressor and Pacific Northwest National Laboratory humidifiers is recommended. Principal investigator should exercise caution about modeling a high temperature system until more robust information and results about such systems are provided. Principal investigator runs the risk of using too many unfounded assumptions at this point.

Strengths and weaknesses

Strengths
- Very clear – no confusing details.
- Adds much needed modeling capabilities especially in air management, heat exchangers, and water management. There are also possible benefits in reductions in platinum loadings.
- When given component-level collaborator information, the project aggressively seeks to incorporate it in its models.
- The addition of variable area nozzle for the air management system was a realistic step.
- The acknowledgement of oxygen loss issues in the enthalpy wheel was a needed addition.
- Argonne National Laboratory has developed a background in fuel cell systems that should provide support to DOE.
- Model ability to provide sensitivity analysis and gauge where progress need to be made to achieve maximum value for effort.

Weaknesses
- There seemed to be no planned modeling efforts in the areas where it is clear that "real-world" effects are having disastrous consequences relative to projected durabilities and efficiencies. This area should have very high priority.
- The model has not embraced widely varying operating conditions and modes.

- Assumptions regarding static stack operation must be removed unless hybridization is also an assumption (which, at present, it is not).
- The principal investigator has not developed system-level collaboration relationships. In fairness to the investigators, though, it must be acknowledged that many parties that could be helpful to this project have been reluctant to contribute.
- The limited interaction with fuel cell system component companies provides only a narrow view for analysis by Argonne National Laboratory. The incorporation of portable, stationary, and backup power would suggest that other fuel cell system designs will become important in the near term.
- The focus on steady state systems limits the value of the Argonne National Laboratory analysis. Transient systems are real world and need to be addressed.
- Not including transients is a weakness of the Argonne National Laboratory analysis.
- Information in is only as good as the information put in. Principal investigator must be clear about assumptions and clearly state references, etc.

Specific recommendations and additions or deletions to the work scope

- Expanding from static to dynamic modeling would be great.
- Use composite National Renewable Energy Laboratory data (among other sources) to try to better take into account the various losses and adverse effects associated with repeated starts, idling, short run times, shutdowns, etc. of fuel cell vehicles.
- More emphasis should be placed on planning follow-on modeling and simulation.
- Cultivate relationships with multiple parties that run automotive fuel cell systems. Even though confidential borders exist, there should be some non-confidential means available of providing more realistic operating conditions and component assumptions. The possibility exists that just the operating conditions alone will be able to drive more realistic component assumptions once the operating condition implications are realized.
- Delete the impurity study.
- Ignore any feedback to perform system-level validation. The project is not yet ready.
- Consider transient operation.
- Argonne National Laboratory should include atmospheric fuel cell systems in their analysis using systems that are consistent with backup power, stationary power, portable power, and industrial motive power.
- Argonne National Laboratory should include transient evaluations in their analysis.

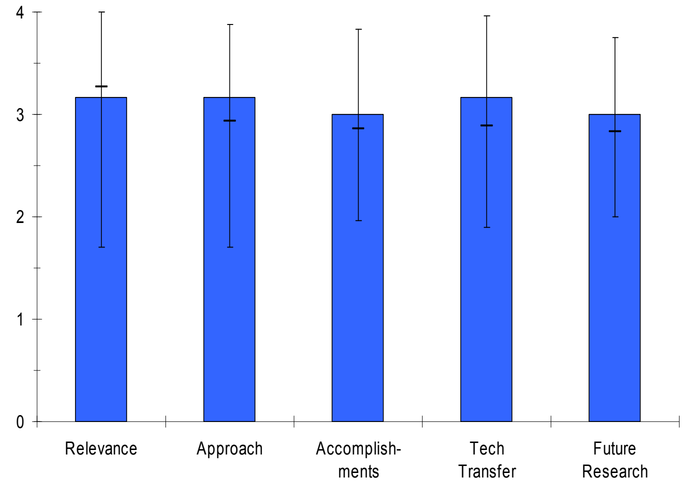
Project # FC-07: Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell System for Automotive Applications

Brian James; Directed Technologies, Inc. (DTI)

Brief Summary of Project

The objectives of this project are to 1) identify system design and manufacturing methods for an 80-kW_e direct H_2 automotive polymer electrolyte membrane fuel cell system based on three technology levels (2007 status technology, 2010 projected technology, 2015 projected technology); 2) determine costs for these three technology level systems at five production rates (1,000, 30,000, 80,000, 130,000, and 500,000 vehicles per year); and 3) analyze, quantify, and document the impact of system performance on cost. Some costs were not included (warranty, building costs, sales tax, and non-recurring engineering costs).

Overall Project Score: 3.1 (3 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.2** for its relevance to DOE objectives.

- Very good – captures cell stack assembly costs and balance-of-plant.
- The principal investigator demonstrated the relevance of the project to directing projects of technologic importance to meeting the long-term cost targets.
- The principal investigator demonstrated alignment with the major changes in technology metrics for the overall Program.
- Well-aligned with understanding the cost and path forward.
- By design does not address improving technical problems.

Question 2: Approach to performing the research and development

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

- Very good – systematic approach. Balance-of-plant could have been further itemized (like the cell stack assembly) to focus industry as to where to focus development.
- The design for manufacturing and assembly approach provides a good basis for the analysis of the materials and assembly costs.
- Neglecting the building, safety and waste handling costs may have a significant effect especially at the lower volumes.
- Approach seems basically fine, though assumptions such as leaving out mark-up can be debated.
- It would be nice if impacts of excluded systems at some generic level could be an input to see if there are system-wide optimization trade-offs possible.
- Need to expand the sensitivity analysis of assumptions.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Very good. Cell stack assembly component breakdown is detailed.

- The principal investigator demonstrated that the model has been refined from the previous year to reflect technological accomplishments and demonstrate key cost drivers at low and high volume production.
- The principal investigator demonstrated consideration of potential technology drivers that may increase the cost such as bipolar plate coating and stack conditioning.
- Re-evaluated the stack with updated projections. Seems they have gotten closer to a real system.
- Showed very different cost of high vs. low volume.
- Showed power density and Pt loading drive cost with membrane at low volume.
- Work has value but the rate of progress is not high.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.2** for technology transfer and collaboration.

- Estimated to be very good. It is assumed that the values and trends come for industry input and quotes.
- The principal investigator highlighted collaboration efforts to remain current with changes with technological metrics overall strategy.
- Suitable intersection with producers.

Question 5: Approach to and relevance of proposed future research

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

- Very good – Agree that balance-of-plant is the weak point.
- The project plans address some key cost assumptions that need further analysis in the model for the stack.
- Any significant cost drivers in the building and facilities management including safety and waste handling should be addressed in the cost drivers for the membrane electrode assembly and membrane processes.
- Suitable, but not aggressive.

Strengths and weaknesses

Strengths
- Cell stack assembly cost model.
- Balance-of-plant estimates.
- The project provides some good general direction and confirmation of the future direction for the importance of technical projects.
- The principal investigator seems to have taken into account changing technology metrics for the stack and system design into the evaluation of future cost.

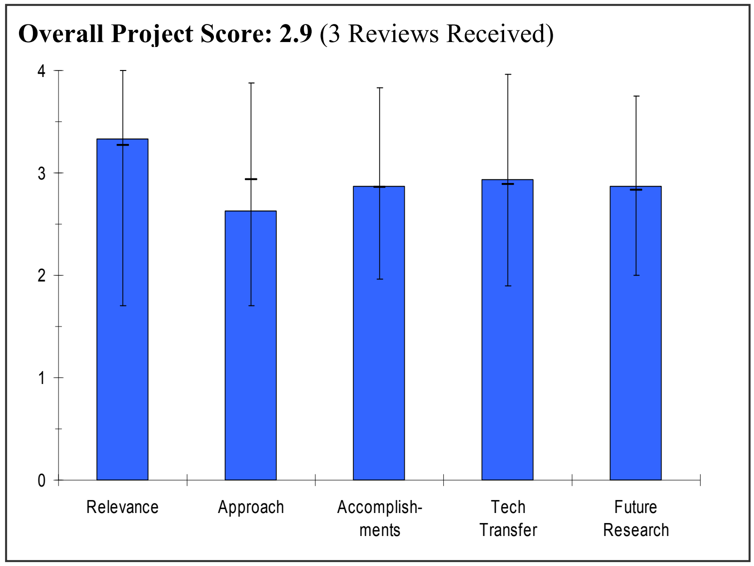
Weaknesses
- Platinum cost estimates.
- Balance-of-plant component details.
- The project uses potentially divergent assumptions of the lowest cost manufacturing and the highest performance membrane electrode assemblies, which may lead to divergent results and may need to be taken into account more fully in the sensitivity analysis.
- The cost of the building and infrastructure was not taken into account and may be a major sensitivity especially at the lower volume.

Specific recommendations and additions or deletions to the work scope

- No mention of synergy between stationary and transportation markets. One area of synergy would be balance-of-plant hardware: regulators, valves, sensors, blowers, etc.

Project # FC-08: Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications
Jayanti Sinha; TIAX

Brief Summary of Project



The overall objective of this project is a bottom-up manufacturing cost assessment of an 80-kW direct H_2 polymer electrolyte membrane fuel cell system for automotive applications. The objectives for 2007 were to 1) conduct a high volume (500,000 units per year) cost projection of the Argonne National Laboratory 2007 polymer electrolyte membrane fuel cell system configuration assuming a nanostructured thin film-based membrane electrode assembly and a 30 µm membrane; 2) conduct a bottom-up manufacturing cost analysis of balance-of-plant components; 3) perform a sensitivity analysis on stack and system parameters; and 4) economies-of-scale impacts on 2007 balance-of-plant costs. The objectives for 2008-2011 are to provide annual updates of high-volume cost projections.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Cost analysis is important to identify technology path toward commercial viability.
- Allows evaluation of status of cost and sensitivity of cost that are important in making progress in this one metric.
- Analysis of the manufacturing cost of state-of-the-art fuel cell technology is critical to appropriating research and development funds appropriately and should be undertaken annually, or as frequently as the rate of technology development progress justifies.

Question 2: Approach to performing the research and development

This project was rated **2.6** on its approach.

- Only one technical assumption is used. Various technology assumptions should be analyzed to identify promising technology path.
- Enthalpy wheel is not a very likely component, but may have seemed so once. Otherwise reasonable approach.
- Only one state-of-the-art membrane type was considered; analysis of additional membranes or fuel cell systems would ensure that all of the potentially important manufacturing cost factors are identified.
- Assumptions and approach appear to be appropriate.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.9** based on accomplishments.

- More detailed sensitivity study is required.
- Dedicated balance-of-plant components, such as H_2 blower and turbo compressor, should use bottom-up cost model. Off the shelf components, such as the radiator, should use industry standard.
- Economies-of-Scale analysis is good.
- Detailed breakdown is necessary.

- See that material is 44% of cost for balance-of-plant and labor is 33%.
- New assumptions lower cost significantly but have similar sensitivity.
- Compressor-expander is a high-cost item in the balance-of-plant.
- TIAX has completed its 2007 manufacturing cost estimate using a 3M-like membrane.
- Costs have been analyzed for the stack and the balance-of-plant.
- Sensitivities to various parameters were presented, and the most important ones were identified.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.9** for technology transfer and collaboration.

- Collaborates with Argonne National Laboratory and accesses suppliers' information.
- Proper contact with suppliers and original equipment manufacturers through the FreedomCAR Fuel Cell Technology Team.
- TIAX has coordinated with component developers and vendors to ensure that the appropriate assumptions and inputs are used and has plans to vet the model and results with them as well.

Question 5: Approach to and relevance of proposed future research

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

- Future plans are appropriate.
- Analysis of additional membranes/systems should be considered in future years.

Strengths and weaknesses

Strengths
- TIAX seems to have strong collaborations with technology developers and vendors to acquire appropriate inputs for their model and to vet the assumptions and results.
- The project strongly supports the DOE research and development program by examining the cost impacts of fuel cell system components and suggesting research priorities.
- The bottom-up approach to cost analysis is appropriate for a state-of-the-art system where some of the parts are not yet manufactured in volume.

Weaknesses
- Duplication with the Directed Technologies, Inc. project.
- Analyzing only one state-of-the-art membrane/system may limit the identification of potential manufacturing cost impacts.

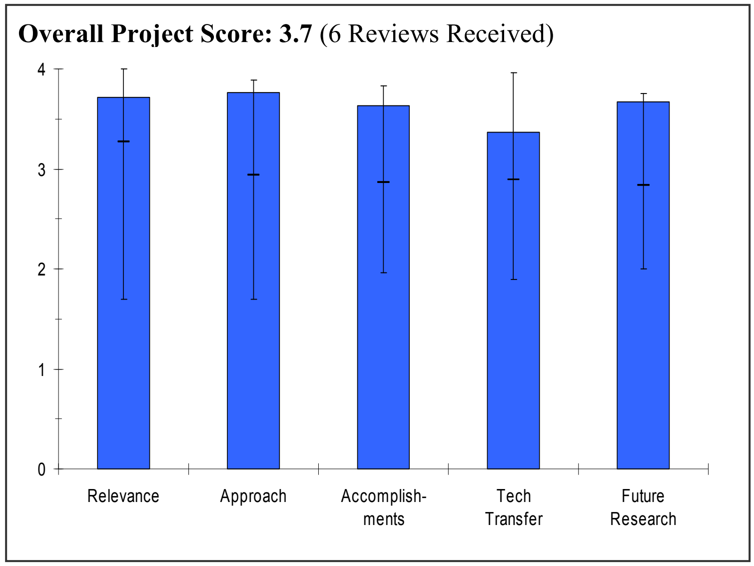
Specific recommendations and additions or deletions to the work scope

- Consider analyzing multiple fuel cell systems in future manufacturing cost estimates.

Project # FC-09: Microstructural Characterization of PEM Fuel Cell MEAs

Karren More; Oak Ridge National Laboratory

Brief Summary of Project



The overall objectives of this project are to 1) identify high resolution imaging and compositional/chemical analysis techniques for characterization of the material constituents comprising polymer electrolyte membrane fuel cell membrane electrode assemblies; 2) apply these analytical and imaging techniques for the evaluation of microstructural and microchemical changes that determine fuel cell stability; and 3) elucidate microstructure-related degradation mechanisms contributing to polymer electrolyte membrane fuel cell performance loss. Collaboration with industry, academia, and national laboratories will be conducted to make these techniques (and expertise) available to correlate structure and composition with membrane electrode assembly processing and life-testing studies.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- Critical program for obtaining fundamental insight into the structural nature of fuel cell materials.
- The study of catalysis and supports is critical to President's Hydrogen Fuel Initiative.
- Microstructural analysis is needed to gain scientific understanding of the effect of structural parameters of fuel cell materials (including changes occurring as a result of specific operating conditions) on their performance and durability.
- Project has provided significant value to DOE program. Insight into structure and durability gained by pictures obtained are invaluable to other researchers.
- Tool development is novel and interesting. Tools can address key aspects of catalyst durability and structure.
- This project is valuable to the overall objective since it provides another analytical tool to observe and measure catalyst activity in fuel cell applications. Full understanding of catalyst activity and distribution is fundamental to achieving loading targets.

Question 2: Approach to performing the research and development

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

- Excellent state-of-the-art facilities and knowledge of how to use them to address the durability and structural aspects of catalysts.
- Very high-resolution microscope down to 0.75 angstroms, probably a unique tool for catalysis imaging.
- 3-D profiling, able to image metals on carbon.
- I*n situ* microscopy.
- Advanced Electron Microscopy techniques are very suitable for atomic-scale characterization of structure and composition.
- All tools, know-how, and experience necessary to meet the project milestones are available.
- *In situ* imaging is needed to better understand aging effects in fuel cells. The size scales investigated in this project have not been approached by other techniques.
- Depth profiling has value in non-precious and low loading catalysts.

- Tool development helps others in their development efforts but does not directly address critical barriers.
- Very strong technical tools. Should work to maximize available insight.
- Work should focus on providing high throughput characterization, with associated statistics, of most important catalysts.
- The work would benefit from a much better feel for how common some of the reported effects are. Because of the inherent singular nature of sampling and studying images, one is left with a question (whether justified or not) of how pervasive a given effect is.
- Additional quantitative analysis, provided by modeling coupled to investigations of kinetics of particle growth processes, particle size dependence of processes, etc would be highly desirable.
- The principal investigator is using a very high resolution technique to film catalyst orientation and migration. Currently the technique has not been demonstrated *in situ* in a fuel cell application or in a fuel cell environment (e.g., in an ionomer dispersion). This is the next step required to achieve a representative observation of catalyst activity in a true fuel cell environment.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.6** based on accomplishments.

- The principal investigator and her colleagues have demonstrated a significant amount of progress and output of results for the resources applied to this project. They are pushing the envelope in terms of catalyst structure characterization. This knowledge should translate well to understanding how to overcome the durability or performance targets.
- Acquired new microscope upgrade.
- *In situ* microscopy observed agglomeration of Pt particles on the nm scale.
- Continued excellent evaluation of catalysts.
- *In situ* microstructural characterization of materials in a fuel cell environment is an important accomplishment to accelerate understanding of fuel cell degradation mechanisms.
- Depth sectioning and 3D reconstruction enable a more detailed determination of the structure of catalyst nanoparticles, such as core-shell.
- Visualization of Pt migration across the surface at high temperature can be very valuable to durability issues.
- Depth profiling and single atom resolution have been very impressive.
- There can be no doubt that this work is a tour de force.
- This provides an excellent and unique picture of critical processes occurring on the supported catalyst.
- Automation of the film is the next logical step and principal investigator indicates that that work is in progress.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.4** for technology transfer and collaboration.

- Very good outreach attempts and communication of results.
- Excellent, biggest goal is to collaborate with industry.
- Provides extremely useful characterization to several other DOE contractors.
- The principal investigator works with key members of the fuel cell community and has excellent collaborators.
- The expertise gained by this project hasn't been passed along to other members of the TEM community; the discrepancy between other researcher's TEM quality and this project's TEM is significant. Educating the community to provide higher quality data would be beneficial.
- Strong effort to pull together most major players.
- Given the potentially limitless supply of possible collaborators and sample sources, I would suggest that the principal investigator put together an unbiased advisory group to help to set priorities.
- Principal investigator has just recently demonstrated feasibility of concept and tool and is openly seeking partners to test materials. Success of this technique will depend on successfully collaborating with many catalyst developers using different techniques and materials.

Question 5: Approach to and relevance of proposed future research

This project was rated **3.7** for proposed future work.

- Some aspects of the future work plan should be reconsidered. Trying to solve carbon support degradation mechanisms with TEM may not be sufficient, and in the end, it will not likely be able to eliminate the corrosion that is a fundamental limitation of carbon supports. Increased application to understand better things that work well (e.g., catalyst aspects which give increased activity) may have greater impact than studying things that are destined to fail.
- *In situ* holder for microscopy extended to voltage cycling, liquids, and electrolyte.
- Statistical analysis.
- Collaborations for relevant experiments.
- Further develop 3D technique.
- This is a comprehensive and ambitious plan.
- Tools demonstrated to date will be extremely useful.
- It is unclear that proposed *in situ* tests (humidity, liquid water) will give enough information to be useful.
- With the addition of quantization and statistics, this project could be invaluable.
- Principal investigator will automate system and attempt to view activity of particles in an ionomer dispersion (i.e., fuel cell environment); this is the next key milestone for them.

Strengths and weaknesses

Strengths
- The experience of the principal investigator and team combined with the great facilities and willingness to apply their tools to others' problems of interest.
- Dedication of extremely powerful imaging techniques to fuel cell relevant catalysts.
- Unique capabilities and expertise to address the need for microstructural visualization of catalysts and membrane electrode assemblies.
- Enables other DOE contractors to improve performance, durability and cost of materials they are developing.
- Widely applicable to other projects. This project alone will not enable fuel cell commercialization. However, it is advancing the state-of-the-art significantly and has a broad collaboration base.
- Some of the most powerful microscopy equipment expertise available.
- Very strong technical leadership.
- Taking advantage of access to advanced and relevant catalysts.
- This technique allows researchers to greatly improve observation of catalyst particle migration which will clearly lead to improved catalyst/ support designs in the future.

Weaknesses
- Need for more *ex situ* synthetic manipulation at Oak Ridge National Laboratory to support project.
- Could use statistics and collaboration with strong modeling.
- Technique might not be suitable for all catalyst alloys – i.e., the principal investigator indicated that the technique does not distinguish well between Pt and Ir in a Pt/Ir alloy.

Specific recommendations and additions or deletions to the work scope

- Recommend reducing the effort to study carbon corrosion and spend more effort on developing capabilities to reveal surface structure and surface composition of catalysts that determines activity and stability under high voltage.
- Educating the community to provide higher quality data would be beneficial.
- Collaboration with group or groups that model nanocatalysts would be ideal.

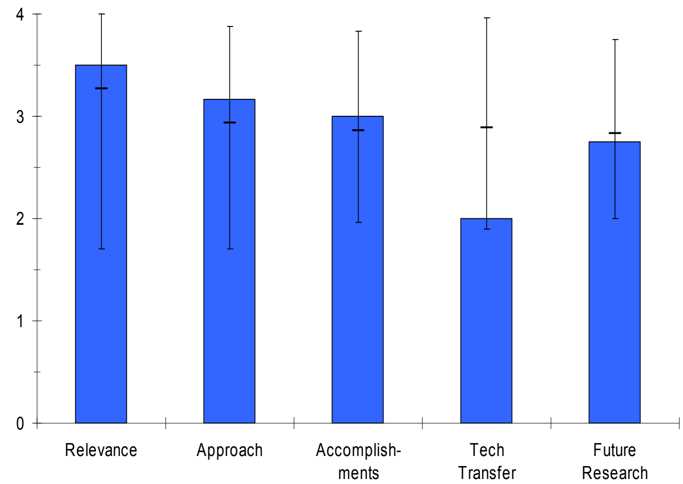
Project # FC-10: Applied Science for Electrode Cost, Performance, and Durability

Christina Johnston; Los Alamos National Laboratory

Brief Summary of Project

The overall objective of this project is to assist the Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies Program in meeting cost, durability and performance targets by addressing issues directly associated with electrodes. In 2008, Los Alamos National Laboratory will explore the effect of catalyst ink composition and processing on utilization and performance. Additionally, Los Alamos National Laboratory will use microscopy and other tools to better understand structure and impact on performance.

Overall Project Score: 3.0 (3 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- The work reported is interesting but will not yield significant findings to advance the electrode inks that the membrane electrode assembly companies do not already understand.
- Cannot see how this program will yield fundamental knowledge.
- Pt catalyst/electrode is one of the most critical technical areas.
- Comprehensive investigation on Pt catalyst/electrode is valuable to characterize electrode/membrane electrode assembly.
- The project is focused on the major barriers to fuel cell commercialization, namely performance, durability and cost.

Question 2: Approach to performing the research and development

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

- The approach is not at a high enough level for the talent of the group. Also, the electrodes in these studies may not reflect what are actually used in commercially available membrane electrode assemblies. It is expected the learnings will be utilized by the membrane electrode assembly manufacturers but they should already have these data.
- The ionomer in the electrode and its effectiveness as a proton conductor should be studied in greater detail. In particular, the "architecture" of the electrode.
- Selected methods, like ball milling, are not considered serious fabrication methods as 1) ball milling will break up agglomerates, not nanoparticles, 2) ball milling is well known to introduce impurities which come from the media.
- Should use jet milling.
- It is good to cover various approaches in a project.
- A more detailed explanation of the approach would be helpful.
- How do ink composition and processing affect electrode durability?

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Work reported is not representative of what should be coming out of Los Alamos National Laboratory in particular the role of the ionomer in the electrode (slide 20). This result should be a sign of the role of the ionomer in the structure of the electrode.
- There are other properties of the electrodes which should be looked at to try to correlate performance with such key properties, e.g., pore size distribution, effect of microlayer, ionomer composition and placement, particle (and agglomerate) size, tortuosity – all as a function of processing.
- Good analysis on electrochemically active surface area methodologies.
- Some insight into the catalyst ink processing and effect of ionomer to catalyst ratio was gained.
- More compelling conclusions are needed to help fuel cell developers.
- Properties of "advanced" catalyst should be described in more detail, and an explanation offered why they behave differently than the conventional catalyst.
- Data suggests that half-cell results are not relevant to fuel cell operation.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.0** for technology transfer and collaboration.

- This is satisfactory as there needs to be an environment to report the results openly.
- Should encourage closer ties to membrane electrode assembly companies or companies that supply the inks.
- For the research to be helpful to fuel cell developers, the studies should be applied to common classes of catalysts, which should be described in sufficient detail to allow application of the results to any particular catalyst.

Question 5: Approach to and relevance of proposed future research

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

- The role of catalyst layer interactions studied by neutron scattering is highly recommended in addition to the proposed work on solutions.
- Greater emphasis on architecture and the structure and placement of the catalyst particles is suggested to assess electrochemically active surface area.
- It is good to cover ink solution to characterize electrode. Development of water management metric will be necessary.
- It is recommended to extend Pt alloy catalysts for electrode characterization.
- It is recommended to pursue a durability evaluation.
- Correlating composition and processing to aging is extremely important.
- Study of advanced supports has the potential to better integrate this project with other DOE projects focused on developing such catalysts.

Strengths and weaknesses

Strengths

- National lab facilities and talent.
- Independent.
- Fundamental studies can be focused on significant details science-wise.
- Project has potential to provide some fundamental understanding of basic ink and electrode parameters.
- Electroanalytical results were correlated to microstructural analysis.

Weaknesses

- This is a very difficult topic and one which needs the strength of the national labs but with the ties to a membrane electrode assembly company. The proposed work suggests looking at alternative supports, etc. Stick to the current scope.
- Approach is not well defined.
- Durability has not yet been addressed.

Specific recommendations and additions or deletions to the work scope

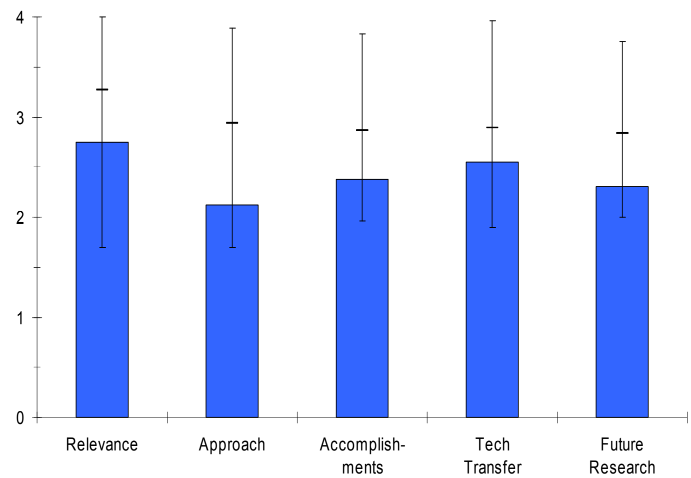
- Take the science to the next level and do not dilute the effort. The learnings here are too valuable and must be representative of real world ink processing. Get the guidance from meetings with the membrane electrode assembly companies.

Project # FC-11: Low-cost Co-Production of Hydrogen and Electricity
Fred Mitlitsky; Bloom Energy

Brief Summary of Project

The objectives of this project are to 1) demonstrate cost-effective, efficient, reliable and durable solid oxide fuel cells for stationary applications; 2) determine the economics of hydrogen and electricity co-production for comparison to stand-alone hydrogen production facilities; and 3) determine the feasibility of a delivered cost of hydrogen below $2.50 per gallon of gasoline equivalent. The rated power of the planar solid oxide fuel cell system, planar solid oxide fuel cell system efficiency, of >45%, and remote monitoring was demonstrated. The hydrogen pump design was validated with a 15-cell prototype connected to the planar solid oxide fuel cell test stand.

Overall Project Score: 2.4 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **2.8** for its relevance to DOE objectives.

- This project does not address the barriers in the DOE H_2 Program for polymer electrolyte membrane fuel cell stationary units, as the system is a solid oxide fuel cell.
- Economic analysis of the hydrogen production has not been done yet.
- This project addresses programmatic infrastructure goals through distributed production of hydrogen from natural gas.
- Target of $2.50 per gallon of gasoline equivalent.
- Stationary power generation using a solid oxide fuel cell.
- Project is highly relevant. High electrochemical efficiency (low power required/kg H_2) ~$0.12/kg H_2@ $0.10/kWh electrical costs seems compatible with DOE targets.
- It is an excellent idea to build and test a dedicated fuel cell system for using the hydrogen that is not consumed at the anode for some useful purpose. The value of the hydrogen as a fuel or industrial resource could in some niche markets be greater than the value of the electricity. Diverting a reformer for hydrogen production exclusively/primarily could increase the capacity utilization of this device, and therefore its economics.

Question 2: Approach to performing the research and development

This project was rated **2.1** on its approach.

- It is uncertain how a small demonstration project like this one can hope to realistically demonstrate the feasibility of a delivered cost of hydrogen below $2.50 per gallon of gasoline equivalent. The hydrogen is produced and not delivered anywhere outside of the demonstration site. It is not a true delivery scenario.
- Approach is a planar solid oxide fuel cell coupled with H_2 pump.
- Demonstration target is H_2 of sufficient purity to power a polymer electrolyte membrane fuel cell.
- Hydrogen outlet gas constituent compositions are not discussed.
- Technology is based on solid oxide systems. These types of high temperature systems offer the potential for the highest efficiencies but have the most severe materials issues (interfaces, sealing, etc.).
- Co-production of hydrogen and electricity by combining a solid oxide fuel cell with an electrochemical pump.
- System will run on (mostly) natural gas. Future system proposed to run on liquid fuels like ethanol.

- Exhaust gas from the solid oxide fuel cell stack is utilized in the H_2 pump. Essentially the pump removes residual H_2 for transportation polymer electrolyte membrane fuel cell uses. Turn down in solid oxide fuel cell system produces more hydrogen.
- Water gas shift system greatly reduces power needs to operate.
- Bloom has excellent understanding of solid oxide fuel cell barriers and has apparently overcome many at least short-term barrier issues. However, not enough stack data provided.
- The project is too loosely integrated. Other concepts have a more integrated solid oxide fuel cell/electrolyzer that will probably have better efficiency. The electrochemical pump is a subcontracting project and almost an add-on.
- Principal investigator should describe the electrochemical hydrogen separator in more detail, in achieving purity requirements.
- The system uses external reforming (not internal) with good thermal management (slide 6). Slide 6 with the schematic of the system design is excellent.
- Although the project team evaluated pressure swing adsorption vs. electrochemical H_2 pumping vs. partial pressure swing absorption), it could have also considered chemical separation, such as preferential oxidation or methanation. It should state the reasons for downselecting to H_2 pump over these options as well.
- The project team is planning to test the system with which liquid fuel?

<u>Question 3: Technical accomplishments and progress toward project and DOE goals</u>

This project was rated **2.4** based on accomplishments.

- Hydrogen purity discussed in round about fashion – gas impurities targeted were only CO and CO_2, how is S in reformed natural gas removed?
- The benefit of a Hydrogen pump is its ability to produced H_2 at high pressures for storage in vessel or delivery to vehicle, otherwise all it is a separation membrane. Why isn't higher pressure H_2 produced?
- Performance degradation not discussed and principal investigator indicated stack technology is off limits for discussion.
- H_2 pump is under construction.
- Operation of planar solid oxide fuel cell at >45% system efficiency.
- H_2 purity analysis concentrated only on CO_2 and CO; need to consider other impurities especially H_2S.
- Demonstrated 3000 hr of balance-of-plant component testing.
- Demonstration in Alaska in Q3 of 2008 (this has slipped from planned start in Q1).
- The 120-cell hydrogen pump stack was just recently developed. The state of development and testing of the Bloom solid oxide fuel cell system is uncertain.
- Hydrogen pump earlier validated with 15-cell prototype.
- System efficiency of 45% for solid oxide fuel cell claimed. Good but not overly impressive. Apparently over 50% has been demonstrated in the lab.
- No publications or presentations listed.
- There was little data presented. It is difficult to evaluate the electrochemical tradeoff between fuel cell/reformer/electrochemical pump.
- Slide 15 shows a decrease in electric power required per unit of hydrogen when water gas shift reactors are used. The primary reason for this is the increase in hydrogen concentration in the gas stream after the water gas shift reaction, resulting in a lower power requirement per unit volume of hydrogen gas. The increase in hydrogen concentration at the anode might be expected to lead to an increase in electrical power requirements per unit volume of gas due to the lower concentration gradient of hydrogen across the hydrogen pump's electrolyte. Therefore, Slide 15 implicitly shows the trade-off between 1) higher electrical power requirements per unit volume of gas due to a lower H_2 concentration gradient across the electrolyte in the case of water gas shift use and 2) the higher concentration of hydrogen in the water gas shifted reformate leading to more H_2 available for diffusion. However, it would be helpful to clarify Bloom's desired take-aways from this slide.
- Bloom seems to have accomplished good progress considering the funding level.
- 25 kW system tested for > 3000 h, team of operators trained, remote monitoring was set-up, and control systems developed for transient operation.

- Demonstrating above 45% net electrical efficiency (DOE goal) in the lab is quite good. Principal investigator should show these results in the field. Principal investigator should report hydrogen generation efficiency, and overall efficiency (electricity and hydrogen), as a function of hydrogen generation rate.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.6** for technology transfer and collaboration.

- Collaborations are weak. H_2 Pump is the only collaborator discussed in presentation.
- Partnership between Bloom Energy and H_2 Pump LLC, with each partner concentrating on individual components.
- Collaboration with system component supplier (H_2 Pump LLC) and University of Alaska for demonstration.
- Bloom may or not be the commercializer; however, likely will need a commercialization partner and this is not evident.
- Bloom works well with University of Alaska. Remote monitoring will greatly aid the project.
- Excellent to collaborate with a local university (University of Alaska, Fairbanks). This collaboration brings educational and research opportunities for the university, and is excellent educational outreach.
- Downselect process for Anchorage Airport as installation site is based on having excellent potential commercial customer there. Great partnering.
- Bloom Energy outsources the electrochemical hydrogen separation entirely to third-party supplier (H2 Pump LLC). This approach is of greater benefit to the DOE, in that other fuel cell system developers also have the opportunity to use this technology in their systems and push technology progress forward more quickly, collectively.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.3** for proposed future work.

- Future work weak. No mention of demonstration. It appears that all work is on H_2 pump, which is not really a pump.
- Remainder of project fabricates H_2 pump, connects to planar solid oxide fuel cell and installs in Alaska.
- As Demo project, there is little in the manner of research.
- Phase II will provide a field demonstration for a 25 kW solid oxide fuel cell system in Alaska. 50% peak net electrical efficiency demonstrated in lab testing in California.
- The hydrogen pump module will be tested in California; plans call for the integrated system to be tested in California. Not clear why the integrated system planned to be tested in Alaska is not to be done although it appears that there have been some slippage in the project plan.
- Project appears to be on schedule to achieve goals.
- Demonstration of the economics of hydrogen co-production is an excellent future task.
- Electrochemical hydrogen separator testing and optimization and integration with solid oxide fuel cell onsite is an excellent future path.
- Principal investigator should show more results similar to slide 15 illustrating the effect of system design changes on H_2 pumping efficiency, system efficiency, H_2 production rate, etc.
- Slide 6 shows a water gas shift reactor orientated at the anode exhaust. While water gas shift reactors have been developed for use between a fuel reformer and the fuel cell stack (in polymer electrolyte membrane and phosphoric acid fuel cell systems), this change in orientation of the water gas shift may be expected to require additional research and development work. For example, water gas shift reactor catalysts tend to work well at relatively low temperatures (around 200°C). To better integrate a water gas shift reactor with a high temperature solid oxide fuel cell, it may be helpful to conduct additional research and development on higher temperature water gas shift reactor catalysts.

Strengths and weaknesses

Strengths
- Demonstration project with novel design.
- Good choice of technology for best efficiency.

- Good plan for demonstration.
- Separates fuel cell from hydrogen generation - does not do what some have proposed by combining solid oxide fuel cell and electrolyzer in one device, which would not be desirable from a materials standpoint.
- Uses reasonable electricity costs to evaluate system efficiency for hydrogen production.
- Good system integration to improve efficiency but timetable to demonstrate this is not clear.
- A strength of the project is successfully designing, building, and testing systems with a high net electrical efficiency.
- Speaker was polite, diligent, and informed in response to reviewer questions, and with clear communication style.
- Bloom seems to have accomplished good progress considering the timeline and funding level.
- Successful collaboration with many parties (such as local utilities).

Weaknesses

- Principal investigator was evasive, no real information was disclosed.
- H_2 pump should produce usable pressure. There are several electrochemical compressors under development with DOE funding that can delivery 4000 psi today. There are also working H_2 separation membranes that can be purchased off the self. The purpose for H_2 pump needs to be defined.
- Very little science discussed.
- Little in-lab long term testing before attempt field demonstration - only 3000 h of testing to date and only on balance-of-plant components. Previous researchers have found this to not be desirable.
- System cycling could present very severe materials issues.
- Overall system costs not clear.
- Bloom Energy appears to view electricity as more valuable than heat recovered for hot water and space heating, and as a result, does not do cogeneration at this site. However, in Alaska, the demand for heat can be great. At certain times and in certain locations (such as at night in a cold climate such as Alaska), heat can be more valuable than electricity. Therefore, some exploration of cogeneration of heat could be useful.
- Although the project team evaluated pressure swing adsorption vs. electrochemical H_2 pumping vs. partial pressure swing absorption, they could have also considered chemical separation, such as preferential oxidation or methanation.
- Bloom should report H_2 production rate as a function of H_2 generation efficiency and overall efficiency (electricity and hydrogen).

Specific recommendations and additions or deletions to the work scope

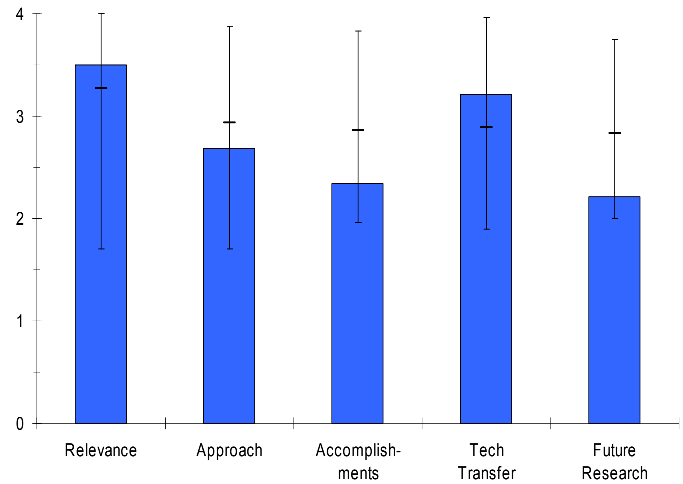
- Analysis of H_2 purity from H_2 pump, concentrating of polymer electrolyte membrane fuel cell poisoning species (H_2S, S-containing hydrocarbons, CO).
- Need economic analysis of the hydrogen production
- Provide date and evidence for integrated system testing; would have been nice to have done this in Alaska as originally planned.
- Include analysis for system integration parameters/strategy to show optimum overall system efficiency.
- Bloom should work more closely with researchers from Sandia National Laboratories and the National Renewable Energy Laboratory to include accurate representations of similar systems in these laboratories including environmental and financial models of hydrogen co-production.
- Slide 6 shows a water gas shift reactor orientated at the anode exhaust. While water gas shift reactors have been developed for use between a fuel reformer and the fuel cell stack (in polymer electrolyte membrane and phosphoric acid fuel cell systems), this change in orientation of the water gas shift may be expected to require additional research and development work. For example, water gas shift reactor catalysts tend to work well at relatively low temperatures (around 200°C). To better integrate a water gas shift reactor with a high temperature solid oxide fuel cell, it may be helpful to conduct additional research and development on higher temperature water gas shift reactor catalysts. Also, Bloom should investigate and show the results for the benefits/drawbacks of placing the water gas shift reactor 1) between the reformer and stack, or 2) after the stack's outlet at the anode exhaust.
- Bloom should report hydrogen generation efficiency as a function of hydrogen generation rate, hydrogen purity, and overall efficiency (electricity and hydrogen).
- If the system uses precious group metal (PGM) in the catalytic afterburner, it could be useful to investigate reducing reliance on PGMs in this component. The same holds for the electrochemical hydrogen separation.

Project # FC-12: Improved, Low-Cost, Durable Fuel Cell Membranes
James Goldbach; Arkema

Brief Summary of Project

The objectives of this project are to 1) develop a membrane capable of operating at 80°C at low relative humidity (25-50%); 2) develop a membrane capable of operating at temperatures up to 120°C and ultra-low relative humidity of inlet gases (<1.5 kPa); and 3) elucidate ionomer and membrane failure and degradation mechanisms via *ex situ* and *in situ* accelerated testing. Mitigation strategies will be developed for any identified degradation mechanism. Membrane formulation M41 was shown to have superior durability in accelerated *in situ* testing, and M41 membrane electrode assemblies met the target of 20,000 relative-humidity cycles.

Overall Project Score: 2.7 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Addresses relevant DOE goals.
- More durable, broad-operating-range membranes are critical to achieving DOE technical targets.
- Ultimate objective is development of high-temperature, low-relative humidity membranes.
- Quite relevant – new and alternative membranes are required to provide developers with options, as well as equal or better current materials properties.
- New membranes for drier proton conduction/higher durability are critical to President's Hydrogen Fuel Initiative.
- Polymer electrolytes are not the most significant barrier for fuel cell commercialization.

Question 2: Approach to performing the research and development

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

- Not clear what the strategy or approach is to obtain conductivity under low-relative humidity conditions. What other ionomers are they planning to use? Use of mixed sulfonic - phosphonic acids is one approach- what other ionomer approaches is Arkema using?
- The presentation gives the impression of empiricism and doesn't adequately discuss the rationale for the choice of polyelectrolytes.
- Good approach to develop new membrane materials tailored to high-temperature and low relative humidity.
- This reviewer rates it a "3", because more work needs to be focused only on the membrane. The electrode work is important yet secondary. Would like to see testing take place at the conditions being proposed by the effort and would like to see physical, mechanical, and chemical properties relevant to the fuel cell application, including surface chemistry for electrode interface and improvement development, and the cross-sectional microscopy analyses to determine if thinning due to chemical attack is happening at the inlet areas.
- Decouple proton conductivity from other membrane properties.
- Blend highly sulfonated hydrocarbon-based polyelectrolyte with Kynar.
- Investigating Kynar as a potential cheap/durable polymer is sensible for a company with poly (vinylidene fluoride) experience.
- The use of polymer blends brings up issues of phase stability over longer periods of time.

- Fuel cell testing has been too limited; *ex situ* tests are not addressing key issues of low conductivity particularly at low relative humidity.
- The approach presented to increase low-relative humidity conductivity is unclear in that information was not presented on chemistry or how the approaches planned to go forward would likely lead to increased conductivity.
- Incorporation of phosphonic acid as replacements to sulfonic acids is unlikely to lead to conductivity improvements.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.3** based on accomplishments.

- Mixed acid ionomers had poor conductivity and the sulfonated membrane had poor conductivity compared to Nafion.
- Steady and methodical progress is being made on several fronts – conductivity, mechanical properties, cell performance, and durability.
- Relatively new project – only 20% complete to date. Good start.
- Good performance for new material at higher relative humidity and normal temperature – need to emphasize extension to low relative humidity and 120°C.
- To date, M41 is another high water content sulfonic acid membrane. Reviewer would like to see fluoride release data. Open circuit voltage data is an electrode stability event more than a membrane issue.
- Separate membrane from electrode issues at this stage of the program.
- No apparent voltage vs. time data. It is clear the membrane is conductive; therefore a polarization curve should be a reflection of the electrode. Again focus on the membrane properties (permeability, stability, mechanicals, etc.).
- It is unclear how the conclusion is reached that M41 is a good platform for low-relative humidity membrane (slide 23).
- Improved mechanical strength versus Perfluorinated Sulfonic Acid (PFSA).
- Best conductivity 130 mS/cm at 70°C is only obtained in liquid water.
- Stability of 700 h with no sulfate/fluoride is not very long.
- Performance (membrane electrode assembly and conductivity) presented is below state-of-the-art Nafion. Conductivity is far below targets, and only minor improvements were found by processing differences between M41 and M43. No reason to believe significant improvements should be expected.
- Substitution of sulfonic acid sites with phosphonic acid sites only led to decreases in performance.
- No fuel cell lifetime data was presented. Open circuit voltage tests are function of crossover rates primarily and these are almost always lower in novel ionomers than in PFSAs.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.2** for technology transfer and collaboration.

- Work with partners at Virginia Tech and Oak Ridge National Laboratory should help define structure-property relationships.
- Excellent broad collaborations with universities, industry, and national labs.
- Arkema is leading a strong, well-balanced team with expertise in all areas needed to address project goals and objectives including *in situ* fuel cell performance testing.
- Appropriate teaming is in place.
- Interaction with industry, national labs and universities.
- Several high quality partners are involved in the project. The level of interaction was difficult to assess.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.2** for proposed future work.

- Plans for future are vague. It is not clear what the strategy is to obtain conductivity at low relative humidity; therefore, it is difficult to judge the potential for success.
- Unclear what class of electrolytes will be investigated.
- Vague description of work - how will you investigate structure property relationships? What will you vary, chemical structure of the ionomer or structure of the ionomer/ poly (vinylidene fluoride) blend while keeping the same ionomer as M41? (This would be unlikely to have desired conductivity at high temperature, low relative humidity. Are you varying both?)
- General approach is sound but specific information on candidate electrolytes is lacking.
- Good plan for continued effort addressing project objectives and DOE targets.
- More development and testing of membrane properties to guide further work.
- Improved scaffold.
- Use of phosphonic acid groups to retain water.
- Future directions presented did not include approach to increase low-relative humidity conductivity (information on chemistry or how the approaches planned to go forward would likely lead to increased conductivity).
- Little information has been given on processing conditions and how changes in processing conditions affect performance.
- Incorporation of phosphonic acid groups has only led to decreased performance.

Strengths and weaknesses

Strengths
- Team has people with the right experience and knowledge.
- Good approach and plans.
- Strong and knowledgeable team.
- Scaffold.
- Cheap/chemical resistant polymer systems could lower cost of fuel cell ionomers.

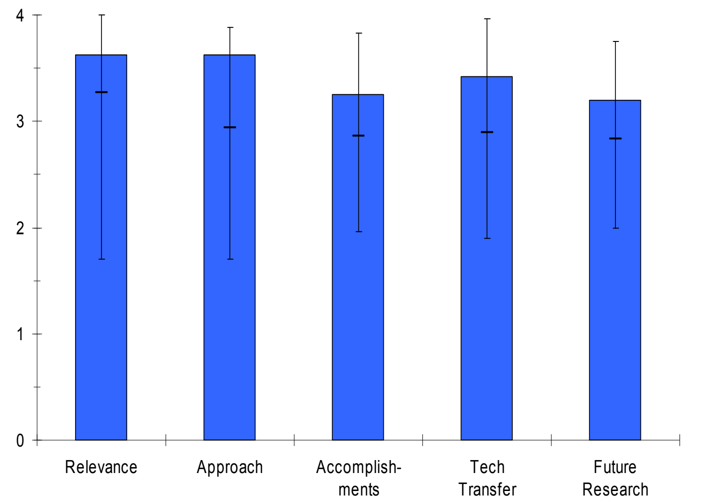
Weaknesses
- Plans are too vague and do not allow one to gauge the probability of success. Presentation must reveal more information - this can be done while still protecting intellectual property.
- Too dependent on conventional approaches.
- Behaves like a hydrocarbon ionomer, i.e., conductivity falls off rapidly with relative humidity.
- Phosphonic acid groups may not improve conductivity.
- Performance (membrane electrode assembly and conductivity) presented is below state-of-the-art Nafion. Conductivity is far below targets, and only minor improvements were found by processing differences between M41 and M43. There is no reason to believe significant improvements should be expected.
- The approach presented to increase low-relative humidity conductivity is unclear in that information was not presented on chemistry or how the approaches planned to go forward would likely lead to increased conductivity.
- Reviewer expected significantly more progress for a project funded at this level.

Specific recommendations and additions or deletions to the work scope

- Fuel cell testing needs to include H_2/air rather than H_2/O_2 in order to provide more useful performance data.
- Needs to focus on better polyelectrolytes.
- The strength here is the scaffold; team should look at PFSAs in the scaffold, not hydrocarbons of questionable value.
- Lifetime fuel cell testing (including cyclic testing) to better understand the stability of the polymer blend under operating conditions.

Project # FC-13: Membranes and MEAs for Dry, Hot Operating Conditions
Steven Hamrock; 3M

Overall Project Score: 3.4 (4 Reviews Received)



Brief Summary of Project

The objective of this project is to develop a new polymer electrolyte membrane with higher proton conductivity and improved durability under hotter and drier conditions compared to current membranes. 3M Fuel Cell Components is developing new membrane additives for both increased conductivity and improved stability/durability under dry conditions. Experimental and theoretical studies will be conducted of factors controlling proton transport both within the membrane and mechanisms of polymer degradation and membrane durability in a membrane electrode assembly.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Strong alignment with DOE barriers to performance and durability.
- The goal of developing a new polymer electrolyte membrane with higher proton conductivity and improved durability under hotter and drier conditions compared, to current membranes is of high relevance.
- The development of membranes capable of operating under a wide variety of conditions, especially under low relative humidity and higher temperatures will drastically improve system performance and lower system complexity and cost.
- Project addresses development of membranes that operate at higher temperatures and lower relative humidity which is consistent with automotive requirements.
- Project does not address membranes for stationary or backup power that may not require higher operating temperatures (no radiator size limitation).

Question 2: Approach to performing the research and development

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

- Good scientific rationale for polymer modification approaches.
- Good combination of experiment and theory.
- Good balance between exploring the fundamentals and demonstrating improvements.
- Excellent approach to evaluate broadly initially, with intent to combine the best of the approaches to achieve the final targets.
- A shotgun approach to improve conductivity and durability is proposed: new polymers, fluoropolymers, non-fluorinated polymers and composite/hybrid systems; new membrane additives; experimental and theoretical studies on proton transport and mechanisms of polymer degradation and membrane durability in a membrane electrode assembly; new membrane fabrication methods; and processes which are scalable to commercial volumes. Tests will be performed in conductivity cells, single fuel cells and short stacks using realistic automotive testing conditions and protocols. This approach appears to be overly ambitious and costly. The work should be redirected so that more milestones and go/no-go decision points eliminate unfruitful paths.

- The approach is extremely broad and should be focused to allow faster progress in what is deemed the approach with the highest probability of success. Focus on 3M's strength in low equivalent weight fluoropolymers; many promising approaches for improving the low-relative humidity conductivity of this material were presented.
- The project systematically addresses multiple approaches to resolving the technical issues associated with higher temperature and lower humidity operating conditions.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Project on schedule per milestones given in presentation.
- Initial materials results are promising for several approaches. Reasonable progress on the individual approaches.
- Difficult to fully assess progress at this point since still in highly exploratory stage. Progress at next Annual Merit Review & Peer Evaluation will be significant indicator of potential of this project to make a breakthrough since first promising materials sets should be identified by then.
- Good progress in developing and finalizing test conditions for materials testing.
- Project seems to be gaining momentum.
- It is well known that lower equivalent weight perfluorinated sulfonic acid (PFSA) ionomers improve the conductivity, but that their water solubility increases. Work to cross-link is proposed, but it is unclear whether the partners will contribute to this task. It is also unclear what ionomeric materials will be used in the catalyst layer. If the 3M nanocatalyst approach is used, how will the changes in the membrane's physical properties alter the performance of the catalyst? Will additives to the membrane alter the performance of the catalysts? Conductivity of membranes is reported as a function of temperature, not as a function of relative humidity at a fixed temperature. This form of graphical presentation does not make it clear if milestones are met.
- Considering the project is already 25% complete, there are too many tasks remaining in future work and not enough accomplishments.
- Good progress in meeting the interim room temperature conductivity target.
- The technical accomplishments are reasonable based on short period the project has operated.
- The data provided suggest that progress is being made and greater understanding of the composition of the membrane and fabrication of membranes has and will be obtained.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.4** for technology transfer and collaboration.

- Limited interaction between team members so far, but appears to be developing in most areas and specific areas of initiated collaboration identified. It is expected that these collaborations will evolve before next year's Annual Merit Review.
- While there are several partners in this program who are doing good work, it does not appear that the partners will provide a path for success. The presentation bounced around too much and treated the partners as separate projects.
- Good interaction with universities.
- 3M has established a strong team that provides a broad base of technology for membrane development.

Question 5: Approach to and relevance of proposed future research

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

- Not covered in presentation (ran out of time), so reviewer is dependent on slides on the compact disk to assess.
- Natural follow-on tasks proposed, and they are consistent with schedule presented.
- Will be telling at next Annual Merit Review whether collaborative projects are beginning to pay off and whether there is a combination of approaches that can be integrated to achieve the DOE targets.
- Better focus and a better path involving interaction from the partners to achieve success are required.
- Future work should be focused on the most promising areas rather than a "shotgun" approach.
- Most of effort is future effort.

Strengths and weaknesses

Strengths
- An outstanding team is assembled and many approaches are proposed to achieve success.
- Strength in low equivalent weight fluoropolymers and modifying properties of this material.
- 3M brings a combination of membrane understanding at a molecular level and membrane manufacturing.

Weaknesses
- A shotgun approach will not lead to success. It is not clear how the team members will be used to provide success.
- Approach is too broad.
- It was not clear how the program would address the water solubility of heteropoly acids.

Specific recommendations and additions or deletions to the work scope

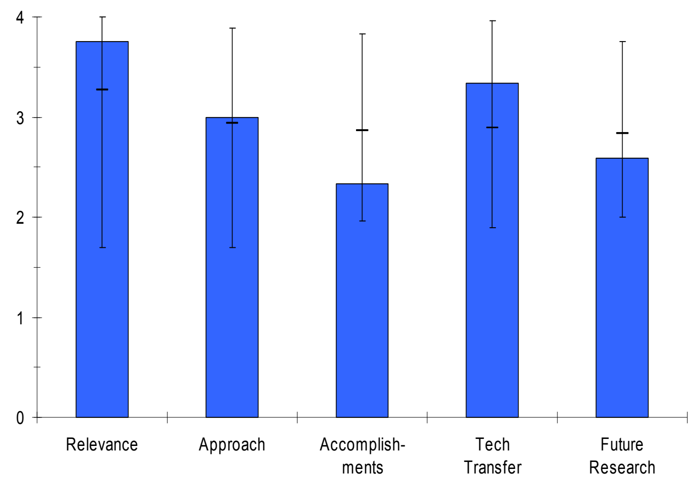
- Go/no-go decision points should be added to eliminate unsuccessful paths.
- Recommend deletion of scope of materials outside of the fluoropolymer approach.

Project # FC-14: New Polyelectrolyte Materials for High Temperature Fuel Cells
John Kerr; Lawrence Berkeley National Laboratory

Brief Summary of Project

The objectives of this project are to 1) investigate the feasibility of solid polyelectrolyte proton conductors that do not require water to achieve practical conductivities (0.1 S/cm at 120°C); 2) significantly simplify fuel cell systems (heat and water management and water rejection); and 3) provide car manufacturers with the knowledge of how to prepare the next generation materials. Proton-conducting materials will be prepared and tested based on heterocyclic bases (imidazole) and acids (sulfonates, sulfonylimides, phosphates). Solid polyelectrolytes will be prepared and tested where only the proton moves. Both solvent and acid groups will be tethered.

Overall Project Score: 2.9 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.8** for its relevance to DOE objectives.

- The project is relevant to the high-temperature membrane development requirement to meet overall DOE objectives.
- The goals and objectives of the project are designed satisfactorily.
- The multi-year plan is in line with DOE research and development objectives.
- Project outcome and learning are valuable for determining the degree to which current material can be modified or re-engineered to meet the goals. Quite relevant to the long term outcome of the effort, as membrane materials are one of the limiting components in this technology.
- The goal of developing a new polymer electrolyte membrane, with higher proton conductivity and improved durability under hotter and drier conditions compared to current membranes, is of high relevance.
- Developing a membrane that can conduct protons without water would be a significant step towards the commercial viability of fuel cells.
- Membranes for proton conduction under drier conditions are critical to President's Hydrogen Fuel Initiative.
- High-temperature polymer electrolyte membranes are needed for transportation applications (to facilitate thermal management) as well as for stationary applications (higher value heat in combined heat and power and/or CO-tolerance).
- Polymer electrolyte membranes that are highly proton conducting in the absence of water have the potential to significantly simplify polymer electrolyte membrane fuel cell systems.

Question 2: Approach to performing the research and development

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

- The project has been designed appropriately to address the technical barriers of low-relative humidity and achieving higher conductivity.
- The approach of the project is good and its outcome will address some of the key technical barriers.
- The technical feasibility of the synthetic route to an oxidatively stable ionomeric polymer is doubtful.
- The oxidative stability of the new polymer should have been considered.
- The modified backbone (slide #21) is expected to be oxidatively degradable under fuel cell operating conditions.

- Interesting approach – as the right questions are being asked and novel ionic groups are being evaluated yet the effort needs to focus on expanding such ionic species – yet it seems like modeling of selected ionic species might yield additional concepts.
- Performing relevant tests at the 120°C and desired relative humidity range, should be stressed, rather than just at room temperature.
- The magnitude of the storage modulus is critical, but why is the glass transition temperature from dynamic mechanical analysis data THAT critical?
- The older General Electric electrode work using hydrophobic electrodes should be investigated for its learning value.
- Preparing and testing proton-conducting materials based on heterocyclic bases (imidazole) and acids (sulfonates, sulfonylimides, phosphates) is not new. Tethering both the solvent and acid groups is new. Unfortunately, all the work presented was on material properties, and the tethering work did not appear until slide 16, and then it appears to be started mostly by the subcontractor Los Alamos National Laboratory.
- The approach of testing ionic liquid conductivity in solution is sound, but if solution phase conductivity is too low, the principal investigator should not spend time and resources making membranes with these ionic liquids.
- The principal investigator should not spend resources studying binders for electrodes until membrane conductivity target is proven.
- Blending ionic liquids with biphenyl sulfone H form should have lower priority than low equivalent weight PFSA/ionic liquid blends.
- Use heterocyclic bases.
- Tether groups to polymer backbone.
- Model anhydrous conduction.
- Control morphology.
- Good selection of materials for synthesis.
- Building on previous experience.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.3** based on accomplishments.

- Since the polymer is chemically modified PFSA material, the cost of the material will be much higher than existing PFSA material.
- The conductivity efficiencies of proposed new polyelectrolyte material are not known.
- If the new polyelectrolyte functions, as proposed by the team, then the benefit would be immense.
- The technical progress had been good and the development plan is satisfactory.
- The screening process has yielded valuable insight and will provide guidance for the next generation membranes.
- Lawrence Berkeley National Laboratory needs additional guidance and then they should perform testing, especially *ex situ* testing, to determine membrane properties.
- A reasonable amount of progress had occurred on characterizing the bases and acids, but little to no progress on the tethering of the materials to the membrane. The presentation highlighted the capabilities of the team members, but most of the work was done on other projects and not this project.
- Limited solution phase data does not show promise towards meeting 0.1 S/cm target.
- No data for membranes was presented.
- The project still has a long way to go to achieve goals.
- Team needs to be better integrated.
- More emphasis should be placed on the novel aspects of the project.
- The presentation showed an interesting comparison of different classes of ion-conducting materials.
- Optimized catalyst loading is too high.
- Complete test conditions, such as relative humidity, temperature, pressure, etc., should be provided for all test data.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.3** for technology transfer and collaboration.

- The project has good collaboration for the proposed development work.
- There has been good technical interface and information sharing among the concerned groups.
- The project has an industrial partner as well as another National Laboratory.
- Overall, the project possesses good teamwork.
- The technology transfer appears to be satisfactory at this time.
- The team members are assembled and the synthesis of materials is occurring, but little to no progress was made on the tethering of the materials to the membrane. Work on synthesis of new materials is of no value if the tethering work is not performed!
- Los Alamos National Laboratory focused on sulfonated polymers, which are of lesser value, rather than non-aqueous proton conducting polymers, which would be of greater value.
- Access to 3M low equivalent weight ionomers is beneficial.
- 3M, UCB, and Los Alamos National Laboratory are partners on this project.
- Good collaborations within National Lab system and with industry.

Question 5: Approach to and relevance of proposed future research

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

- The future research with imidazole end group modification of PFSA polymer will not provide a stable membrane.
- The siloxane modified route to new polyelectrolyte is not expected to give an oxidatively stable polyelectrolyte.
- The reviewer questions whether the current effort will yield results and recommends expanding the species or the approach to determine if other ionic species might yield results.
- Tethering of the materials to the membrane must occur. It is not clear that task this will be performed.
- Principal investigator did not clearly describe the primary path to meet near-term or 2015 DOE conductivity targets.
- The future research plan is well thought out.
- Date and criteria of go/no-go decision are not clear.

Strengths and weaknesses

Strengths
- Good group with solid knowledge base of fuel cell fundamentals.
- Good interaction between the collaborative groups.
- Good fundamental approach in understanding the major technical barriers of low-relative humidity proton conductivity.
- Solid team.
- Facilities are appropriate.
- Novel ideas generated for tethering ionic liquids to conductive polymers.
- Very strong team.
- Novel approach with potentially high return.
- The team has significant polymer synthesis expertise.

Weaknesses
- No measures have been in place to evaluate the oxidative stability of proposed electrolyte materials.
- The new polyelectrolyte material may be interesting to study, but it is not expected to give long-term stability under fuel cell conditions.
- Difficult to tell how the electrode development should proceed when the membrane and subsequent membrane properties are moving targets at this stage of the program. Focus on the membrane first, then the electrode.
- Lack of progress.

- No clear direction for meeting targets.
- Modeling efforts focus on system and cell performance rather than conduction mechanism.
- Fundamental model does not show proof of concept.
- Lack of team integration.
- Non-Nafion binder requires significant improvement to reach Nafion's performance levels.

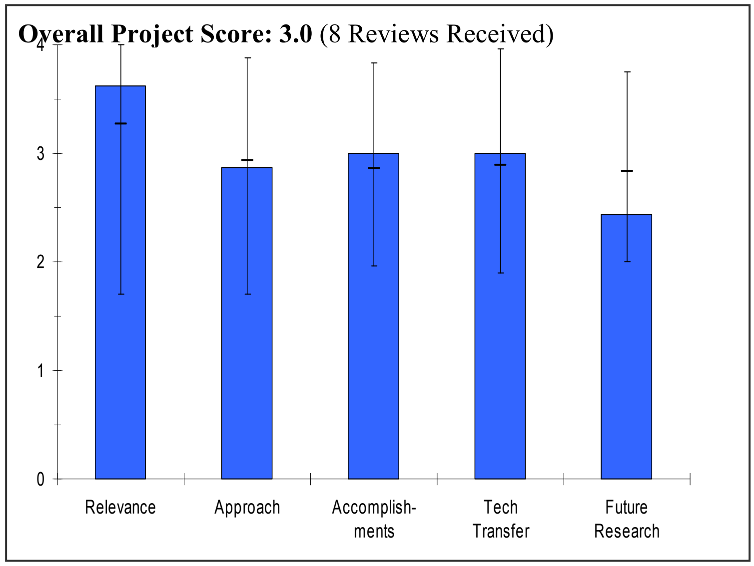
Specific recommendations and additions or deletions to the work scope

- The principal investigator should consider evaluating the oxidative stability of any new polyelectrolyte material.
- The backbone change to manipulate the polymer morphology should be reconsidered and the approach should be changed to synthesize an oxidatively stable polyelectrolyte.
- Discontinue all new synthesis work and focus on the tethering of the ionic liquids to the membrane.
- Eliminate electrode binder work.
- Eliminate cell performance modeling.
- Concentrate more on the fundamentals at this point.
- Deemphasize PFSA.

Project # FC-15: Lead Research and Development Activity for DOE's High Temperature, Low Relative Humidity Membrane Program
James Fenton; U of Central Florida

Brief Summary of Project

The objectives of this project are to 1) investigate new polymeric electrolyte/phosphotungstic acid membranes; 2) develop standardized characterization methodologies, including conductivity, mechanical, mass transport and surface properties of membranes; 3) provide High-Temperature Membrane Working Group members with standardized methodologies; and 4) organize High-Temperature Membrane Working Group biannual meetings. Fuel cell performance will be evaluated and the durability of membranes will be predicted. Membrane electrode assemblies will be fabricated from other high-temperature, low-relative-humidity membrane programs.



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Addresses DOE targets for membranes and is aligned with DOE goals and objectives.
- A coordinated effort to develop fuel cell membranes for operation at elevated temperatures.
- The project is relevant to the Hydrogen Fuel Initiative.
- The goal and objectives fit well with Multi-Year RD&D Plan.
- The focus of the project is aligned with the need of good measurement system and a reliable membrane electrode assembly test protocol.
- Project addresses the development of new membrane materials for polymer electrolyte membrane fuel cells that provide higher conductivity at high temperature and low relative humidity and also have good durability.
- Membranes with improved conductivity at lower relative humidity are important to achieving DOE objectives. Having conductivity as the primary initial focus is a benefit.
- It is imperative to develop a common test protocol and criteria to conduct and screen numbers of technical approaches.
- Addresses DOE targets for membranes and is aligned with DOE goals and objectives.
- This project both leads and participates in the DOE's thrust to develop new and improved fuel cell membranes. This activity has been identified by the Department as a relevant activity.

Question 2: Approach to performing the research and development

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

- Approach as lead of the High-Temperature Membrane Working Group / testing center is addressing the right barriers.
- Membrane durability/degradation testing should use already developed protocols and not develop new protocols.
- Approach for improving membranes is not described well. Not clear what they plan to do to improve their current membranes.
- Effectively addressing the challenge of membrane conductivity and durability at 120°C.

- The approach to the project is good and phosphotungsticacid is well known to have good impact on membrane conductivity.
- The approach is technically feasible and it will address the low-relative humidity proton conductivity issues.
- The testing method development is well integrated with other research groups.
- Project has a bi-directional approach to development of membrane materials (PFSA- phosphotungsticacid and sulfonated poly(ether ether keytone)- phosphotungsticacid. These are alternative materials to Nafion 212 which will not meet desired high-temperature requirements.
- Also has a team approach to characterize membrane electrode assembly performance and standardize testing.
- Eleven team members.
- Sound scientific approach; however, testing protocols that are being developed may not apply to all classes of materials, in particular those that swell or require more equilibration.
- The principal investigator should work with partners on a more individualized basis. These new materials will have very different properties, and it is important to evaluate their potential of meeting DOE targets once they are optimized. This may require a more individualized testing regime done in closer collaboration with each individual partner. This is more work for the principal investigator, but it is important so that promising materials are not overlooked.
- The principal investigator should work with the membrane providers in some cases to assess why certain samples either did not meet the target milestones or did not give the same results as when tested by the membrane providers.
- Proton conductivity is a direct measure but it depends on thickness, which should be determined by other factors, such as hydrogen permeability and membrane electrode assembly durability.
- A normalized process is necessary to compare proton conductivity.
- The activity is structured in a way that this principal investigator both supervises a number of principal investigators that are working competitively, and works on one of those competitive activities.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Have met DOE milestone for relative humidity conductivity.
- Have increased conductivity 50% over Nafion 212 at 120°C, 50% relative humidity.
- Have developed conductivity testing protocols for in-plane and thru-plane conductivity.
- Have completed testing of samples submitted by the other members of the High-Temperature Membrane Working Group.
- Effectively developing standardized test procedures. Individual members are making significant progress in new membrane material discovery.
- Good technical progress has been made so far.
- The cost of the new membrane (Florida Solar Energy Center samples) fabricated by the workgroups is not known.
- It will be nice to know the cost of the new membrane material.
- The benefit of Florida Solar Energy Center samples in low-relative humidity, low-temperature regime is clear. More development is needed for its application in high-temperature, low-relative humidity region.
- Materials from all team members tested at 30, 80, and 120°C.
- Promising new materials Florida Solar Energy Center -3 investigated with better conductivity than Nafion.
- Materials showing much lower fluoride emission rates and better durability than Nafion demonstrated.
- Manufactured membrane electrode assemblies from new Florida Solar Energy Center membrane materials.
- The samples prepared by the principal investigator show good conductivity.
- Simple comparison on proton conductivity is not apples-to-apples. It should be normalized by thickness and other factors.
- Targets for low relative humidity and for high conductivity not met.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.0** for technology transfer and collaboration.

- Have had good collaborations within the High-Temperature Membrane Working Group.
- Could have better coordination with groups which have already developed or are developing durability test protocols such as the US Fuel Cell Council (USFCC).
- Extensive collaborations among the High-Temperature Membrane Working Group participants with support from several independent testing organizations.
- The team is the lead for High-Temperature Membrane Working Group and they are working on the project with many Universities and Industry.
- The project evaluates membrane samples from other industry/institute and universities.
- The team has good network among the lead Fuel Cell research organizations.
- Eleven team members, including industry but not industry that could be involved in commercialization.
- Very interactive in area of development of standardized testing protocols; has web-based interactive service.
- Good interaction with BekkTech and Scribner.
- The program would benefit with a closer, collaborative relationship with membrane providers, not just "screening" membranes. Lead the team technically; don't just test their membranes.
- It is necessary to leverage inputs from membrane electrode assembly research to normalize proton conductivity.
- Have had good collaborations within the High-Temperature Membrane Working Group.
- Collaborations listed are with vendors, which don't count.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.4** for proposed future work.

- Plans for improving conductivity of their current membranes are not clear. Path to achieving 120°C target is not apparent.
- Plans for 8-cell durability test station are good and will allow for durability testing of High-Temperature Membrane Working Group members samples more rapidly and uniformly.
- Plans to use Nafion as catalyst layer ionomer in high-temperature membrane electrode assembly, when Nafion will not perform under the high-temperature, low-relative humidity conditions is questionable - limits of ionomer in the catalyst layer will limit membrane electrode assembly performance and not allow a true measure of the performance of the new membranes in the membrane electrode assembly under high temperature, low-relative humidity conditions.
- Plans for continued high-temperature membrane development are reasonable.
- The proposed research is too broad.
- More details should have been given on the future work plans.
- Focus on the role of particle size and casting procedures in order to improve performance.
- Focus on underlying mechanisms for mechanical decay.
- Not explicitly described in presentation.
- The future research proposed is a list of milestones. How will these be achieved?
- It is good to look at durability and mechanical degradation. However, it is necessary to identify the quality metric (measure) to evaluate membrane durability.
- Test protocols should be verified with Gage R&R (repeatability and reproducibility).

Strengths and weaknesses

Strengths
- Testing and involvement of BekkTech and Scribner.
- Good collaboration with different workgroups which will help in obtaining many samples.
- The team has good expertise in conductivity measurements and membrane fabrication.
- The team has extensive knowledge of fuel cell membranes.

- Good correlation method for determining cell performance with membrane conductivity and electrochemically active surface area has been established.
- Good team participation.
- Good go/no-go milestone on materials in Q3 for conductivity - 0.1 S/cm, 50% relative humidity, 120°C.
- Provides good intercomparison between materials from the various team members.
- Good combined synthesis and measurement capability.
- The focus on improving membrane conductivity is a benefit to the program.
- The collaboration with BekkTech and Scribner provides a strong team.
- Testing and involvement of BekkTech and Scribner.
- A testing protocol (using a commercial apparatus) has been scripted that will result in more reliable evaluation of conductivity. Studies in polymer degradation mechanisms are necessary and useful.

Weaknesses

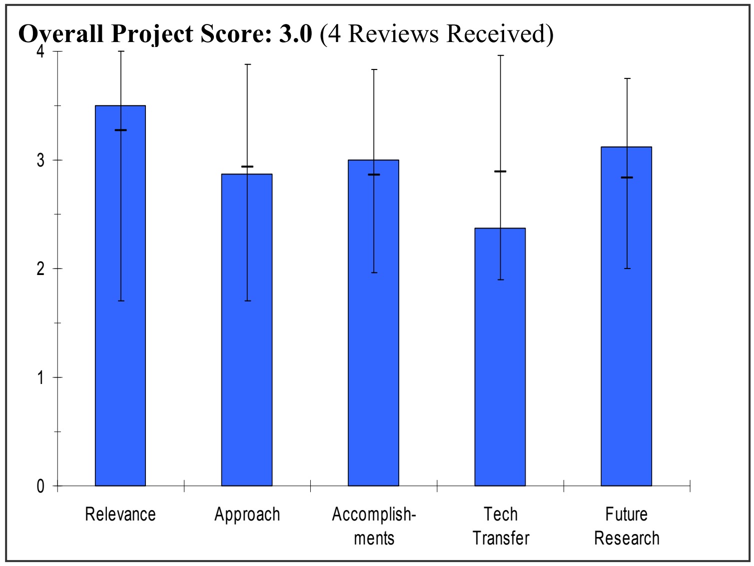
- Interaction with USFCC groups working on durability protocols appears to be lacking.
- Needs to work on different membrane fabrications methods.
- Beside phosphotungsticacid, the team should develop other ideas for making high-temperature membrane.
- Testing protocols may not have universal applicability.
- No industry involvement that could provide direction in terms of ultimate manufacturing potential.
- More collaboration between the principal investigator and the membrane providing partners will benefit this program.
- The part of this project focused on leading the team and the part of this project focused on developing a new membrane should be presented separately.
- Communication with membrane electrode assembly research teams.
- No mention of reproducibility and uniformity of test polymers samples and characterization measurements.

Specific recommendations and additions or deletions to the work scope

- Must resolve disagreement among participants regarding standardized conductivity measurement.
- The project is on right course and nothing should be deleted.
- Team should start developing more ideas on how to make high-temperature membranes.
- Downplay the development of standardize testing protocols because they may not apply to all materials. Use these only internally for team members. If want to widely disseminate, then DOE must become involved in arbitration/or establishment of a committee to examine the protocols developed.
- Incorporate longer term testing as milestone go/no-go.
- Increase emphasis on understanding mechanism for mechanical decay and develop more solid plan for using this information in follow-on studies.
- There is need to settle the controversy about the validity of the conductivity test protocol document. In addition to the measurement of polymer protonic conductivity, all other evaluation measurements that characterize polymer performance need to have similar proscribed testing protocols. This includes polymer synthesis and subsequent workup. There also needs to be discipline in statistical analysis of testing results that illustrates the reproducibility of the testing and evaluation efforts.

Project # FC-16: Advanced Materials for Proton Exchange Membranes
James McGrath; Virginia Tech

Brief Summary of Project



The objectives of this project are to 1) design, identify, and develop the knowledge base to enable polymer electrolyte membrane films and related materials to be utilized in fuel cell applications, particularly for H_2/air systems at 100-120°C and low relative humidity; 2) develop nanophase separated hydrophilic-hydrophobic thermally stable multi-block copolymers; 3) correlate water diffusion coefficients with proton conductivity under partially hydrated conditions; and 4) relate thermodynamics of nanophase formation to ordered morphology and to conductivity, diffusivity, and novel membrane self assembly.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Addresses membrane development only, and at the level of new materials synthesis primarily. This is important but therefore limited in its ability to address multiple DOE objectives.
- The objectives of this project are consistent with the Hydrogen Fuel Initiative.
- This membrane development effort clearly addresses the DOE research and development objectives.
- Very relevant work that demonstrates the importance of all aspects of making membranes from scratch all the way to manufacturing methods.
- Perhaps the large emphasis on manufacturing is not so appropriate at this stage and possibly is more suited for the DOE Manufacturing efforts so that more resources are available for the fundamental work.
- It is not clear to this reviewer how these materials could reach a conductivity of 0.1 S/cm at 120°C. The conductivity mechanism is still dependent upon water.

Question 2: Approach to performing the research and development

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

- Appears to be a potentially effective approach to improve membrane conductivity and cost. It may therefore impact one or more barriers.
- Tailoring morphology to optimizing membrane performance and durability is a very sound approach.
- It is not clear that this approach will enable achievement of 2015 DOE conductivity target.
- More effort should be given to addressing the stability and durability characteristics of these materials.
- The morphology control provided by this block co-polymer approach is an excellent tool in meeting the DOE objectives. The principal investigator is doing an excellent job here.
- The project is well-designed, particularly feasible within its goals and integrated. However, there seems to be no effort at all to reach the high-temperature goal. There is no effort to find a different mechanism of solvation or charge transport. This is a significant weakness that undermines the value of all the fine work that is done. This reviewer is concerned that all the work will finish by producing another Nafion-like material with the same limitations.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Recently achieved values of conductivity the principal investigator reported are very promising. Progress on film casting is also very promising to allow correlation of the end material properties with the processing conditions as well as the material properties.
- Limited progress shown since last year's review towards meeting DOE targets.
- Demonstration of continuous casting process is promising.
- Utilization of hexaflluorobenzene linkage group may enable synthesis of polymers with superior properties.
- Benefit of hydroquinone-based hydrophilic oligomers has potential, but still unproven.
- Increasing conductivity and controlling swelling through changing block sizes is an important result.
- Progress towards the 120°C goal is not evident. This is the only, albeit large, weakness.
- The technical accomplishments and progress are terrific. All areas attempted are carried out admirably and the results are extremely valuable. The development of membrane synthesis methods, morphology control and processing methods are very valuable for the DOE program and can be adapted to provide membranes that do not depend on water for conduction.
- The swelling issues are worrying. Cross-linking can help with this but the curing has to be totally uniform else there will be non-uniform current distributions that will accelerate failure.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.4** for technology transfer and collaboration.

- The interactions are fairly limited to the principal investigator's institution. But this is not inappropriate for the nature and status of the project at this time.
- Good collaboration with Giner on data verification.
- Roll of industrial partners (Nissan, Arkema) is unclear.
- The membrane casting work should be done in collaboration with and industrial partner.
- The disagreements with Florida Solar Energy Center contractors over measurement methods should have been resolved privately. This indicates a lack of communication that is disturbing.

Question 5: Approach to and relevance of proposed future research

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

- Increased emphasis on the film casting is good as it will bring in another dimension to the effort to develop a new membrane material.
- Future research plans should include relative humidity cycling testing to verify mechanical benefit of multi-block structures.
- Polymer synthesis and characterization plans are sound.
- Understanding the chemical stability of these polymers should be a focus.
- Non-open circuit voltage lifetime tests in fuel cells should be performed.
- Future plans have no provision for reaching the 120°C goal.
- Plans are continuation of what has gone before without much attempt to be really radical.

Strengths and weaknesses

Strengths
- Knowledge and experience of the principal investigator with these materials.
- Principal investigator has excellent polymer synthesis and processing capabilities.
- Approach has proven that controlled polymer morphology leads to improved conductivity.
- Techniques are proven to enable tailoring of membrane dimensional stability.

- Excellent focus on understanding structure property relationships related to conductivity.
- Very strong on synthesis, morphology, and membrane processing.

Weaknesses

- Approach may not be sufficient to achieve DOE performance targets.
- It should be made clearer how the membrane casting work contributes to meeting the objectives of the program. Is the relationship between casting methods or conditions and performance or durability being evaluated? If not, the principal investigator should identify the chemistry and morphology needed to meet the DOE objectives before looking at scale-up.
- No attempt to eliminate water problems and find 120°C solution. This approach will not solve the problems for the fuel cell vehicles. There is a need to collaborate with the more unconventional projects that are trying to replace the water.

Specific recommendations and additions or deletions to the work scope

- The principal investigators may want to consult a membrane manufacturing company for input on any constraints to solvents allowable in some industrial film processing plants.
- Principal investigator should conduct relative humidity cycling of most promising membranes.

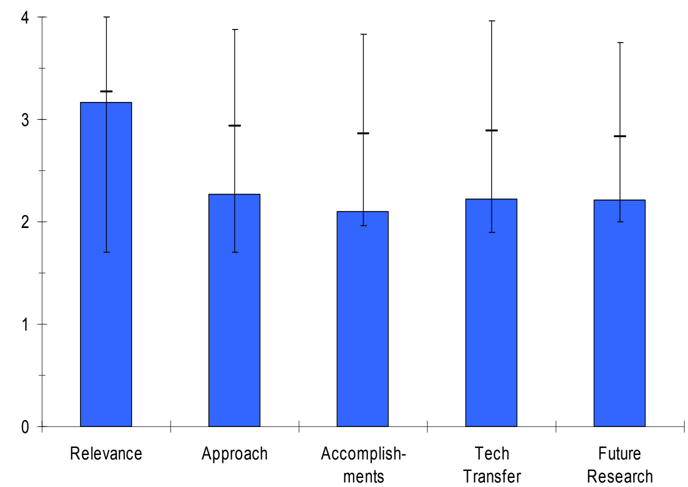
Project # FC-17: Protic Salt Polymer Membranes: High-Temperature Water-Free Proton-Conducting Membranes

Dominic Gervasio; Arizona State

Brief Summary of Project

The objective of this project is to make proton-conducting solid polymer electrolyte membrane materials having 1) high proton conductivity at high temperature (up to 120°C); 2) effectively no co-transport of molecular species with protons; 3) reduction of fuel cell overvoltage; and 4) good mechanical strength and chemical stability. Polymer electrolyte membranes are being made based on "solvent-free" protic ionic liquid concepts, which can be used to model membranes (stability, conductivity) and to act as plasticizers in membranes. Acid and base moieties and polymers are varied to optimize properties in two kinds of polymer electrolyte membranes. Proton conductivity will be characterized by electrochemical impedance spectroscopy from -20 to 120°C.

Overall Project Score: 2.4 (9 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.2** for its relevance to DOE objectives.

- The objectives of this project are consistent with the President's Hydrogen Fuel Initiative.
- This membrane development effort addresses the DOE research and development objectives.
- Proton conductivity with no dependence on co-transport of molecular species is leading to dry operation membrane.
- This technology would be an enabler to make balance-of-plant less complex and imperative to achieve system cost target.
- Polymer electrolytes are not the most significant barrier for fuel cell commercialization.
- The project supports the President's Hydrogen Fuel Initiative.
- This project is part of the DOE's hydrogen fuel cell technology thrust, working to develop new materials for polymer electrolyte membranes. Membranes for this purpose have been identified as a relevant topic.
- This is an important area for DOE investment.
- This project has significant flaws that impact its relevance. These are not proton conductors.

Question 2: Approach to performing the research and development

This project was rated **2.3** on its approach.

- Novel approach, focus should shift more to immobilized ionic liquids rather than ionic liquid filled membranes.
- Potential for truly water-free protonic conduction.
- Ionic liquids have fundamental potential to conduct protons without water.
- Significant effort wasted on fuel cell testing of unstable membranes.
- Conductivity of base ionic liquid solutions lower than DOE target – questions whether membranes would ever meet targets.
- Significant efforts wasted on electrode development when membrane performance not yet proven.
- It needs to be demonstrated that the conductivity measured in proton conductivity.

- The polymers shown are aliphatic hydrocarbons. These are known to not survive under fuel cell operating conditions.
- It needs to be demonstrated that the ionic liquids are stable at the electrodes.
- Taking a novel approach (protic ionic liquid concept) which shows good progress for proton conductivity.
- The investigation of protic ionic liquids for proton transport has interesting fundamental aspects for non-aqueous conduction of protons; however it is very unlikely to yield materials suitable for broad commercial applications.
- Conductivities reported, essentially salt solutions, are only marginally more interesting than acid solutions. The typical approach looks like it is replacing protons with ammonium ions that almost certainly act as proton shuttles. This often happens in ammonia-poisoned fuel cells and significantly lowers performance.
- The approach is to form ionic liquids, formed from pure acid-base pairs that could serve as a membrane for fuel cells. This idea depends on finding two suitable compounds, which when mixed, will form an aggregate that results in fast proton transport. This appears difficult because most useful materials are those which are strong acids, and such aggregates just cannot be strong acids. This approach does not seem promising.
- The approach has serious shortcomings. The 'salts' are not proton conductors.
- Conductivity measured does not reflect proton conductivity.
- The project is supposed to focus on membranes but barriers given are for 'Electrode Performance'.
- Creative approach but they really need to get to proton conductivity.
- The project seems doomed to study anomalies in systems that are not viable fuel cell electrolytes because of lack of free protons.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.1** based on accomplishments.

- The membrane electrode assemblies with these membranes have low open circuit voltage and have only achieved fairly low current densities.
- Membranes with non-leachable protic ionic liquid have not been obtained (one example given was unstable and water soluble).
- This is a new area and progress from the starting point has been good, but a long ways to go to catch up to established membranes and longer to meet DOE membrane targets.
- Have achieved conductivity close to the milestone, but with a membrane with leachable ionomer.
- Non-leachable protic salt membranes synthesized.
- Fuel cell tests done, but results are very, very poor.
- The fuel cell performance is very poor. The principal investigator should use conductivity or hydrogen pump measurements to help explain this.
- The principal investigator suggested that Pt oxide will not be formed because this is a "non-aqueous electrolyte". Water is still present, so why is this? What data suggests this?
- Good progress on proton conductivity, however, fuel cell performance is too low.
- It is making sense to focus on gas permeation due to lower open circuit voltage. It is still necessary to explain low current density performance.
- Membrane resistance (*in situ*) is highly temperature-dependent. It may indicate that proton conductivity of this membrane still depends on water transport.
- Further investigation is necessary.
- The researchers have made ionic liquids, put them in membranes, and characterized them using electrochemical and fuel cell testing.
- Fuel cell performance and resistance measured in cells is extremely low and is only presented with liquid electrolytes; acid solutions in the same environment would have given better performance. Immobilizing the ammonia in the membrane resulted in lower performance.
- A path towards useful materials was not shown and would not be expected based on the results presented.
- Results disappointed. The aggregates were only conductive in the presence of water.
- There is no unambiguous evidence that these are proton conductors. Ammonium ions will simply not be a reasonable proton source.

- Electrochemical nuclear magnetic resonance (NMR): the principal investigator carried out Electrophoretic NMR. Electrochemical NMR is different.
- The imidazole-containing polymers provide a possible path forward.
- The polarization curves tell the story: there is little fuel cell activity before a large drop in voltage.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.2** for technology transfer and collaboration.

- Only coordination was with Akron for polymer synthesis.
- This project would benefit from collaboration with someone having more fuel cell experience (Los Alamos National Laboratory?) to clarify the viability of this approach.
- Some collaboration.
- Part of the High-Temperature Membrane Working Group. Samples have been transferred for testing.
- This is not ready for transfer.
- Not responsive to FreedomCAR Fuel Cell Technology Team recommendations.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.2** for proposed future work.

- A large portion of future work focused on leachable protic ionic liquid membranes, not what this project should be directed at.
- Other planned work to look at electrode interactions, while relevant, is really outside the scope of membrane development.
- Working with hpolyphosppazenes is only specific idea for new chemistry approach, but benefit is unclear.
- The principal investigator needs to clarify his plan for moving to materials that have the chemical and oxidative stability for use in a fuel cell.
- It is necessary to pursue further investigation of low fuel cell performance with current materials.
- Proposed research focuses on understanding the system better, but not how conductivity and fuel cell performance can be improved by some systematic approach. Using ammonia as a proton shuttle is unlikely to be stable or lead to improvements over current systems.
- The principal investigator suggested a change in direction, moving to a classical polymer structure that would imbibe the protic liquids.
- A rather significant change in direction is suggested--shifting to an imidazole on a polymer.
- Project seems like it will end up focusing efforts on understanding spurious phenomena unlikely to lead to promising materials.

Strengths and weaknesses

Strengths
- Novel idea.
- Potential for water-free conduction over the desired temperature range.
- Protic salts are a unique approach to non-aqueous proton conduction.
- There is value in studying new proton-conducting materials with different conduction pathways.
- Leverage NMR for analysis.
- Creative approach, with lots of synthetic input.

Weaknesses
- Not focused on membranes that would be applicable for the automotive application DOE is targeting.
- Unclear from data if principal investigator is measuring proton or salt cation (ammonium) conduction.
- Principal investigator spends too much time on membrane electrode assembly testing of unstable materials with low conductivity.
- More work should be done understanding the stability of these materials.

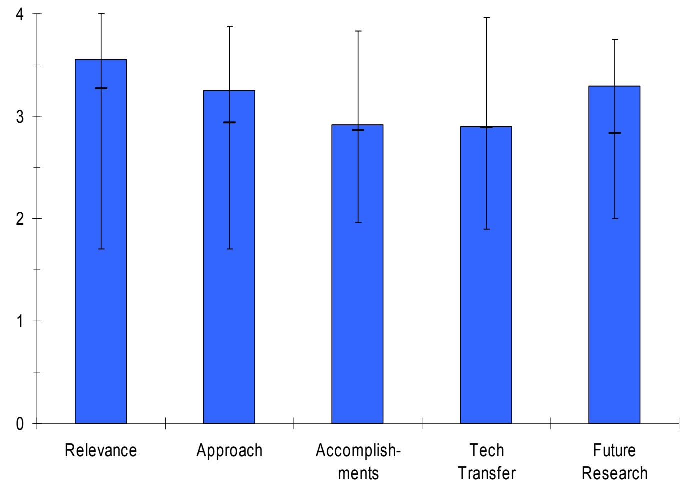
- Show that conductivity is due to proton transport.
- Interaction with collaborators.
- Ammonium ionin fuel cells "reacts" (ammonia/ammonia+proton dynamics are complicated) at the cathode and has the ability to liberate the ammonia. Ammonium ion is likely an order of magnitude slower than protons; hence the large resistance in fuel cells shown. Performance of these materials is abysmal and will only get worse with tethering of functional components.
- Flawed approach: difficult to see that proton conduction will be significant.
- Presenter constantly referred to results shown at Electrochemical Society meeting (3 weeks earlier) that were 'not available' for presentation. It seems unlikely that several significant results emerged in the space of a few weeks.
- Polymer-bound imidazole approach has already been shown to be insufficient due to lack of mobility.

Specific recommendations and additions or deletions to the work scope

- Focus on making unleachable membranes and measuring proton conductivity.
- This project needs to be restructured, perhaps with a change in scope.

Project # FC-18: Fluoroalkyl-phosphonic-acid-based Proton Conductors
Stephen Creager; Clemson

Overall Project Score: 3.1 (5 Reviews Received)



Brief Summary of Project

The objectives of this project are to 1) synthesize and characterize new proton-conducting electrolytes based on fluoroalkylphosphonic acid functional group; and 2) perform a simulation study of structure and proton conduction in fluoroalkylphosphonic acid-based electrolytes. Tasks were to 1) synthesize and/or purify at least 5 g each of one or more trifluorovinyl-ether (TFVE) fluoroalkylphosphonic acid monomers; 2) complete development and validation of classical force fields for fluoroalkylphosphonic and fluoroalkyl-bis-phosphonic acids and perform MD simulations of these acids as a function of fluoroalkyl chain length; 3) perform density function theory-based Born Oppenheimer Molecular Dynamics simulations; and 4) complete synthesis of TFVE and development and validation of models. Year 2 milestones include testing the membrane for electrolyte conductivity of 0.07 S/cm at 80% RH at ambient temperature and delivering a sample membrane to the Topic 2 Contractor for evaluation.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Durability, cost and performance improvements of membranes are all highly necessary for fuel cell commercialization.
- Project addresses cost, durability, and performance goals in the development of new membrane materials for polymer electrolyte membrane fuel cells. Relative to the standard of Nafion materials, these new materials must provide higher conductivity at high temperature and low relative humidity and also have better durability.
- Good studies of model compounds and modeling of proton transport that addresses the DOE needs to come up with new mechanisms of proton transport.
- Project focus appears to be diverted by better results with water present which is resulting in the development of another Nafion-like material with the same limitations. The amphotericity of the phosphonic and phosphinic acids are the interesting property (Kreuer) and this aspect is not receiving adequate attention.
- Seeks to develop high-temperature membranes with good conductivity at low relative humidity – key DOE goal.
- This is an important area for DOE investment.

Question 2: Approach to performing the research and development

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

- Fundamental look at performance limitations with model compounds and modeling is strong.
- Phosphonated "Nafion" like material has the potential to be a good learning experience but ultimately will not be the goal.
- Project seeks to synthesize and characterize new proton-conducting electrolytes based on the fluoroalkylphosphonic acid functional group. Computational chemistry used to understand order and mechanisms and improve molecular design.
- Excellent end-to-end plan including small molecule analysis, synthesis, characterization, theory/computational method.
- Targets of membrane conductivity greater than 0.1 S/cm at 120° C and water partial pressure of 1.5 kPa.

- Starts from a small molecule approach.
- Logical project plan at least at start.
- The approach of using model compounds combined with modeling in order to guide the polymer synthesis is excellent.
- The project is losing focus due to better results in the presence of water. Should focus on how to get high conductivity with little or no water. This is the barrier that needs to be addressed.
- Methodical approach going from model compounds to ionomers.
- Good balance between theory and experiment.
- Well-organized, comprehensive team.
- Model compounds studies are very revealing.
- Not clear how polymerization will improve the shortcomings revealed by model compound studies.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.9** based on accomplishments.

- Model compound work is high.
- Synthetic approach and results are impressive – characterization of membrane however is weak.
- Computer modeling results are highly interesting and may be of value.
- Quantitative correlation made between acid:water ratios and conductivity; more water up to 1:20 yields higher conductivity for monomers.
- Good study of monomers. Increased fluorocarbon character shows decreased conductivity because lower volume of acid in condensed phase to conduct protons.
- Synthesis of membranes by casting of ionomers.
- Have begun to understand the relationship between number of waters needed to deprotonate the acid group.
- Good progress and accomplishments in model compound studies, modeling and polymer synthesis.
- Needs to consider how to obtain high conductivity without water.
- Good Progress.
- Membranes fall short of milestone but do hold promise.
- Need to get membrane preparation optimized.
- Good definition of 'limits' of approach via model compound study.
- What water content is acceptable for conductivity measurements?
- It is unfortunate for these researchers that they have taken a more basic approach, synthesizing membranes from scratch, as opposed to others who focus on processing existing materials.
- It is important to follow through completely with this project in spite of a somewhat slower 'delivery rate' caused by the high degree of difficulty of getting the synthesis and processing right.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.9** for technology transfer and collaboration.

- Excellent collaboration between Clemson and University of Utah (UT) is evident.
- Possibility to include industrial partner in the future may speed up/focus development.
- All academic involvement; industry only involved in measurement.
- Very good experimental/theory coordination.
- Strong theory effort done at Utah.
- Co-ordination between the two partner institutions is good but need to be talking with Kreuer and others much more.
- Need to collaborate with others to eliminate the water.
- Good integration with modeling effort.
- Appropriate samples have been sent out, in spite of the workers being at a self-professed early stage.

Question 5: Approach to and relevance of proposed future research

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

- Future work is in the right direction.
- Research on phosphonated, short-side chain, low equivalent weight, and reinforced membrane should be highest priority to achieve state-of-the-art status; otherwise it will just be an academic exercise.
- Concentrate on processing to keep ionomers fully protonated. Need to make sure that the principal investigators use proper annealing procedures and get all cations out to evaluate how the new materials compare to Nafion.
- Focus on understanding barriers to proton transport in membrane structures to improve conductivity. Model domain structures.
- The future plans do look as if the project may well refocus on non-water mechanisms of proton transport. The plans look reasonable for this.
- Recommend that the project be more explicit about looking for non-water based conduction.
- Going to lower equivalent weight is a good idea.
- Why is durability not addressed?
- A clear path forward exists.
- Processing these materials will take much effort.

Strengths and weaknesses

Strengths
- Chemical synthesis.
- Computer modeling.
- Excellent experimental/theory coordination.
- Well-defined targets.
- Use of model compounds, modeling and strong synthesis is well-balanced and very appropriate.
- Strong team.
- Good integration between modeling and experiment.
- Methodical approach.
- Organized and systematic.
- Excellent theorist involved.
- Truly unique materials.

Weaknesses
- Lack of industrial partner may lead principal investigators down non-fruitful pathways.
- Lack of deep understanding on why water is still needed even in a phosphonic acid polyelectrolyte.
- Lack of thorough membrane characterization.
- No real industry involvement.
- Must avoid looking too much like an Office of Science project, although clear value in doing theory in project.
- Project is being derailed by trying to meet milestones using water. This should not divert attention from the need to come up with non-water conduction mechanisms.
- Durability aspect is lacking.
- May be prone to the same durability issues as PFSAs.
- Slow progress due to high difficulty.

Specific recommendations and additions or deletions to the work scope

- Add industrial partner.
- Focus strongly on phosphonated, short-side chain, reinforced material.
- Increase membrane characterization.
- Need to develop a stronger membrane evaluation effort so can tell if these efforts will ultimately produce advanced materials that can be used in membrane electrode assemblies. Some concrete go/no-go milestone dates.
- With time must become more applied. This should begin next fiscal year.
- Include at least an estimation of membrane durability under automotive conditions.

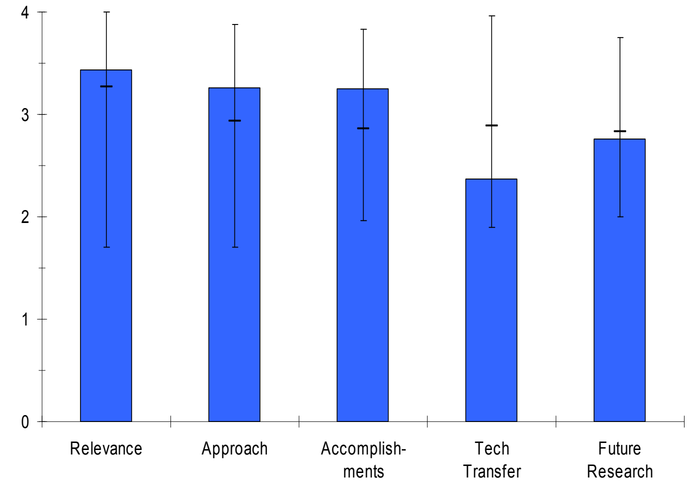
Project # FC-19: Rigid Rod Polyelectrolytes: Effect on Physical Properties Frozen-in Free Volume: High Conductivity at low RH

Morton Litt; Case Western Reserve University

Brief Summary of Project

The objectives of this project are to 1) synthesize polyelectrolyte membranes that reach or exceed Department of Energy low humidity conductivity requirements; 2) use materials and synthetic methods that could lead to cheap polymer electrolyte membranes; 3) understand structure/property relationships to improve properties; and 4) develop methods to make these materials water-insoluble and dimensionally stable with good mechanical properties. Case Western Reserve University has decided to work with poly(p-phenylenes) with one and two sulfonic acids per ring. These materials have lower equivalent weights and cannot hydrolyze.

Overall Project Score: 3.2 (8 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.4** for its relevance to DOE objectives.

- Addresses high-temperature membrane performance.
- Project addresses relevant DOE barriers and aligns with DOE objectives.
- The project is relevant to DOE's Multi-Year (RD&D) plan.
- The project directly correlates to the challenges associated with DOE's Hydrogen Program.
- Developing a membrane that can conduct protons at low relative humidity levels would be a significant step towards the commercial viability of fuel cells.
- This membrane development effort clearly addresses the DOE R&D objectives.
- Project addresses relevant DOE barriers and aligns with DOE objectives.
- Polymer electrolytes are not the most significant barrier for fuel cell commercialization.
- The project supports the President's Hydrogen Fuel Initiative.
- This project is part of the Hydrogen Program's effort that explores new fuel cell membranes. The emphasis in that activity is to find materials that perform well at higher temperatures and at low values of water relative humidity.

Question 2: Approach to performing the research and development

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

- Focused on the development of new materials with specialized structures projected to have good performance under high-temperature, low-relative humidity conditions.
- Approach is focused on achieving conductivity targets developed by DOE.
- The choice of material to make cost effective polyelectrolyte has some limitation.
- The Fenton's stability of the polyelectrolyte is doubtful.
- The rigid rod nematic liquid crystal polymers are very robust and strong materials, but they don't make a good membrane-electrode interface.
- The fragile nature of the electrode makes it hard to integrate well to the tough membrane surface created by nematic liquid crystal polymers.

- Development of extremely low equivalent weight ionomers is an excellent approach toward meeting DOE conductivity targets.
- More focus needed on making insoluble membranes.
- The principal investigator has developed a well-designed electrolyte and understands the need to transform it into a stable membrane.
- Approach is focused on achieving conductivity targets developed by DOE.
- Investigating extremely low equivalent weight materials and using rigid rods to freeze in free volume are both interesting approaches to address increasing conductivity at low relative humidity.
- Cross-linking already brittle systems for the purpose of decreasing water uptake/solubility seems likely to only worsen already poor mechanical properties; other approaches addressing mechanical properties are necessary.
- The proposal is to use rigid rod polymers that, when aggregated, will form a structure, that will facilitate proton transport.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Poly(phenylenedisulfonicacid) material has good conductivity at lower relative humidity and ~80°C and needs to be extended to higher temperaturetemps.
- Reasonable progress to date with promising new materials.
- Good progress in developing materials with high conductivity, but mechanical stability is lacking.
- New poly(phenylenedisulfonicacid) materials show promise.
- These materials appear to be very anisotropic (see swelling in only the Z direction) and expect conductivity to also be anisotropic and higher in-plane, where water appears to be held. Need thorough-plane conductivity data for these materials to determine if conductivity extends in a direction where water isn't forming a path.
- Modest technical progress has been made so far.
- The problem of layered spacing to accommodate minimum water for proton conduction has been addressed well.
- The conductivity of poly(phenylenedisulfonicacid) is commendable.
- More work is needed to understand the physical property of the membrane material, and to assess the feasibility of fabricating a good membrane electrode assembly interface.
- This is the only membrane project to demonstrate clear path to meet 2015 DOE performance targets.
- Dimensional stability and mechanical durability still a big problem.
- Preferential Z-swell should help with mechanical durability.
- The conductivity shown is outstanding.
- High conductivities of the novel ionomers presented are promising for developing materials with decreased conduction losses.
- Disappointingly few "new results" in this year's presentation compared to prior year presentation.
- Validation of conductivity measurements by another source would lend validity to reported values.
- Considerable numbers of polymer samples have been fabricated and tested.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.4** for technology transfer and collaboration.

- Apparently some internal collaboration, but no significant interactions with outside organizations.
- Collaboration outside of Case Western Reserve University (with original equipment manufacturers if possible) would be helpful.
- The team lacks direct links to National Labs and Industries.
- The team may have National Lab/Industry link through Tom Zawodzinski, but direct link would have been better.
- Future technology transfer for these ionomeric materials is not very clear.
- No external collaboration.
- Modeling the morphology of the hydrated ionomer would be a useful addition to this project.

- The principal investigator should work with BekkTech or others for additional, independent high-temperature conductivity testing.
- Relatively little interactions, however not particularly needed them at this point in time. Validation of conductivity measurements is most important aspect of this criterion.

Question 5: Approach to and relevance of proposed future research

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

- Problems have been identified and plans are structured to resolve these problems.
- Plans are to address mechanical property shortcomings
- The proposed research on LCP materials seems to have more academic interest.
- Viability of a practical functional membrane using such LCP is doubtful.
- The research should focus beyond just conductivity enhancements. It should look into the polymer properties that are responsible for making good membrane electrode assembly interfaces.
- Only plan for reducing solubility is chain extension with non-polar biphenols & bi-thiols (they can be oxidized later to sulfones).
- The principal investigator clearly understands the need to couple these molecules with a stable phase or otherwise create a stable, flexible membrane. The path towards this goal should be shown more clearly.
- Plans are to address mechanical property shortcomings
- Cross-linking approach gives additional concerns over already poor mechanical properties.
- Increasing molecular weight may provide improved properties, both in terms of water solubility and mechanical properties.
- Chain extensions may be a mechanism to provide additional improved properties, but other approaches should also be considered.
- The principal investigator proposes moving to complete synthesis and testing with the intent of meeting DOE targets before the December go/no-go decision.

Strengths and weaknesses

Strengths
- Have shown good initial results.
- Good concept to prove the structural advantage of nematic liquid crystal polymers in retaining water at high-temperature and low-relative humidity conditions.
- The project proves the need of minimum water in interlattice spaces of liquid crystal polymers for proton conduction under high-temperature, low-relative humidity conditions.
- Very high conductivity at low relative humidity demonstrated.
- Principal investigator has made very low equivalent weight monomers.
- Poly-p-phenylenes have preferential Z-swelling, which should help with mechanical durability.
- The principal investigator has developed a well-designed electrolyte and understands the need to transform it into a stable membrane.
- Have shown good initial results.
- Extremely high conductivities have been observed, the only example in this program to suggest targets might be able to be far surpassed.
- The principal investigator is an excellent polymer chemist, a very artful, clever, and experienced scientist.

Weaknesses
- Must improve mechanical properties.
- Anisotropic nature of the materials means through-plane measurements are necessary.
- Material properties for making membrane electrode assemblies should be assessed.
- Lack of collaboration with researchers who can help improve mechanical stability.
- Reported values have not been validated through verification by other laboratories.
- Mechanical properties are extremely poor, including issues with water solubility.

- This project may have concerns with in-plane versus through-plane conductivity as swelling seems to be a 1-dimensional phenomenon that may make x-y issues different than z direction issues.
- The molecular weight of the subject polymers is perhaps at too low a value to prepare insoluble materials.

Specific recommendations and additions or deletions to the work scope

- The focus of the project should be beyond just conductivity improvement, it should also focus on the material stability under practical fuel cell condition.
- Material surface property study for membrane electrode assembly fabrication should be added.
- Fenton's test study on all the materials should be carried out and it should be added as a part of the project.
- Focus on blocking the poly(p-phenylenes) with hydrophobic units to reduce solubility.
- More collaboration to help solve solubility problem.
- Focus on mechanical properties almost exclusively. Conductivity values are easily high enough; consider trading off conductivity for mechanical property advantages.
- The screening is focused on conductivity, certainly important, but just one of several critical attributes. Durability, low cost, etc. are equally important, but not equally strived for.

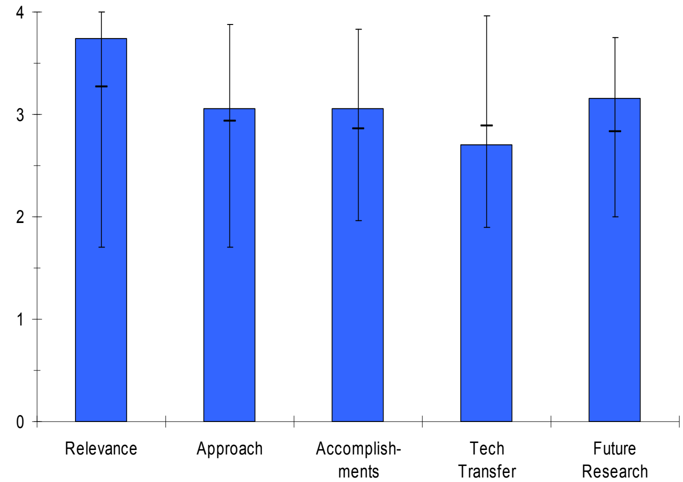
Project # FC-20: NanoCapillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells

Peter Pintauro; Case Western Reserve University

Brief Summary of Project

The objective of this project is to fabricate and characterize a new class of NanoCapillary Network proton-conducting membranes for hydrogen/air fuel cells that operate under high temperature, low humidity conditions. The 2007-2008 project goals were to fabricate membranes with the following properties: 1) 0.07 S/cm proton conductivity at 30°C and 80% relative humidity; 2) good mechanical properties; and 3) low gas permeability; and to identify a roadmap to achieve high conductivities at lower humidity and higher temperatures.

Overall Project Score: 3.2 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- Durability, cost and performance improvements of membranes are all highly necessary for fuel cell commercialization.
- Clearly oriented towards DOE goals.
- The objectives of this project are consistent with the Hydrogen Fuel Initiative.
- Making membranes that conduct protons and separate the gases. This is good and relevant to DOE goals.
- High-temperature polymer electrolyte membranes are needed for transportation applications (to facilitate thermal management) as well as for stationary applications (higher value heat in combined heat and power and/or CO-tolerance).

Question 2: Approach to performing the research and development

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

- Very unique approach to improving membrane durability.
- Electrospinning of fibers can provide a lot of flexibility on polyelectrolyte chemistry and geometry.
- Inert matrix also provides a lot of flexibility.
- Polyhedraloligomeric silsesquioxanes material can provide even more benefits for performance.
- Nanofibers are promising novel approach, maybe still high risk, but high potential.
- Convincing strategy to overcome remaining hurdles.
- Use of binder inherently limits conductivity.
- Sulfonated polyhedraloligomeric silsesquioxanes improves conductivity but is still unstable in its current form in the membrane.
- The high-temperature conductivity goals are not being addressed. 0.1 S/cm at 120°C and 50% relative humidity is not practical for a vehicle. How is this going to work at <25% relative humidity?
- Interesting approach to provide ionic conductivity within a network of continuous nanofibers.
- Voids between fibers filled with ionically non-conductive polymer must be minimized for high conductivity.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.1** based on accomplishments.

- Has demonstrated materials that meet DOE interim milestones.
- Has proven fiber technology with matrix.
- Understands/identified the newly discovered shortcomings (softness of inert material, sulfonated polyhedraloligomeric silsesquioxanes solubility).
- Good results, but still considerable risk for real high temperature application.
- Status with respect to time-line is okay.
- Met intermediate DOE conductivity target.
- Mechanical durability still unproven and a concern.
- Good progress made in the objectives that are addressed.
- Study of sulfonated polyhedraloligomeric silsesquioxanes loading has shown higher conductivities with greater amounts of sulfonated polyhedraloligomeric silsesquioxanes, providing evidence of the benefit of sulfunated polyhedraloligomeric silsesquioxanes.
- The stability of the sulfonated polyhedraloligomeric silsesquioxanes within the nanofiber composite membrane needs to be verified.
- The room temperature conductivity milestone was met, as verified by BekkTech.
- The conductivity of the sulfonated poly(arylene ether sulfone) /sulfonated polyhedraloligomeric silsesquioxanes nanofiber composite membrane at 120°C and low relative humidity is lower than Nafion's.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.7** for technology transfer and collaboration.

- What is collaboration with Wright State University?
- Pursuing industrial partner that is highly recommended by the reviewer.
- Actually this question is premature for the project.
- The project is worthwhile to be continued
- Outside interaction limited to polyhedraloligomeric silsesquioxanes supplier.
- This could stand improvement.
- The universities appear to collaborate well.
- The role of each party should be more clearly stated.

Question 5: Approach to and relevance of proposed future research

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

- Based upon newly identified shortcomings, new approaches will be pursued to overcome them.
- Lining up industrial partner will speed up/help focus development.
- Reasonable strategy for going further.
- Tests of new more thermally stable binder planned.
- No clear path presented to meet 2015 DOE performance and durability targets.
- Future plans should include better collaborations with other groups. Project is now getting into the harder work and it needs help.
- The future work is well focused on increasing the membrane conductivity at higher temperatures and lower relative humidity.

Strengths and weaknesses

Strengths
- Unique approach to membrane development.
- Electrospinning technology.

- Good and clear presentation, not lost in details but emphasizing the general route.
- Electrospinning has potential to enable stabilized low equivalent weight ionomers.
- Electrospinning does show promise and real membranes result.
- High mechanical strength (Young's modulus) and low gas permeation has been shown.

Weaknesses

- Making no attempt to find a proton conduction mechanism that does not involve water.
- Lack of sufficient membrane characterization (swelling, gas permeability, etc.).
- Lack of industrial partner for the time being.
- Binder inherently lowers conductivity.
- Poly aryl ether sulfones are not highest performing starting ionomers.
- Not addressing water free or water-poor conduction. Need to consider how to do this.
- Higher ionic conductivities at 120°C and low relative humidity have yet to be demonstrated.
- Ability to fabricate a membrane electrode assembly is not known.

Specific recommendations and additions or deletions to the work scope

- Improve membrane characterization.
- Add industrial partner.
- Investigate if electrospinning can enable preferential conductivity through plane of membrane instead of isotropic conduction.
- Cost analysis of process warranted to verify if process could be cost effective.
- Use more conductive polymers (such as Professor Litt's poly-p-phenylenes).
- Effect of swelling on epoxy-bonded fiber mats should be investigated to ensure mechanical integrity during automotive drive cycles.

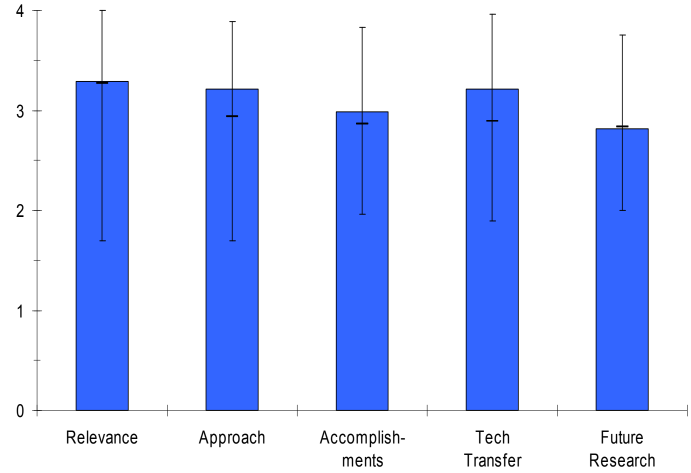
Project # FC-21: Novel Approaches to Immobilized Heteropoly Acid (HPA) Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes

Andrew Herring; Colorado School of Mines

Brief Summary of Project

The overall objective of this project is to fabricate a hybrid HPA polymer from HPA functionalized monomer with $\sigma > 0.1$ S cm^{-1} at 120°C and 25% relative humidity. The 2008 objective is the synthesis and optimization of hybrid HPA polymers for conductivity from room temperature to 120°C with an understanding of chemistry/morphology conductivity relationships. Materials synthesis will be based on HPA monomers; novel "high and dry" proton conduction pathways will be mediated by organized HPA moieties.

Overall Project Score: 3.1 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Project is aligned with DOE goals and targets.
- Project addresses requirement for high-temperature, low-relative humidity membranes.
- High-temperature membrane with high conductivity at low relative humidity is needed.
- The project is relevant to the objectives of DOE's Multi-Year RD&D plan.
- The improvement of low-relative humidity, high-temperature membrane conductivity is critical to the success to DOE's Hydrogen Fuel Initiative.
- The goal and initiatives are all aligned with DOE's objectives.
- Project is aligned with DOE goals and targets.
- Polymer electrolytes are not the most significant barrier for fuel cell commercialization.
- The project supports the President's Hydrogen Fuel Initiative.
- This activity is part of the "high-temperature membrane" project, and the relevance is tied to the goals of that activity, the search for a polymer electrolyte membrane that operates under high-temperature and low-relative humidity conditions.

Question 2: Approach to performing the research and development

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

- Novel approach that has the potential for achieving water-free conduction. A new class of ion-conducting polymer.
- Systematic, well designed experimental plan.
- Approach to work with Si-linked model compounds and model linkers has allowed for faster progress and proof-of-principal type experiments.
- Approach involves systematic and logical exploration of polymers based HPA functionalized with organic monomers design space.
- A different approach than most other membrane projects.
- The approach of making composites using HPA is good.
- HPA does have good conductivity under low-relative humidity, high-temperature conditions.
- Incorporation of HPAs using polystyrene (PS) chains is not good, since PS is known to be vulnerable under fuel cell conditions.

- The approach of using 3M's monomer to anchor HPA is good as PFSA chain will be more stable than PS chain.
- Novel approach that has the potential for achieving water-free conduction. A new class of ion-conducting polymer.
- Systematic, well-designed experimental plan.
- Approach to work with Si-linked model compounds and model linkers has allowed for faster progress and proof-of-principal type experiments.
- HPAs have high conductivity and represent a novel class of materials that merit further study.
- Incorporating HPAs covalently into membranes addresses one of the key problems of these materials, leaching out when not covalently bound.
- The use of a hydrocarbon backbone limits chemical stability, even though HPA may reduce impact of radicals. Even though PFSAs are being proposed as covalently bound hosts, until shown, it is not certain they can be made.
- Lack of a method of externally influencing the distribution of HPAs in the membrane means the only path forward is to increase loading. This is improving performance, but reducing mechanical properties.
- Herring proposes assembly of membranes through the polymerization of monomers that include reactants with organo-metallo moieties. This approach is indeed novel, but not obvious. Vinyl monomers were the initial candidates for membrane fabrications.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Colorado School of Mines has developed a new class of proton-conducting polymers.
- Colorado School of Mines has been successful at immobilizing HPA and preventing HPA leaching.
- Colorado School of Mines has developed and begun initial testing of new membrane materials. To date material performance at lower relative humidity has not been acceptable.
- Good results to date.
- Overall technical progress has been satisfactory.
- Impressive conductivities have been demonstrated by the membrane identified as PolyPOM75.
- The cost of the composite membrane should be addressed to account for the overall system cost.
- There is relative humidity benefit at high temperature, but the water uptake at lower temperature is very high and it can be a problem.
- Colorado School of Mines has reported membranes based on higher HPA loadings have conductivities that are beginning to approach current targets; still, reported values are only 2/3rds of the target.
- Increased conductivity is coming at the price of increased water uptake.
- Mechanical properties and durability are still large concerns yet to be addressed.
- Progress has been made and some samples show acceptable conductivity. However some samples appear to become brittle with aging. So, results are still preliminary.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.2** for technology transfer and collaboration.

- Collaborations in the team (especially with 3M) have been very productive.
- Close collaboration with 3M who is making significant contributions to the project.
- Too early in project to have significant collaboration other than 3M.
- The technical collaborations with industry and National Lab are adequate.
- There is good interaction with other fuel cell research groups.
- The project will help in building good knowledge base at the School of Mines.
- Interactions are limited, but 3M collaboration is yielding significant improvements to the project. At this level further interactions are likely not needed.

Question 5: Approach to and relevance of proposed future research

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

- Future work is directed towards appropriate barriers, trying to control morphology, and addressing durability.
- Plans adequate to continue material development; however attention must be focused on mechanical stability of developed membrane.
- Proposed research by 3M on anchoring HPA using PFSA monomer seems applicable.
- Si-anchored polymer compound may not be very stable under fuel cell conditions.
- Future work is directed towards appropriate barriers, trying to control morphology, and addressing durability.
- Further increasing loadings of HPAs in polymers could increase conductivity, but likely at the expense of mechanical properties/water uptake that are already likely to limit material usefulness.
- The resulting properties, if incorporation of HPAs into perfluorinated polymers is achievable, will be interesting to see, but resulting structures are not likely to be easily influenced through processing, and chemistry options are limited.
- The suggested future directions were to complete the project, moving along the present pathway.

Strengths and weaknesses

Strengths
- Novel proton-conducting polymer system.
- Diverse team with the needed expertise, appropriate work breakdown and with good working relationships.
- The project is well thought to use additives for retaining water under high-temperature, low-relative humidity conditions.
- There is a potential to this method of water retention, if HPA is anchored to an oxidatively stable polymer.
- The project demonstrates the flexibility of using HPA with different polymeric systems.
- Novel proton-conducting polymer system.
- Base materials, HPAs, show unusual and compelling conductivity properties. Exploring these materials in covalently bound systems where leaching is not an issue is a worthwhile approach.

Weaknesses
- No clear indication of finding an oxidatively stable polymer for anchoring HPAs.
- High water retention of HPAs under low temperature could be an issue in the system.
- Better HPA with low water uptake properties at lower temperature regime should be explored.
- Lack of morphological control or ability to influence distribution of HPAs in membranes make it uncertain that base properties of HPAs can be taken advantage of in covalently-bound membranes.
- Phosphates in fuel cell systems need to be thought through. Compounds with C-P bonds can be biologically active, and can have some adverse properties, like human toxicity. The indirect methanol fuel cell systems tended to emit methyl phosphate at times. There probably is no problem, but the potential problem needs clarification.

Specific recommendations and additions or deletions to the work scope

- New HPA with lower water uptake across the fuel cell operational regime should be explored.
- Si-cross-linked method has no practical purpose, since most of the Si polymers are unstable under fuel cell operational conditions. Therefore this part of the project can be deleted.
- Strongest recommendation for this project would be to focus on investigating methods of controlling morphology (distribution of HPAs) in the membrane.

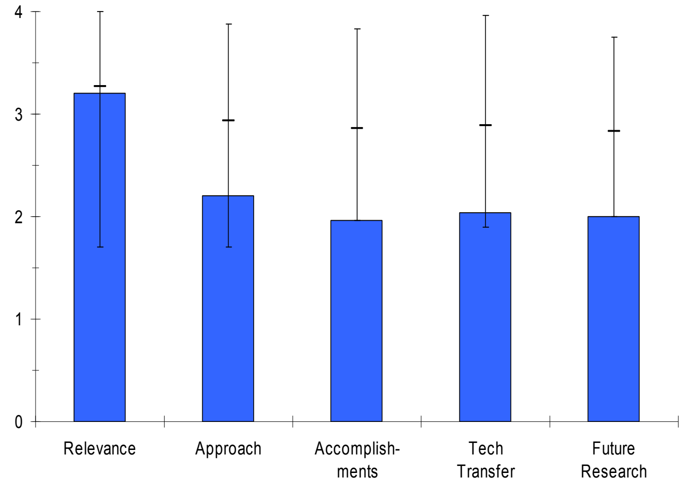
Project # FC-22: New Proton Conductive Composite Materials with Co-Continuous Phases Using Functionalized and Cross-linkable VDF/CTFE Fluoropolymers

Serguei Lvov; Pennsylvania State University

Brief Summary of Project

The overall objectives of this project are to 1) contribute to Department of Energy efforts developing high temperature polymer electrolyte membranes for transportation applications; and 2) develop a new composite membrane material with hydrophilic inorganic particles and VDF/CTFE polymer matrix to be used in polymer electrolyte membrane fuel cells at -20-120°C and relative humidity of 25-50%. The year 2 objectives are the 1) scaling up of the supply of inorganic proton-conductive materials and polymers; 2) reaching the milestone of proton conductivity of 0.07 S/Cm at 25°C and 80% relative humidity; and 3) selection of the best membrane based on test results and adjustment of the synthesis procedures.

Overall Project Score: 2.3 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.2** for its relevance to DOE objectives.

- Durability, cost and performance improvements of membranes are all highly necessary for fuel cell commercialization.
- This membrane development effort addresses the DOE research and development objectives.
- Membranes are being made but probably these membranes are not likely to be stable. Since this presentation does not provide evidence that the work is providing insight into new conduction mechanisms or other novel properties, it appears that the project is becoming irrelevant to the overall DOE objectives. Given that the goal is to provide membranes that allow operation at high temperatures.
- High-temperature polymer electrolyte membranes are desirable for transportation applications (to facilitate thermal management) as well as for stationary applications (higher value heat in combined heat and power and/or CO-tolerance).
- The project is relevant to the DOE high-temperature membrane targets.

Question 2: Approach to performing the research and development

This project was rated **2.2** on its approach.

- Overall synthetic theory is appealing and has high potential if pursued correctly.
- Sulfonated styrene is well known to desulfonate and should have been avoided even as a "model" compound.
- Sulfonated alumina is well known to dissolve in highly acid environments and should have been avoided even as a "model" compound.
- It is thought by many that polystyrene-containing systems do not have the required durability for long-term fuel cell use. When asked about this, the principal investigator stated that the plan was to replace this with an inorganic proton conductor. It needs to be explained how sPS is a good model for an inorganic proton conductor.
- The approach to performing the research is not very well designed, does not seem to be very feasible and appears to not be well integrated with the needs of the fuel cell. Nothing is mentioned about durability!

- Combining fluoropolymers with proven durability with inorganic proton-conductive materials is quite feasible and has potential to yield good near-term results.
- The approach appears to be unfocused. The first two year's work developed conductivity measurement capability and synthesized membranes that do not appear to have the stability necessary in a fuel cell environment. Better if the approach looked at developing stable systems first even if they are more difficult to synthesize.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.0** based on accomplishments.

- A variety of materials have been prepared; polyelectrolytes and inorganics. Approach, however, was very poor due to chemically weak material selection; the data thus far is not of high value unless new materials with the same properties are found with high chemical durability.
- The addition of hexafluoropropylene to the polymer provided increased dry conductivity. This should be repeated and explained.
- Both this polymer system and these inorganic materials have been studied by others. It needs to be fully explained what is new here in light of past work.
- Progress is modest towards the goals that the project has identified and towards the interim DOE goals. However, there seems to be no thought on how to achieve the ultimate goals and how a durable membrane can be produced that can conduct at 120°C. No thought is given to alternate proton conduction mechanisms; the high temperature performance may be achieved by retention of water by the particles, a strategy which is not really helpful.
- Developed method for *ex situ* measurement of proton conductivity of additives.
- Conductivity improvements at 120°C and low relative humidity have not yet been realized.
- The project has been underway for two years. Progress has been mixed. Pennsylvania State University faced a considerable challenge in obtaining conductivity measurements. Some of their results did not agree with literature values. Pennsylvania State University has developed membranes that meet conductivity targets but are unlikely to be stable in the fuel cell environment. There is also concern that the inorganic additives would leach out of the membranes.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.0** for technology transfer and collaboration.

- Some disagreement in data with sole outside collaborator, BekkTech.
- Should include industrial partner to avoid so many material dead-ends.
- This project would benefit from a collaboration with someone with fuel cell experience (e.g., National Renewable Energy Laboratory or Los Alamos National Laboratory).
- Non-existent!
- The principal investigator collaborates with other professors at Pennsylvania State University.
- BekkTech is essentially providing a conductivity measurement service.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.0** for proposed future work.

- If new materials can be found with improved chemical properties, future work can be of interest.
- The program would benefit if future work were focused on understanding structure-property relationships and using this information to optimize performance through control of factors such as inorganic particle size and distribution, polymer chemistry and morphology, etc. and not focused on "fabricating" or "producing" samples which meet conductivity targets.
- Future plans contain no mention of durability!
- Development of new polymers and inorganic proton conductors appears necessary to improve the chances of meeting the 2009 conductivity milestone.

- The proposed plans are vague. A clear path forward to achieving the DOE targets is not evident in the presentation.

Strengths and weaknesses

Strengths
- High material development skills.
- The observation of the effect of added hexafluoropropylene is interesting.

Weaknesses
- Use of sulfonated styrene.
- Use of alumina inorganic salts.
- Lack of industrial partner.
- Lack of complete membrane characterization (swelling, gas permeability, etc.).
- There are few "new" materials used here.
- No collaboration.
- The project participants seem to be paying no attention to the needs of fuel cells and appear to be ignoring important needs.
- Requirements for the additives are not clearly defined (size, morphology, proton conductivity etc.).
- The project needs a clearer focus on a path forward to achieve a stable membrane that achieves the DOE targets.
- Several reviewers pointed out that the styrene side chains are not likely to survive in the fuel cell environment.
- Rationale for selecting the polymer candidates for grafting to the backbone and for the inorganic additives is not obvious.

Specific recommendations and additions or deletions to the work scope

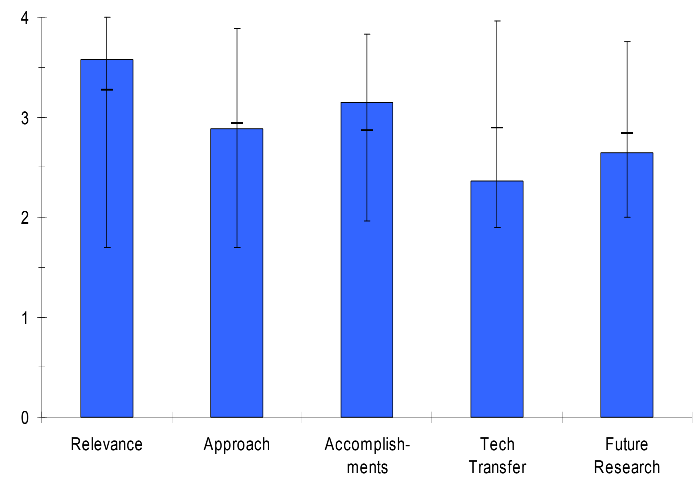
- Better selection of materials even if used as "model" compounds.
- Industrial partner to speed up/focus research.
- Since this project appears to make no effort to investigate new conduction mechanisms or the fundamentals of the behavior of the nanoparticles in contact with the polymer, very little of value is appearing. This project should be refocused or terminated.
- The project should consider a layered membrane approach with the inorganic additive contained in the middle layer to prevent the inorganic additives from leaching out of the membrane.
- Other side chains should be considered based on their resistance to oxidative attack.

Project # FC-23: High Temperature Membrane with Humidification-Independent Cluster Structure
Ludwig Lipp; FuelCell Energy, Inc.

Brief Summary of Project

FuelCell Energy, Inc. performed three iterations of polymer membranes, examined three types of additives and analyzed the conductivity of over 20 samples. A 20% improvement in conductivity was demonstrated over 2007 and approximately three times higher than Nafion 112 without loss in mechanical properties. Composite membranes show significantly better cell performance at low relative humidity than expected from conductivity tests. Low cell resistance was also achieved.

Overall Project Score: 3.0 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Very relevant to high-temperature, low-relative humidity membrane applications.
- The project fits well with DOE's Multi-Year RD&D plan.
- The goal of developing a new polymer electrolyte membrane with higher proton conductivity and improved durability under hotter and drier conditions compared to current membranes is of high relevance.
- Membranes for proton conduction under drier conditions are critical to thee presidents hydrogen initiative.
- Project addresses relevant DOE goals and objectives.
- Project fits into the DOE goals of reducing cost and obtaining improved performance of fuel cell materials. Even so, the high temperature part of those targets is now of less importance.
- High temperature membranes are an important area for DOE investment.
- Project addresses relevant DOE goals and objectives.
- Proposed work falls within the expectation of DOE's Hydrogen Fuel Initiative and FCE is in line with the progress of the work.

Question 2: Approach to performing the research and development

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

- Very innovative and well-thought approach.
- Different additive components for different functionalities are interesting.
- The approach is to combine four elements (co-polymer, support polymer, water additives and conductivity additives) into a membrane. This approach is being addressed by several groups in addition to FuelCell Energy. No information is given about what the four materials are, so evaluation of their interactions is impossible. Is 1+1+1+1 going to be more than 4 or not?
- Supported polymer with additives for water retention and proton conductivity.
- Not particularly novel.
- Composite approach has potential and has several knobs to turn to meet targets.
- The plan was to insert additives into commercial materials, thus improving performance.
- Interesting approach to the problem via empirical equation.
- Not certain that conductivity terms are strictly additive.
- Difficult to judge approach without details on polymer and additives' chemistry.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.1** based on accomplishments.

- Initial results look very promising.
- Membrane casting method development needs more work to address processing related issues.
- The cost of the composite membrane has not been addressed.
- Technical challenges to integrate electrodes to this composite membrane should be addressed.
- Membranes have been only fabricated using the co-polymer presumably by the unnamed polymer partner. Work on the additives has not been reported and this work is to be done by the consultants who are not named? If University of Connecticut (investigator not named here either) is doing the cross-over and conductivity work, what is FuelCell Energy doing? Some fuel cell testing work is presented but it is at too high of system pressure (> 20 psig) and no current interrupt measurements were reported so the resistance of the membrane under the conditions of the test (not completely reported) was not presented. What ionomer was used in the catalyst layers?
- Met milestone but not validated by BekkTech.
- Area specific resistance lower at standard conditions.
- Fuel cell tests run.
- Achieved low temperature conductivity milestone (testing at FCE, not with measurements at Florida Solar Energy Center).
- Have achieved ~3x the conductivity of Nafion 212 at 120°C 25% relative humidity.
- Have demonstrated membrane in a membrane electrode assembly at 120°C 25%relative humidity with excellent performance (Pt loading not indicated, so difficult to compare directly without a standard Nafion membrane membrane electrode assembly with same loading and conditions given).
- The short-sidechain PFSA clearly had improved properties following modification by "additives", easily meeting the DOE conductivity target.
- Meeting minimum DOE targets with some samples.
- Good polarization data.
- Seems like there are electrode difficulties.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.4** for technology transfer and collaboration.

- There is good collaboration with different university and testing laboratory.
- Interaction with National Laboratory could have been beneficial.
- As none of the partners are listed by name, it is impossible to judge the interaction or coordination.
- No National Laboratory, but collaboration with original equipment manufacturer planned.
- Collaborations would look better if we knew who the polymer partner was.
- No significant collaborations discussed.
- Electrode performance suggests need for collaborator in this area.

Question 5: Approach to and relevance of proposed future research

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

- Work should be dedicated to develop better membrane electrode assembly interfaces with these novel composite membranes.
- The proposed future work is so general that will be impossible to benchmark success.
- Improve everything, but approach not necessarily validated yet.
- Without knowing a bit more about the ionomer and additives, it is difficult to judge the future plans. A little more information would be very useful in judging the prospects for success and to determine how much this project overlaps others in the area.

- Essentially, FuelCell Energy announced plans to wrap-up this activity, with additional activities that would continue onward on the "additive" route.
- Future work is a straightforward continuation of ongoing work.
- Difficult to project what is to be expected with higher additive loadings.

Strengths and weaknesses

Strengths
- Well thought out concept, seems to be low cost membrane alternative.
- Good initial data; seems to be promising material.
- The approach is a good one, unfortunately it is not unique.
- Well-conceived empirical approach.

Weaknesses
- Membrane manufacturing processes should be fine tuned to demonstrate fabrication of consistent quality material.
- Membrane electrode assembly interfaces with these composite membranes should be addressed.
- No technical information is provided to benchmark success. Interactions with unknown partners also make benchmarking impossible.
- More details need to be provided regarding the membrane. More information regarding the ionomer identity, the types of additives, etc. are necessary so we can judge the potential for success as well as the overlap of this project with others in the membrane area.
- Poor electrode performance.
- Additive chemistry is often difficult to integrate into electrodes.

Specific recommendations and additions or deletions to the work scope

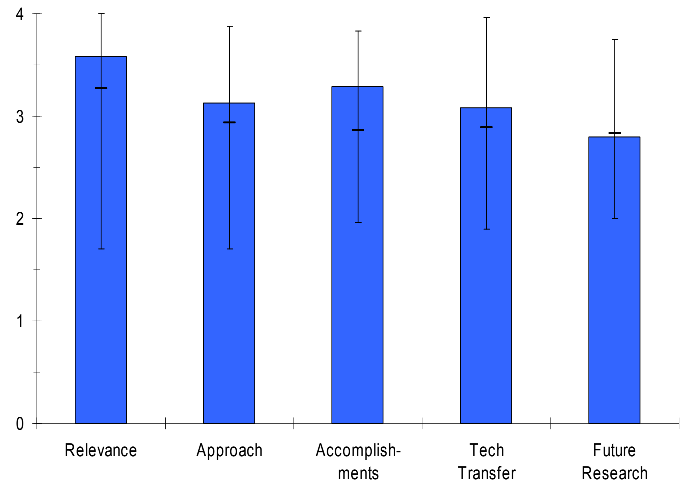
- Development of membrane electrode assembly interface work should be explored for this new membrane material.
- If project will not disclose the chemistry of the materials, this program cannot be properly evaluated, hence it is not clear why this project should continue to receive funding.
- What goes into polymers can also come out—there is need to demonstrate that the additives adhere into the polymers and do not result in accelerated polymer degradation.
- Advisable to collaborate with some electrode production expertise.

Project # FC-24: Dimensionally Stable Membranes
Cortney Mittelsteadt; Giner

Brief Summary of Project

The ultimate goal of the project is to meet performance targets with film that can be generated in roll at DOE cost targets. The year 2 milestones were achieved and interim conductivity targets have been met. Improvements in fuel cell performance have been shown, including electrode improvements. A realistic pathway for meeting cost targets can be seen for both 2- and 3-dimensionally stable membrane paths. To reach the ultimate DOE goals, Giner might consider incorporating the low equivalent weight materials that have been developed at State University of New York-Syracuse.

Overall Project Score: 3.2 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Durability, cost and performance improvements of membranes are all highly necessary for fuel cell commercialization.
- The project objectives are relevant to DOE's RD&D plan.
- The project addresses the fundamentals of low-relative humidity proton transport issues.
- Membranes for proton conduction under drier conditions are critical to the President's Hydrogen Fuel Initiative.
- Good program, focused on providing membrane materials that not only meet the immediate milestone but also shows progress towards the final goal.
- The project is highly relevant to the DOE high-temperature (HT) membrane goals.
- High temperature membranes are an important area for DOE investment.
- Particularly relevant approach because of focus on dimensional stability.
- Good to see electrode preparation directly integrated into project.

Question 2: Approach to performing the research and development

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

- Reinforcement technology and modification is highly unique but of high cost.
- New reinforcement layer is less novel but could meet cost targets.
- In-depth analysis of existing polyelectrolytes was performed.
- Catalyst-coated membrane vision is also of high value.
- The approach seems to be technically not feasible.
- The dimensionally stable membrane material possesses low void area and membrane impedance will be very high.
- The material research of dimensionally stable membranes seems to be interesting, but it may be associated with prohibitive cost.
- Very low equivalent weight PFSA, but this is water-soluble.
- 2D-reinforced support.
- Will there be membrane electrode assembly testing?
- 3D support (commercially available), but how is this different than Gore's approach?

- Excellent approach, addressing the barriers, looks to be very technically feasible and is integrated. However, not enough detail given on the new polymers made at State University of New York. Cannot make a judgment. Also would like data on durability. Is there a weak spot where the ionomer meets the support?
- The approach is very good. Rather than develop a completely new membrane that has the required physical characteristics and durability under fuel cell operating conditions, Giner is attempting to use dimensionally stable membranes that can retain an imbibed electrolyte under fuel cell operating conditions.
- Very solid and elegant approach.
- The investigators are using fairly conventional materials with the main innovation coming in the processing approach.
- Approach provides an opportunity to readily introduce materials from other projects into a processable membrane.
- Small quibbles with a few details: in question and answer session, commented that water permeation is fast so equilibration will be fast; however, uptake of water is often surface-driven.
- It is not clear how improvements will be realized given the nature of the conducting materials.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Met DOE milestone target.
- Low equivalent weight material from partner shows promising results but no chemical information was shared so difficult to judge.
- Analytical characterization is top-level.
- The practical demonstration of dimensionally stable membrane concept had been done well.
- More work is needed with commercial ionomeric materials to validate the concept.
- The cost and efficiency of these substrate materials should be addressed using commonly available ionomers.
- Very close to Go/No-Go at 50% relative humidity.
- Homopolymer in 3D support.
- Good progress demonstrated towards DOE goals. However, durability needs to be highlighted.
- Giner has met the 2007 DOE interim goal of 70 mS/cm conductivity. Achieved 0.8 S/cm at 30°C and 80% relative humidity.
- Nearing DOE 2010 target; have demonstrated 0.08 S/cm at 80°C and 30% relative humidity.
- Membranes developed so far exceed the mechanical properties of the Gore-reinforced membrane.
- State University of New York-Syracuse has successfully synthesized several new low-EW ionomer candidates to meet performance targets.
- Good progress toward real membranes and membrane electrode assemblies.
- Substantial progress toward technical goals.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- Difficult to judge because no real information was shared, however, transferred polyelectrolyte material did meet DOE targets.
- General Motors' interest in Giner will ensure good research direction and focus.
- The project has good academic and industrial partner.
- The project seems to have good interaction with academic and industrial communities.
- University, original equipment manufacturer industry partnership.
- Not very clear how this goes beyond the State University of New York-Syracuse partnership. The role of General Motors is unclear.
- General Motors and State University of New York-Syracuse are collaborators. General Motors provides automotive requirements to ensure performance metrics are met.
- Solid collaboration.

Question 5: Approach to and relevance of proposed future research

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

- Future work on both reinforcement layer and polyelectrolyte is good.
- Cost considerations are being taken into account and attacked.
- More work should be done with commercially available ionomeric materials.
- Membrane electrode assembly interface issues with these membranes should be addressed.
- The high cost and large membrane impedance issues should be addressed.
- Should concentrate on ionomer development before scale-up.
- Future plans seem a bit vague.
- Exactly what durability studies will be done?
- The cross-linking strategy is dangerous. This can lead to major current density distribution issues.
- Not sure which approach, 2D or 3D, membrane support will work. So Giner pursuing both--the molded 2D support shows promise as well as the 3D membrane.
- Realistic pathways appear to be able to meet the DOE cost and durability targets.
- Looking to State University of New York for a new lower equivalent weight ionomers to reach the DOE conductivity goals of 0.1 S/cm at 120°C and 50% relative humidity.
- Emphasis on very thin membranes is appropriate.
- Durability tests are reasonable.
- Very good approach to attack all barriers to get to a usable membrane.

Strengths and weaknesses

Strengths
- Unique reinforcement layer.
- Good analytical abilities.
- Polyelectrolyte potential (hard to judge).
- Well-thought out concept.
- Good alternative approach to expanded poly(tetrafluoroethylene) (Gore-Select) approach.
- Very strong electrochemical capabilities as would be expected from this company.
- The project is close to meeting the 2010 HT membrane targets.
- The project has clearly described a viable path forward to meeting the DOE targets.
- Near-term approach to membrane preparation.
- Broadly applicable.
- Includes electrode optimization.

Weaknesses
- Lack of transparency on polyelectrolyte development.
- The cost issue with substrate fabrication should be addressed.
- More commercial ionomer should be integrated to this substrate.
- Commercial supports too thick.
- Homopolymer water-soluble.
- Not enough chemistry background in the team.
- Not clear how the final goal will be met. This company should know that 25% relative humidity at 120°C is the upper limit. They should be well aware that water is a big problem yet they are making no effort to find a new mechanism of proton conduction. The project is incremental and this represents a major weakness that needs to be addressed.
- Nothing fundamental to deliver better materials for low relative humidity.

Specific recommendations and additions or deletions to the work scope

- Continued hard work down this path.
- More serious evaluation of capillary effect especially in light of recent literature results.

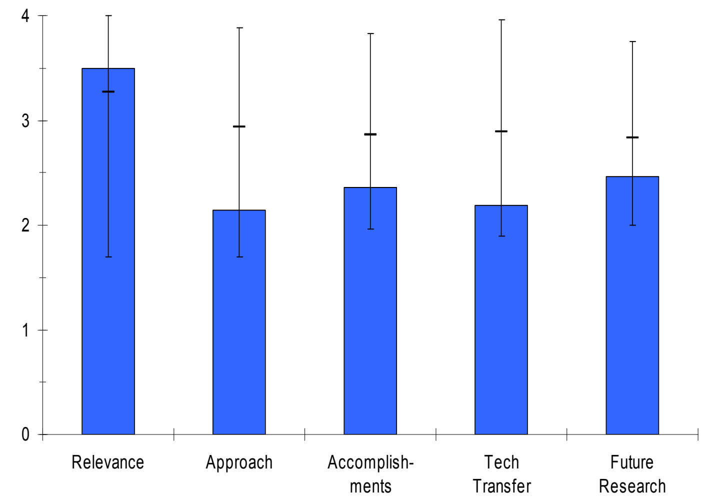
- More commercial ionomers should be used to evaluate the performance with dimensionally stable membrane substrate.
- New dimensionally stable membrane fabrication should be evaluated to reduce the cost.
- More fundamental studies of PFSA polymer.
- How about making some effort to get rid of water and find a new mechanism of proton transport?
- Continue the two-path approach to determine if each can produce a membrane meeting all targets. Then focus development effort on the path that has the lowest cost potential.
- Collaborate with more innovative polymer makers.

Project # FC-25: Poly(cyclohexadiene)-Based Polymer Electrolyte Membranes for Fuel Cell Applications
Jimmy Mays; University of Tennessee

Brief Summary of Project

The objective of the project is to synthesize and characterize novel neat and inorganically modified fuel cell membranes based on poly(1,3-cyclohexadiene) (PCHD). To achieve this objective, a range of materials incorporating PCHD will be synthesized, derivatized, and characterized. Successful completion of this project will result in the development of novel potentially inexpensive polymer electrolyte membranes engineered to have high conductivity at elevated temperatures and low relative humidity.

Overall Project Score: 2.5 (8 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Project addresses relevant DOE targets and barriers.
- The project is relevant to the Multi-Year RD&D Plan of DOE.
- The project is focused to address low-relative humidity, high-temperature membrane issues.
- The objectives of this project are consistent with the President's Hydrogen Fuel Initiative.
- This membrane development effort addresses the DOE research and development objectives.
- Project addresses relevant DOE targets and barriers.
- Polymer electrolytes are not the most significant barrier for fuel cell commercialization.
- The project supports the President's Hydrogen Fuel Initiative.
- Professor Mays added the two critical targets, cost and durability, to the new polymer list, very welcome additions.
- High temperature membranes are an important area for DOE investment.

Question 2: Approach to performing the research and development

This project was rated **2.1** on its approach.

- Not clear how they intend to get conductivity at high temperature, low relative humidity (the target conditions). What is the inorganic additive that will provide good conductivity at low relative humidity?
- Durability of non-aromaticized systems in a fuel cell environment is suspect, as is the durability of S-S linked systems.
- A large portion of the work is being performed on mechanical testing and characterization, which may be premature since conductivity in these materials has yet to meet targets.
- The chemical approach to membrane development is not robust.
- The material, especially the crosslink, is vulnerable to the oxidative condition, especially to Fenton's condition.
- The material may not be stable to fuel cell operational condition.
- Poly(cyclohexadiene) polymers cross-linked via Cl bonds are unlikely to be thermally & chemically stable in a fuel cell environment.
- Focus on thermal analysis provides little insight into relevant performance and durability properties.
- It needs to be made clear how these materials provide a path to membranes with the durability to survive in a fuel cell. Aliphatic hydrocarbons are known to have unacceptable durability in polymer electrolyte membrane fuel cells. Also, while random, sulfonated hydrocarbon polymers are known to have high proton conductivity at

high levels of hydration, the conductivity is very low at low humidification. Why are these expected to be better?

- The pursuit of poly(cyclohexadiene) as an ionomer material is limited because the backbone will have poor durability in fuel cell environments. The pursuit of these materials is unlikely to help achieve DOE targets particularly in the area of durability.
- Anionic polymerization control has some interest in creating polymers of controlled morphology.
- Focus on thermomechanical analysis, dynamic mechanical analysis, and thermogravimetric analysis are the wrong focus for this project. The extent of work in this area reflects the expertise of the co-principal investigator more than what is required to move these materials forward.
- The University of Tennessee chemical synthesis work is first rate. The chemistry seems likely to result in very low cost materials.
- Certainly one of the more original approaches.
- Highly desirable combination of strong synthesis capability with a well-known polymer physical chemist.
- Good level of control of properties. The ability to develop the trade-off between swelling and conductivity is important.
- Very difficult to see these materials achieving even modest durability.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.4** based on accomplishments.

- No work performed on inorganic modification that is intended to provide good conductivity at high temperature, low relative humidity yet.
- Conductivity at low temperature, high relative humidity have not met milestone 2.5.
- The mechanical issues of the membrane are well-addressed.
- No work has been done to address the chemical stability of this polymeric material.
- No fuel cell testing data to see whether the membrane material is functional under fuel cell conditions.
- Principal investigator made films with good wet conductivity – but no data shown at lower relative humidity.
- It needs to be made clear how the thermogravimetric analysis data shown is relevant to fuel cell use.
- The transport properties and chemical stability of these materials need to be evaluated.
- The project has demonstrated materials with reasonable conductivities although reaching target conductivities under target conditions will be difficult.
- Results centering on thermomechanical analysis, thermogravimetric analysis, and dynamic mechanical analysis have little relevance to the limited conductivity data. *In situ* durability data and data related to hydrolytic, oxidative or radical-induced degradation are more important.
- Good progress was evident in the development of low cost materials. Most likely the polymers are good enough, although the DOE target for conductivity was not demonstrated.
- A number of membranes exhibit high enough conductivity for first level milestones.
- Durability not tested and is highly questionable.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.2** for technology transfer and collaboration.

- Little collaboration apparent to date. Collaboration/interactions with experts in fuel cell membrane area would help choices of cross-linkers, etc. that would be more stable in a fuel cell environment.
- No industry partner to give good feedback on the membrane.
- More interactions with Fuel Cell labs and centers are needed to get honest feedback on this material.
- There was no evidence of any external collaboration of future plans for it.
- This project would benefit from a collaboration with someone with Fuel Cell experience (e.g., National Renewable Energy Laboratory or Los Alamos National Laboratory).
- The team has 2 primary participants. The connection between these two participants and how they synergistically benefit each other is unclear.
- Perspective from outside investigators on al requirements of a fuel cell membrane seems almost essential.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.5** for proposed future work.

- Need more focus on membranes that would be stable under fuel cell conditions (aromatic, with stable cross-linkers).
- Need more work on inorganic additives and strategies to provide high-temperature, low-relative humidity conductivity.
- Proposed future research will address some of the durability issues.
- *In situ* chemical stability data should be obtained.
- All the most important tests they have not been conducting are planned for the future (conductivity vs. relative humidity, relative humidity cycling, open circuit voltage).
- No promising plans for improving stability of materials.
- The *ex situ* (Fenton's test) and *in situ* (open circuit voltage) tests proposed are important at this stage and should be done ASAP.
- Future work looks like a laundry list with some items of little relevance. The focus on degradation studies is certainly important, oxygen permeability and dielectric studies will give limited value and seem to be included simply because they are equipment available to the project.
- The future work mentioned was completion of the project, just doing more work, and achieving better performance and lifetime.
- A definite path forward with preparation of inorganic composites, in the lab of highly experienced practitioner planned.
- The investigators clearly understand the issues (durability, further increases in conductivity).

Strengths and weaknesses

Strengths
- Low-cost option.
- New polymer development and thinking outside the box.
- Lots of cross-linking chemistry has been developed, which could teach other groups on cross-link-mediated membrane stabilization methods.
- None.
- The synthetic chemistry is first rate.
- Strong synthesis capabilities.
- Original approach.

Weaknesses
- Durability concerns with polymer structures currently being studied.
- No industrial partner to give right feedback on the requirements of membrane properties.
- No chemical stability work has been conducted with the present polymeric system to assess its use under fuel c ell conditions.
- Too much focus on thermal analysis.
- No data reported on conductivity at low relative humidity.
- No swelling or mechanical data presented.
- Materials being studies are inherently unstable in fuel cell environment.
- This class of materials may not be suitable for fuel cell applications.
- No collaborations.
- Durability concerns with polymer structures currently being studied.
- Too much focus given to mechanical properties. Not enough chemistry development, durability studies, or conductivity data to suggest these materials offer promise. Based on chemistries presented stability and durability are almost certainly poor, and conductivity reported to date is not compelling.
- Fuel cell membrane electrode assembly fabrication and testing should be done in conjunction with DOE partners who excel in those tasks.
- Large questions re: durability.

Specific recommendations and additions or deletions to the work scope

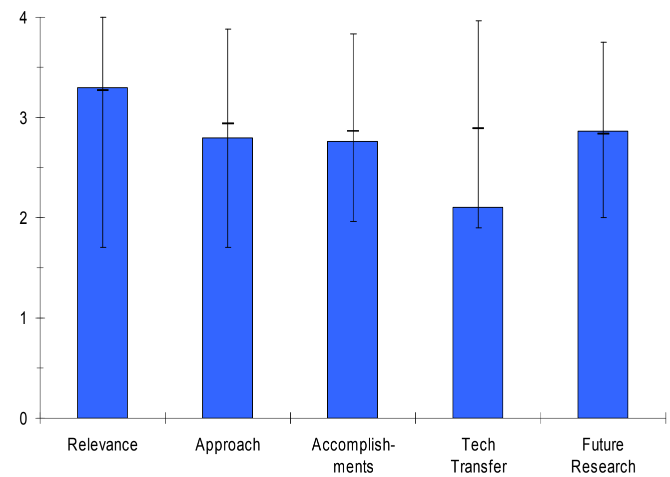
- Fuel cell testing of the material should be included.
- Chemical degradation work, such as Fenton's decay, should be done.
- The polymer stability should be assessed before proceeding to next phase of the work.
- Membrane electrode assembly development process to generate good membrane electrode assembly interface should be carried out.
- Eliminate Cl cross-linkers.
- Increased focus on aromatic membranes.
- Eliminate mechanical property studies; focus on degradation studies and conductivity studies.
- Modify materials set to a set of materials that has some chance of being fuel cell stable.
- The tests with Fenton's reagent should be avoided, since those conditions are just too aggressive. It is important to test to see how long the membrane materials will perform, rather how quickly they can be destroyed!
- These investigators could really use an infusion of experience with membrane requirements for fuel cell operation.

Project # FC-26: PEM Fuel Cell Durability
Rod Borup; Los Alamos National Laboratory

Brief Summary of Project

The overall objective of this project is to quantify and improve polymer electrolyte membrane fuel cell durability to 5,000 hours (with cycling). The objectives of this project are to 1) define degradation mechanisms; 2) design materials with improved durability; 3) identify and quantify factors that limit polymer electrolyte membrane fuel cell durability; and 4) improve durability. Property changes in fuel cell components during life testing will be measured (membrane-electrode durability, electrocatalyst activity and stability, electrocatalyst and gas diffusion layer carbon corrosion, gas diffusion layer hydrophobicity, bipolar plate materials and corrosion products).

Overall Project Score: 2.8 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Deeper understanding of durability mechanisms are needed to meet automotive fuel cell targets.
- Very good – durability is a major issue. Identifying causes of decay is important. Accelerated tests, as noted, may not have adequate fidelity.
- The overall objective of the project addresses a key barrier, durability. It is not clear from the work described how it addresses performance and cost as claimed.
- Original equipment manufacturers carry out in-house durability testing, so project relevance is predicated upon 1) ability to discover new test protocols for uncovering failure modes, and 2) informing DOE on the durability status of relevant materials in relevant cell designs. Further testing is needed to determine whether #1 will be accomplished. #2 has not occurred.
- Goals align well with DOE technical target of 5000 hours durability.

Question 2: Approach to performing the research and development

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

- Research objectives have changed over time which creates more issues.
- Segmented cell analysis is unique and interesting.
- Very good – Activity appears to be using the synergy of previous projects.
- The approach is highly experimentally focused and somewhat split between accelerated test method evaluation and their application to membrane electrode assembly materials.
- It is not clear if the approach should be more focused in one way or the other.
- A project that is seeking to look at stack durability should do *in situ* testing followed by failure analysis, which matches this project's approach.
- Challenges involved in doing such a project include 1) validation of test stand (representative system volume, speed of mass flow controllers, reference electrodes to quantify half-cell voltage), 2) selection of relevant materials, 3) selection of relevant cell design, 4) failure mode isolation with protocol, 5) selection of relevant operating conditions, and 6) reporting correct metrics. Project has reported a focus on #4, but #1-3 and 5 are not reported. Before and after performance should be reported to enhance #6.

- Proposed accelerated testing studies appear sound.
- Most of work focused on accelerated testing studies.
- Not much discussion regarding identification of factors limiting durability, mechanisms for degradation of material, or design to improve durability.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- A lot of superficial work was shown due to vastness of program.
- Some results/experiments are not well-controlled or analyzed (step vs. ramp voltage cycling). Some results/experiments, however, do show high value preliminary results (gas diffusion layer degradation).
- Good – Accomplishments and progress appear to be at the expected level due to the complexity of the issues.
- A lot of good work was accomplished since the recent restart, but spread over application of multiple types of accelerated durability tests applied to undefined types of membrane electrode assemblies. It is good to demonstrate the suite of different tests, but as a result, the progress can only be considered modest in overcoming barriers. It is not clear what was learned specifically about materials issues.
- Start-stop phenomena observed (SU/SD CO_2 loss at different temperatures, purge) need to be put in perspective of half-cell voltage, performance data (e.g., mass activity), and failure analysis.
- Gas diffusion layer degradation phenomena study shows good progress. The next step is to test electrochemical/*in situ* stressors and then do single fiber / sessile drop tests again. Chemical analysis should confirm distinction between exposed carbon fiber and degradation that could have occurred to hydrophobic agent.
- On segmentation, *in situ* work should show whether performances losses were recoverable or were the result of low polymer electrolyte membrane humidification, removable catalyst surface oxide/hydroxide.
- H_2O_2 formation could be higher at 100% relative humidity – validation required. Polymer electrolyte membrane material parameters unknown.
- What is being expected is tough to accomplish, so the efforts thus far should be applauded in spite of low ability to directly apply to automotive realities.
- Have identified certain operational issues important to durability, such as relative humidity and temperature.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.1** for technology transfer and collaboration.

- No official partners hurts the overall program.
- Good/Fair – It would have been cost-effective to leverage the technical activities of Fuel Cell Commercialization Conference of Japan (FCCJ), US Fuel Cell Council (USFCC), and the other academic labs. Consideration should be given in sharing raw data on a Non-Disclosure basis with the other researchers.
- The principal investigator's presentation states there are no formal partners. The stop and recent restart history of the project may be partially responsible for the lack of significant coordination or technology transfer.
- According to the presentation, there are no formal partners, although certain organizations are leveraged for analysis and material inputs.
- Materials sets need to be reported. Membrane electrode assembly composition (gas diffusion layer product code, catalyst loading, polymer electrolyte membrane thickness, etc.) is unknown.
- Materials obtained from other institutions.
- Some analyses performed by others institutions.
- One 2007 and no 2008 publications.

Question 5: Approach to and relevance of proposed future research

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

- All proposed research topics are of high value and interest if done properly with the needed resource and scientific depth.
- Good – Plans are rational, but do not appear to leverage other external activities.
- Proposed focus on four major areas may spread the resources too thinly. Accelerated durability measurements/protocol evaluation and trying to correlate durability with the accelerated tests may be a full time project. Or component-interface durability and correlation with property measurements may be a full time project. But combining them may be too much for the resources available.
- The list of expectations is extraordinary, including accelerated stress testing and correlations with *in situ* durability.
- Fundamental validation of test equipment needs to be reported so that investigators know that realistic stressors are being applied. This needs to be the most immediate focus.
- Continuation of gas diffusion layer component durability work is needed, but needs to be related to *in situ* stressors.
- Fundamental mechanistic studies are proposed.
- Good to correlate accelerated testing with durability.

Strengths and weaknesses

Strengths
- In-depth background knowledge of fuel cells.
- Ability to do a variety of in-house experiments.
- Addressing a complex and timely issue.
- Experience and reputation of the principal investigator and his facilities.
- Investigators involved are greatly experienced and are experts with conventional fuel cell failure mode knowledge and test capability.
- The correct failure modes are being attacked.
- Thorough reporting of *in situ* metrics for polymer electrolyte membrane fuel cell work.
- Proposed accelerated testing studies appear sound.
- Goals aligned well with DOE technical target of 5000 hours durability.
- Have identified certain operational issues important to durability, such as relative humidity and temperature.
- Fundamental mechanistic studies are proposed for future work.

Weaknesses
- Too many research topics.
- No official partners.
- Segmented cell experiments while interesting may not be applicable due to unique cell designs.
- Lack of synergy and collaboration with other researchers doing similar research.
- Lack of closer interactions with key fuel cell system integrators or stack developers for guidance on accelerated tests.
- Relationships with realistic *in situ* stress must be established for all testing.
- Test stand validation needs to be reported (reference electrodes, system volume, etc.).
- Reporting of material set parameters needs to be improved.
- Expectations are extremely high. A direct focus on a failure mode and demonstrating a realistic isolation of that failure mode *in situ* would yield greater benefit.
- Thorough reporting of *in situ* metrics needed for work other than polymer electrolyte membrane fuel cell work.
- No discussion regarding cost barrier.
- Discussion regarding identification of factors limiting durability, mechanisms for degradation of material design to improve durability is limited.
- Progress on the fundamental understanding of decay mechanisms is limited.

Specific recommendations and additions or deletions to the work scope

- Focus on 1-2 key topics.
- Add official partners to program; possibly original equipment manufacturers to help in understanding.

- More collaboration and a willingness to share raw data with other researchers.
- Reconsider the scope of the future work plan to allow accomplishing more and faster progress on just the top one or two most critical aspects of durability.
- Delete chemical hydride work until a validated means of hydrogen storage is known.
- Focus on linking one particular failure mode to realistic stack operation. Once this is accomplished, a similar methodology could be applied to other failure modes. For example, this project could just devote itself to start/stop phenomena, or to gas diffusion layer degradation, and deliver greater results than what is has done so far.
- May want to also suggest fundamental mechanisms for experimental observations.

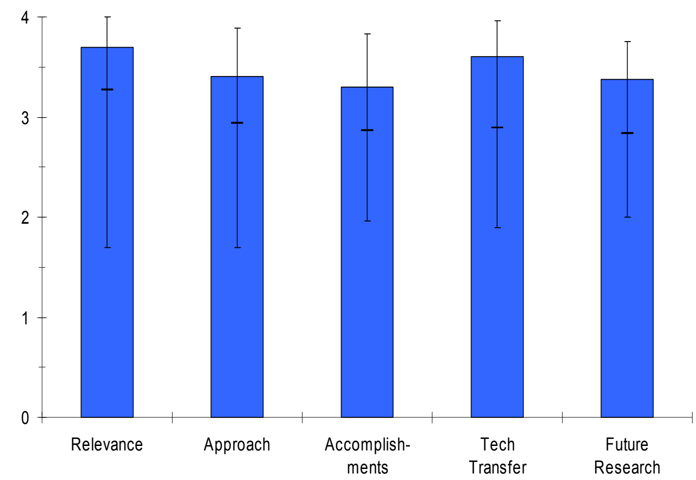
Project # FC-27: Nitrided Metallic Bipolar Plates

Peter Tortorelli; Oak Ridge National Laboratory

Brief Summary of Project

The overall objective of this project is to demonstrate potential for metallic bipolar plates to meet automotive durability goals at a cost of <$5/kW. Ferritic and duplex compositions amenable to both stamping and nitriding have been identified. An alloy and nitriding envelope capable of imparting low interfacial contact resistance and high corrosion resistance at potentially acceptable nitriding cost has been identified (all in the range of Department of Energy targets). Stamped alloy foils without embrittlement and with little warping were also demonstrated.

Overall Project Score: 3.4 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- Metal bipolar plates with a low cost, low thickness, and high durability are needed to meet fuel cell commercialization requirements.
- The project is relevant toward meeting bipolar plate cost targets.
- Cheap mass production of metal bipolar plates is critical to the President's Hydrogen Fuel Initiative.
- This task is strongly relevant to the Hydrogen Fuel Initiative and goals and objectives of the Multi-Year RD&D Plan.
- Durable, cost-effective bipolar plates that meet targets for conductivity and corrosion resistance are essential to the commercial viability of automotive polymer electrolyte membrane fuel cells.
- Nitrided metallic plates – corrosion resistance of metallic plates is key to successful implementation in automotive systems.

Question 2: Approach to performing the research and development

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

- Overall approach and concept are high level.
- It is unclear why two model materials were needed to validate the concept – time and money were wasted.
- Nitriding of metal plates is a unique approach to enable use of low-cost alloys without the addition of conductive coatings.
- Corrosion and durability show potential but more work is required.
- Nitrided bipolar plates and their characterization/mechanical properties.
- Scale-up to single cell, then scale-up to stack.
- The approach is very well laid out and delineated with clear go/no-go milestones.
- Resistivity, corrosion, and cost goals are clearly and methodically being addressed.
- Results to date indicate the approach is technically feasible and reasonably well integrated with other research via the diverse team Oak Ridge National Laboratory has organized.
- Nitriding is a well-developed technology in other industries and should be explored for use in bipolar plates. The principal investigator has a thorough understanding of the materials interaction and coating technologies.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Good progress was shown with materials, however, two model materials slowed down overall progress unnecessarily.
- Durability studies showed good results, however, are the durability conditions valid and worthwhile for automotive conditions?
- The pathway was developed to meet performance and durability targets with low-cost Ferritic plates.
- The principal investigator claims (no data shown) that nitriding can be done without embrittlement and with little warping.
- The project met its first milestone.
- Vary Cr/Ni/V to optimize the plate.
- The corrosion test was passed.
- Ferritic foil was developed.
- The project has achieved the first of three significant go/no-go milestones and is progressing toward the second.
- It appears promising that the second go/no-go milestone will be achieved given that targets for contact and corrosion resistance have largely been achieved.
- Cost estimates indicate that cost targets are potentially within reach. High volume, cost-effective nitriding techniques will have to be further explored to achieve delta of $0.75/kW.
- When looking at level of Nickel addition to alloy, it is a balancing act between stampability, nitride protection, and cost.
- Significant accomplishments have been achieved metallurgically.
- Overall, significant progress has been achieved and clear pathways for further progression are evident.
- Excellent effort in identifying cheaper metals - final step in joining two stamped plates to form the bipolar plate hasn't been demonstrated.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.6** for technology transfer and collaboration.

- Very high level/clear interaction with all of the players.
- All of the key players (minus original equipment manufacturer) are involved and interactive.
- The principal investigator showed good collaborative effort with metal sheet supplier and labs for testing.
- Valuable input from Directed Technologies, Inc. on nitriding cost analysis.
- Good industrial collaborations.
- Continued cost analysis.
- Oak Ridge National Laboratory has built a solid and appropriate team for the task including a commercial alloy foil manufacturer, commercial bipolar plate company, and laboratory/university fuel cell testing entities. All the major bases are covered.
- Teaming arrangement with Allegheny Ludlum and GenCell will provide the basis for future commercialization of the nitrided stainless steel bipolar plates.

Question 5: Approach to and relevance of proposed future research

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

- Proposed research work is well-planned.
- Milestones with go/no-go decisions are wise and well thought-out.
- Detailed characterization of corrosion and electrical properties is planned.
- Planned stack testing will be critical to prove the technology.
- Additional effort should be taken to reduce nitriding process cost by reducing time and temperature or alternating nitriding methods.
- Detailed characterization of corrosion.

- Proposed future research is right on target for achieving the correct balance between stampability, cost, and corrosion protection.
- Oak Ridge National Laboratory has identified several options for achieving low-cost nitriding that will be pursued in collaboration with a commercial company in fiscal year 2009.
- There is little discussion of other options should low cost, nitriding processes not achieved or if an appropriate balance of elements, including addition of Nickel, cannot be achieved.
- Questions were raised during the presentation with respect to the effect of welding or other joining techniques on the durability of the nitride layer. This may be an open issue that should be explored.

Strengths and weaknesses

Strengths
- Key players are all involved.
- Unique surface technology.
- Understanding of cost targets.
- Ability to tailor hydrophobicity of nitride layer.
- Ability to implement lower cost (Ferritic) thin metal plates.
- Excellent project clearly targeted to the needs of bipolar plates for polymer electrolyte membrane fuel cells and the Hydrogen Fuel Initiative.
- Very deep, well rounded team.
- Demonstrating steady, consistent technical progress with strong potential to achieve all targets for bipolar plates.
- The principal investigator identified a reasonable pathway to use cheaper metals and maintain conductivity.

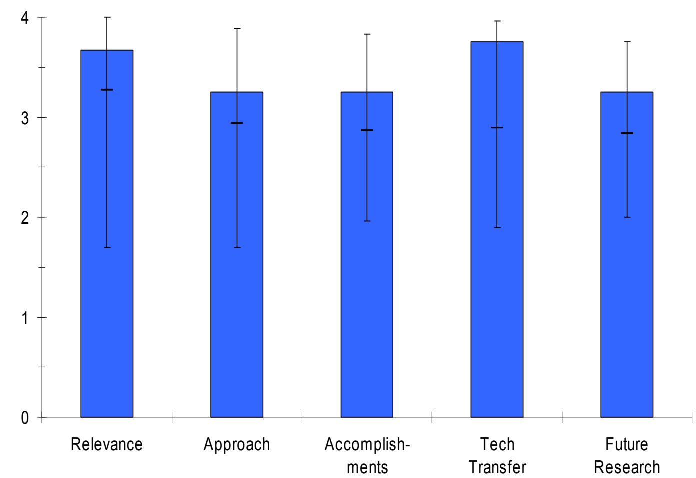
Weaknesses
- Lack of original equipment manufacturer input specifically on durability.
- High temperature, relatively long nitriding process may be cost-prohibitive.
- No significant apparent weaknesses.

Specific recommendations and additions or deletions to the work scope

- Perhaps the addition of original equipment manufacturers to help with targets.
- The principal investigator needs to figure out the last step of joining the plates and preventing scratches and damage of coated plates in shipping, assembly, etc.
- More focus on joining of unipolar plates including welding.
- Look into lower nitriding temperatures and plasma nitriding processing.
- Explore possible effects of fuel cell joining techniques on durability of the nitriding layer.
- Consider other options for squeezing a little more cost out of the alloy and stamping phases, should nitriding prove a little more costly than expected.

Project # FC-28: Next Generation Bipolar Plates for Automotive PEM Fuel Cells
Orest Andrianowycz; GrafTech International, Ltd.

Overall Project Score: 3.4 (6 Reviews Received)



Brief Summary of Project

The overall objective of this project is to develop the next-generation automotive bipolar plates based on an engineered composite of expanded graphite and resin capable of operation at 120°C. The goals for year 1 are to 1) develop a graphite/polymer composite to meet the 120°C fuel cell operating temperature; and 2) demonstrate manufacturing capability of new materials to a reduced bipolar plate thickness of 1.6 mm. The year 2 goals are to 1) manufacture high-temperature flow field plates for full scale testing; 2) validate performance of new plates under automotive condition using a short (10-cell) stack; and 3) show viability of published cost target through the use of low-cost materials amenable to high-volume manufacturing.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- Low cost, thin, highly durable bipolar plates are necessary for fuel cell commercialization.
- Cost and durability at extreme operating conditions are critical. This project addresses both issues for the bipolar plate.
- Project focused on the development of manufacturable, lower-cost bipolar plates.
- The development of a low cost bipolar plate is critical to meeting the targets for the automotive application of polymer electrolyte membrane fuel cells.
- Developing durable, cost effective plates is important to the Hydrogen Fuel Initiative. Currently, no plate technology meets all the DOE bipolar plate targets – particularly for high temperature systems.

Question 2: Approach to performing the research and development

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

- Technical approach for graphite plates is strong – world experts. However, calculation/proof of power density needed for original equipment manufacturers based upon their thinnest bipolar plate design, is imperative.
- Methodical approach to materials selection and processing into plates.
- Project includes testing in full-area stacks.
- Approach has focused on a comprehensive selection of materials over a very large design space to structure graphite-based plates with high-temperature capability and high-volume manufacture.
- Approach is to develop polymer composite material for operation at 120°C.
- Approach is to demonstrate plates in a stack.
- Evaluation and down-selection of graphite and resin.
- The project has a systematic approach to the development of bipolar plates.
- Modifying existing technology to incorporate more stable resins for the higher temperatures is a logical approach for this foil-type technology. Approach, however, does not improve on all the weaknesses of this plate technology – particularly power density.
- Principal investigator needs to also evaluate effects of resin technology on plate porosity, strength, etc.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.3** based on accomplishments.

- Based on principal investigator's criteria, progress is very strong and targets are being reached. However, hydrogen permeability has not been tested yet – there is only an assumption based on nitrogen permeability.
- Potential to meet thickness requirements needed for original equipment manufacturers has not been accomplished.
- Project is on track and has met critical interim technical milestones to date.
- Good progress has been made in material component selection and initial formulation of composite material for plate fabrication. Initial testing of chosen material has been conducted along with preliminary *in situ* fuel cell testing.
- Bipolar plates survived shock tests.
- Plate has operated for 700 h at 120°C (actually 1000 h of operation).
- The project has completed the objectives of Task 2, 3, & 4. G made in Task 1.
- Very good progress made in fabrication and manufacturing tasks. Proof that materials will meet high temperature goals has not been demonstrated and could be a weakness.
- More effort on porosity work is required.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.8** for technology transfer and collaboration.

- High level, clear collaboration between the various partners.
- Ballard might not be considered an original equipment manufacturer now that they have sold off their automotive section.
- Excellent vertical team including raw materials supplier to polymer electrolyte membrane stack manufacturer.
- A strong partnership has been formed and is actively bringing testing, additive, and design expertise to complement GrafTech's capabilities.
- Good selection of original equipment manufacturers and a university.
- Project has good mix of industry and academic researchers.
- Principal investigator is collaborating with a major stack developer. Ballard, who is a major proponent of GRAFOIL technology and will identify appropriate applications for this type of plate (even if it may not be suitable for automotive use in the end).

Question 5: Approach to and relevance of proposed future research

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

- Future research is well described and logical, but needs the calculation of power density based on their thinnest plate design.
- Next steps are logical and follow the original project plan.
- Good plans to continue this project with a focus on manufacturability and cost.
- Future plans include finalized design of plate.
- Future plans include short stack test of full size plates.
- Future plans include economic assessment.
- GrafTech did not identify completion of Tasks 1 and 5 as part of future effort.
- Principal investigator needs to continuously incorporate new plates into stack systems to evaluate performance – such activities are appropriately covered in their future work plan.

Strengths and weaknesses

Strengths
- Key players are world experts in this area.

- Fabrication methodology appears very solid.
- Excellent corrosion resistance.
- Good thermal and electrical conductivity.
- Good flexibility and weight.

Weaknesses

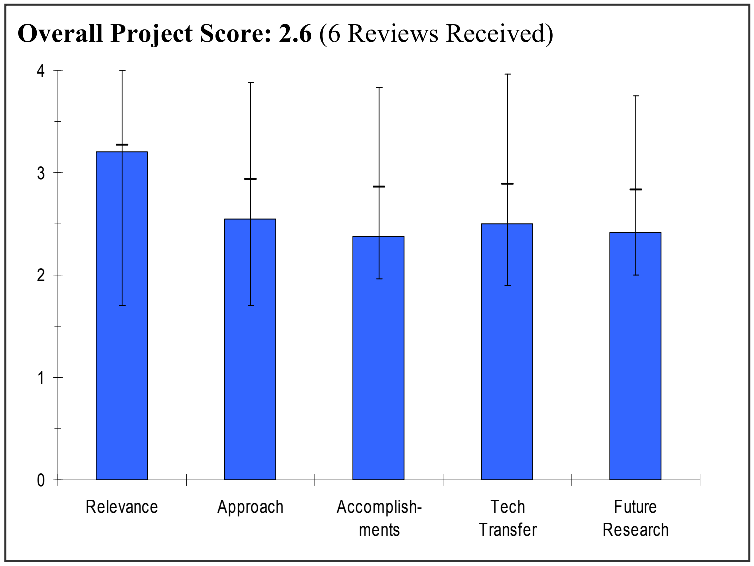
- Lack data to show viable original equipment manufacturer specifications for commercialization.
- High temperature durability is critical to achieving the DOE goals, and fuel cell testing is lagging the rest of the project.
- The project is moving rapidly toward a finished product without key durability and materials stability data. These data are usually obtained early on in a project. It is of little value to develop a process for a material that will not achieve durability and stability values.
- Plates will always remain bulky volumetrically.
- Porosity issues will be difficult to resolve.
- Poor channel formability might create problems for certain stack designs and/or create high contact resistance or poor fit if tolerances of the plates aren't well controlled.

Specific recommendations and additions or deletions to the work scope

- Hydrogen permeability studies.
- Cost calculations based on plate thickness as soon as possible.
- Accelerate durability testing of the materials.

Project # FC-29: Effects of Impurities on Fuel Cell Performance and Durability
James Goodwin; Clemson University

Brief Summary of Project



The overall objectives of this project are to 1) investigate in detail the effects of impurities in the hydrogen fuel and oxygen streams on the operation and durability of fuel cells (CO, CO_2, NH_3, H_2O, HC, O_2, inert gases, and H_2S); 2) determine mechanisms of impurity effects; and 3) suggest ways to overcome impurity effects. The year 1 objectives are to 1) obtain and characterize components of the membrane electrode assembly to be used (20% Pt/C, 30% Nafion/C, Nafion-Pt/C, Nafion membrane); 2) design and set-up measurements of impact of impurities on membrane electrode assembly components; 3) install fuel cell test station; 4) calibrate fuel cell test station measurements in "round robin" test of standard membrane electrode assembly with other Department of Energy contractors; and 5) start characterization of effects of CO and NH_3.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.2** for its relevance to DOE objectives.

- Very good – the compounds listed match the industry concerns. The data on tetrachloroethylene at a concentration of 150 ppm was a very pleasant surprise.
- The project is a mixture of technique development, establishing capabilities and understanding of how to apply those techniques while using some reference impurities. The project is not yet ready to have any significant impact on the durability barrier.
- The project objectives are relevant to the DOE objectives.
- This activity supports DOE's fuel cell development and speaks to fuel purity issues.
- In general, the study of impurities contributes directly to the DOE objective to meet 5,000 h lifetime over a realistic automotive drive cycle.
- Project relevance is weak versus other projects due to heavy amount of work on the most studied impurity in the literature, carbon monoxide
- A project that mostly focuses on carbon monoxide will likely not be useful since most stack original equipment manufacturers already have a strategy for avoiding the ill effects of CO.

Question 2: Approach to performing the research and development

This project was rated **2.6** on its approach.

- Very good – the approach to the testing is basically conventional. The benchmarking to the DOE round robin demonstrated that the data is repeatable (multiple runs in the stand) and reproducible (the same results as seen at other labs involved in the round robin).
- The biggest issue appears to be that the objectives are too broad for the available resources and experience of the principal investigator and team members. For example, the principal investigator's experience with fuel cell testing and characterization is just beginning.
- The approach defined in slide 5 could only be carried out well by a much larger and more experienced team. All four boxes in slide 5 are large endeavors on their own.

- Good approach, however recommend testing of impurity effects using membranes other than Nafion.
- Concerns about duplication with other related projects within the group.
- Development of standard durability testing per impurity needs to be considered.
- The project places too much emphasis on fundamental understanding of the interactions of impurities on the surface of Pt, mainly CO. The fuel cell developers are interested in data that would allow them to develop engineering models that can be used to predict performance loss when using fuel grade hydrogen.
- The approach needs to address longer-term testing to understand the effect of impurities on fuel cell durability.
- The plan is to not only document the effect of contaminants on performance, but to develop an understanding of the chemistry of the performance loss—seeking answers about the actual chemical dynamic changes.
- Proposed model mechanism is missing steps (e.g., diffusion of O_2 across catalyst layer ionomer to the Pt surface as a function of relative humidity).
- Relative significance of tetrachloroethylene is suspect as a system contaminant. University of Connecticut project will also study halogenated compounds and these efforts should be coordinated.
- Round robin testing based only on polarization curves at high dew points. Most round robin tests fail when low dew points are needed, or when stoichiometry sensitivity tests are done (especially with gas blending). H_2/N_2 blending on the anode would help to demonstrate an organization's competency to blend inlet gases.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.4** based on accomplishments.

- Outstanding – starting from scratch, developing test methodologies, getting test facilities online, validating the facilities and methodologies, and generating meaningful data in a year is excellent.
- The project has made progress toward some of its objectives, and shows some interesting new analytical results, but could not claim to have made any real progress toward overcoming the DOE barriers at this time.
- The emphasis on CO is rehashing a much-studied system, going back to the years of membrane electrode assembly development for reformate. Except for training the investigators, this is not likely to provide any new information.
- The electrochemical impedance spectroscopy results should be looked at carefully. The high frequency intercept on the x(real)-axis for the baseline curve cannot be correct since an impedance of 0.5 ohm-cm^2 would imply a voltage loss of 500 mV at 1 A/cm^2 just due to current resistance losses, which can't be true as their round robin polarization curves show.
- Technical results were overall repeated from literature, i.e., NH_3 and H_2S on similar membranes, so more focus should be given to devising mitigation strategies rather than duplicating previous literature.
- Progress in getting started, set-up and calibration of equipment in this project has been reasonable.
- Clemson University has found some evidence of resistance increase in the ionomer and membrane with NH_3 poisoning but there is some question as to the validity of the impedance spectroscopy data.
- Their results appear to be consistent with those from other round robin test participants.
- Much of the information discussed was not that unique. Others have arrived at much the same conclusions earlier. However, what was shown was a series of useful and intelligent diagnostic tools that explore fuel cell electrochemistry. The fuel cell community has invested considerable resources into the South Carolina economy; it makes sense to build strong technical competence to back that investment. That competence was demonstrated.
- High frequency resistance measurements in the NH_3 study show a baseline (with no NH_3) >500 mohm-cm^2. For any standard membrane electrode assembly, like the one used, this number should be between about 20 to 150 mohm-cm^2, even with 50% inlet relative humidity. There is something wrong either with the alternating current impedance measurement or with the cell assembly. This issue is where further collaboration would help.
- NH_4^+ contamination of polymer electrolyte membrane and ionomer is known.
- Recovery from CO poisoning due to surface restructuring is unlikely. Investigators should check O_2 content in gas inlets.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.5** for technology transfer and collaboration.

- Very good – the formal collaboration appears to be as expected. The current level of collaboration with Los Alamos National Laboratory, Hawaii Natural Energy Institute, University of South Carolina, University of Connecticut, and Argonne National Laboratory is a very pleasant surprise.
- The presentation did not make clear what the various contributions were from each collaborator. It appeared that most of the work was done by Clemson University.
- Appears too early yet to expect any technology transfer.
- Collaboration with others, Los Alamos National Laboratory and University of Connecticut, is highly recommended and seems to be lacking.
- Collaborations are evident in the US Fuel Cell Council round robin testing.
- Savannah River National Laboratory and Greenway Energy are partners with University of South Carolina.
- Other than the University of South Carolina, the collaborators involved do not have a rich history in fuel cell research. This is evident in much of the work, some of which appears to be motivated more by a desire to get familiar with fuel cell research than a desire to add to what is known.
- There is no evidence in the presentation of deep involvement by the University of South Carolina, except for the modeling task.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.4** for proposed future work.

- Very good – though research on low levels of CO_2, ethylene and ethane may not be cost effective.
- Future focus on halogenated compounds might arise from H_2 from chlor-alkali processes, heat transfer fluid leaks, or cleaning solvents and may be of more immediate support of DOE goals.
- The proposed research is too ambitious for the resources and time to complete the work.
- The work plan should be significantly focused to allow greater in-depth and higher quality results to be extracted.
- Suggest having a clear direction on mitigating strategies and testing several kinds of membranes, i.e., Pt alloy and membranes other than Nafion.
- Provide a plan clarifying the modeling efforts timeline and impurities down-selection.
- Too much emphasis on developing first principles kinetics and rate expressions.
- The way that this diagnostic tool will be deployed to support fuel cell progress was not obvious.
- CO work needs to be cut.
- Plans to study CO_2, NH_3, and ethylene are reasonable as long as they do not overlap with other projects.
- Given the familiarity of CO_2 and NH_3, and the expected low contamination by ethylene, the project could use some higher impact impurities to study.
- Ethane is not expected to be a highly detrimental contaminant.

Strengths and weaknesses

Strengths
- Current collaboration with other investigators.
- They have demonstrated some interesting new analytical techniques.
- Modeling potentials.
- The investigators are part of the round robin single cell testing being sponsored by the US Fuel Cell Council and have matched the results of the other organizations, which is an indication that their results can contribute to the understanding of impurities effects in fuel cells and the setting of standard fuel specifications.
- Project has responded to feedback to use lower Pt loaded membrane electrode assemblies.
- Project has approached tasks with thoroughness in step-by-step evaluations (Nafion/C vs. Nafion/Pt/C and so forth).
- Project has attempted to make use of less familiar analysis techniques.

Weaknesses

- A potential weakness might be the lack of willingness to share preliminary or unpublished data with other investigators. If the DOE target deadlines are to be met with quality results, researchers will need to be less parochial with the data.
- The project is trying to accomplish too much for the available resources and experience level of the investigators.
- Collaboration with others within the center to avoid duplication.
- The project places too much emphasis on the fundamental understanding of the interaction of CO on Pt surfaces. This has been studied extensively in the catalysis literature.
- The levels of CO (10 and 25 ppm) are almost an order-of-magnitude higher than are specified in the international fuel quality standards that are being developed.
- There is little apparent recognition of the large amount of data that exist on the impurities effects on fuel cells.
- Need to refine high frequency resistance measurements.
- Need to look at less-studied impurities.
- Need to collaborate with experienced partners.
- Need to refine modeling algorithm.
- Need to work on more challenging round robin protocols.
- Need to recheck CO recovery to find if there is an experimental artifact.

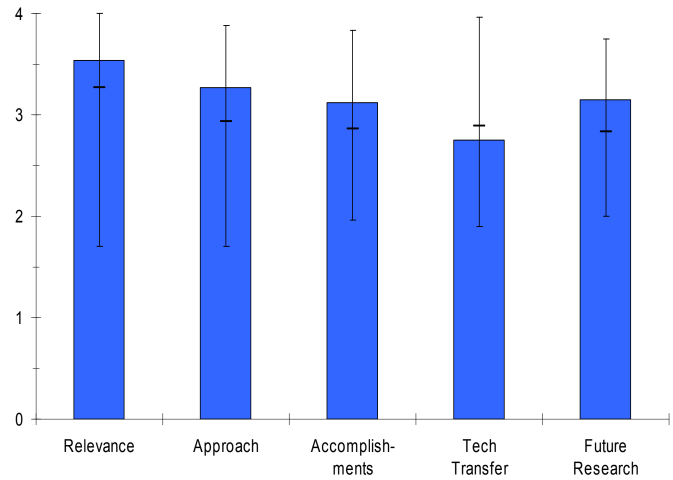
Specific recommendations and additions or deletions to the work scope

- CO, CO_2, NH_3, hydrocarbons (including C_2H_4, C_2H_6, H_2CO, HCOOH), Cl_2, and H_2S support industry activities.
- Data on non-reactive gases such as He, N_2, and Ar are not needed or cost effective.
- Testing on O_2 only appears to makes sense if the decay mechanism with "air bleed" (CO removal) is being investigated.
- Focus on just one of the three main activities and execute it with more in-depth understanding of one class of impurities, or take just one impurity only (but not the old CO) and try to develop a solid understanding of how it impacts the membrane electrode assembly components in depth.
- Suggest keeping the project; however, focus should be redirected for testing several types of catalyst-coated membranes and for mitigation strategies.
- Redirect the project to deemphasize the H_2-D_2 exchange work.
- Use much lower levels of impurities for future work.
- The modeling activity needs to be clearly focused. Fundamental understanding is good but will delay getting more empirical data for use in engineering models that are of interest to the fuel cell developers.
- Coordination between the various organizations involved in impurity research should be stressed to accelerate data collection for impurities of most interest to the organizations involved in drafting fuel quality standards.
- Clemson University should review the existing work on impurities effects—primarily from Los Alamos National Laboratory.
- Delete CO work (except for that which can address loose ends of prior work).
- Consider deleting ethane work if initial experiments do not show a detrimental effect on catalyst/ionomer.
- Add more influential impurities, other than NH_3.
- Add a major collaborator with deep fuel cell experience.

Project # FC-30: Effects of Fuel and Air Impurities on PEM Fuel Cell Performance
Fernando Garzon; Los Alamos National Laboratory

Brief Summary of Project

Overall Project Score: 3.2 (6 Reviews Received)



The overall objective of this project is to contribute to the scientific understanding of the effects of fuel and air impurities on fuel cell performance and how it affects Department of Energy fuel cell cost and performance targets. The specific objectives are to 1) investigate the effects of impurities on catalysts and other fuel cell components; 2) understand the effect of catalyst loadings on impurity tolerance; 3) investigate the impacts of impurities on catalyst durability; 4) develop methods to mitigate negative effects of impurities; 5) develop models of fuel cell impurity interactions; and 6) collaborate with the US Fuel Cell Council (USFCC), the FreedomCAR Fuel Cell Technology Team, industry, and other national laboratories to foster a better understanding of impurity effects.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Very good – the focus on completing sulfur contamination should be followed through.
- Fits only indirectly.
- It is very important to understand effects of both fuel and air impurities to reduce fuel cell system complexity and meet DOE cost and durability targets.
- The project objectives are relevant to the DOE targets.
- Important topic, however, one must examine if some of the impurities can be eliminated using filters/traps.
- Understanding impurity effects on the fuel cell is crucial in learning to develop more robust systems that meet DOE targets.
- Extremely relevant project fully supporting the President's Hydrogen Fuel Initiative and goals and objectives of the Multi-Year RD&D Plan.
- This project is filling a significant need to better understand the effect of fuel and air impurities on polymer electrolyte membrane fuel cells and their impacts on fuel cell durability and cost.
- Project is examining a number of areas previously not studied (such as co-adsorption of CO and H_2S) including poisoning at different temperatures and relative humidity levels, and recovery mechanisms.

Question 2: Approach to performing the research and development

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

- Very good – the approach to the testing is basically conventional. The benchmarking to the DOE round robin, glossed over on slide 5, demonstrated that the data is repeatable (multiple runs in the stand) and reproducible (the same results as seen at other labs involved in the round robin). This means data sets for the various labs can be merged to expedite this activity.
- A lot of tests (all, what is available?) to investigate the effects of a few impurities.
- Good approach for analysis and modeling of results.
- Considers effect of impurities on gas diffusion layer.
- Considers all important parameters (electrode kinetics, ionic and mass transport).

- Important to study crossover of contaminants through the membrane.
- Approach is similar to other members working on impurities effects. A collaboration between the impurity working groups is suggested.
- Good, methodical approach combining theory and experiment.
- One concern is that several of the results may be specific to the membrane electrode assembly studied.
- Project is very clearly addressing key fuel cell technical barriers including impurity tolerance and durability of electrocatalysts and membranes to a number of contaminants including H_2S, CO, CO_2, and alkali cations.
- Technical approach includes testing under steady state and cycling conditions, supporting experiments to measure fundamental parameters required for modeling, and analyzing and modeling data. Solid balance between empirical and modeling components within the approach.
- An appropriate approach is the project's intent to determine the limits of impurity tolerance within the bounds of the technical targets for electrocatalyst PGM loading.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.1** based on accomplishments.

- Good – the sulfur results while interesting have not been completed. There is mention of completing low catalyst loading tests, but the data were not included.
- The start on combining impurities effects is interesting. Data other than an electrochemically active surface area would have been interesting.
- A huge amount of data.
- Increased knowledge, but no solutions or recommendation to prevent degradation.
- Good experimental and mechanistic study of the effect of H_2S.
- Co-adsorption of CO and H_2S results confirm expectations.
- Interesting study of effects of cations on electrodes.
- Effect of catalyst loading not presented.
- *In situ* characterization of H_2S and its crossover is good however quantifying the amounts chemisorbed as function of H_2S exposure time and concentrations is suggested.
- Determination of cationic contamination for *in situ* conditions is suggested.
- Good progress towards stated goals.
- Project is geared towards studying the effects of poisoning and hence it is inappropriate to consider the extent to which project improves performance. However, the information gathered in this study will help design mitigation strategies.
- A number of technical accomplishments have been achieved including determination of performance degradation due to H_2S anode poisoning as a function of catalyst loading; modeling and validation of impurity effects in polymer electrolyte membrane fuel cells including effects of alkali cations; and assessment of combined CO and H_2S contamination.
- Technical accomplishments encompass balanced empirical and modeling results with a solid pace of results given the project started in October, 2006.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- Good – the formal collaboration appears to be as expected. The current level of collaboration with Savannah River National Laboratory/Clemson University, Hawaii Natural Energy Institute, University of South Carolina, University of Connecticut, and Argonne National Laboratory is a very pleasant surprise.
- Apart from dissemination in some groups/teams, no indication of transfer.
- Collaboration with Case Western Reserve University appears to be fruitful.
- Collaboration with other groups working on impurities is recommended and does not seem visible.
- Center is somewhat limited partner wise–they don't have a major stack original equipment manufacturer or automotive original equipment manufacturer as a partner to help them determine reasonable impurity sources

for the system. However, Los Alamos National Laboratory is very open with the information they share and consistently seek feedback from the original equipment manufacturers.
- Presentation early on mentions as a specific objective collaboration with the USFCC, the FreedomCAR Fuel Cell Technology Team, industry and other labs to foster a better understanding of impurity effects. However, with the exception of Case Western Reserve University, this objective was not really elaborated on and leaves some question as to the extent in which this is taking place with other entities.

Question 5: Approach to and relevance of proposed future research

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

- Very good – the question is can we close the story on H_2S by the end of this year?
- Somehow straightforward but not really clear.
- Hydrocarbon and particulate impurities are important, maybe also SO_2.
- It is important to identify the lowest level of any particular impurity or combination of impurities that can be tolerated without significant impact on cell life.
- Gas diffusion layer studies mentioned in the approach are not included in the future work.
- Suggest collaboration with groups modeling the impurities effect on fuel cell performance.
- It is suggested that fuel cell performance degradation due to anode and crossover be quantified to predict fuel cell degradation under prolonged exposure to low concentration impurity in real life scenarios.
- Future plan proposed is logical.
- The project provides a very clear sense of proposed future work including continuation of some existing activities such as continued contaminant crossover studies and the effects of divalent cations, as well as new studies looking at air contaminants including hydrocarbons and particulates.
- Presentation does not provide a clear sense of how partnerships with other entities will be used in the future to leverage Los Alamos National Laboratory activities.

Strengths and weaknesses

Strengths
- Current collaboration with other investigators.
- Good fundamental understanding of H_2S poisoning.
- Study of co-adsorption of two impurities (CO and H_2S).
- Systematic approach.
- Good integration between theory and experiment.
- Focus on fundamentals is encouraging.
- Extremely relevant project with regards to effects of contaminants on fuel cell durability and cost encompassing a strong approach balancing empirical and modeling activities and results.
- Solid pace of technical accomplishments and plan for future work.

Weaknesses
- A potential weakness might be the lack of willingness to share preliminary or unpublished data with other investigators. If the DOE target deadlines are to be met with quality results, researchers will need to be less parochial with the data.
- No life studies carried out to date.
- Collaboration with others is not visible.
- Suggest proposing mitigation techniques as the effects are investigated.
- Unclear if model includes forming parameters, and if so, if a sensitivity analysis has been performed.
- Unclear as to full extent of collaboration with other industrial, lab, and university organizations.

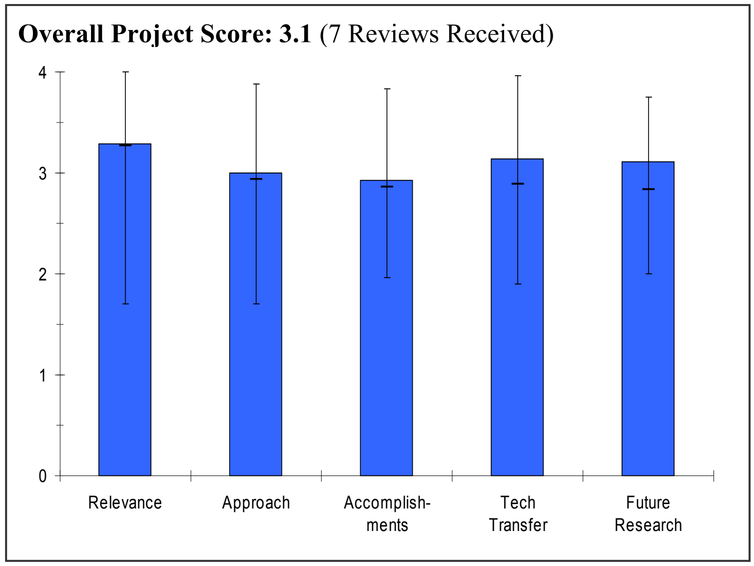
Specific recommendations and additions or deletions to the work scope

- Complete the story on H_2S so that the effects based on pressure, temperature, relative humidity, current density or cell voltage and catalyst loading can be predicted.

- Study effect of catalyst loading.
- Encourage further studies of combined effect of two or more impurities.
- Suggest keeping the project; however, collaboration with others working on impurities is suggested to avoid duplication.
- May benefit from a modest increase in overt collaboration with other research and industrial entities to leverage activities and maximize impact of results at commercialization interfaces.

Project # FC-31: The Effects of Impurities on Fuel Cell Performance and Durability
Trent Molter; University of Connecticut

Brief Summary of Project



The overall objective of this project is to develop an understanding of the effects of various contaminants on fuel cell performance and durability. The specific objectives are to 1) identify specific contaminants and contaminant families present in both fuel and oxidant streams; 2) develop analytical methods to study contaminants; 3) conduct experimental design of analytical studies; 4) create novel *in situ* detection methods; 5) develop contaminant analytical models to explain effects; 6) establish an understanding of the major contamination controlled mechanisms that cause material degradation in polymer electrolyte membrane fuel cells and stacks under equilibrium and especially dynamic loading conditions; 7) construct material state change models that quantify that material degradation as a foundation for multiphysics modeling; 8) establish the relationship between those mechanisms and models and the loss of polymer electrolyte membrane performance, especially voltage decay; 9) validate contaminant models through single cell experimentation using standardized test protocols; 10) develop and validate novel technologies for mitigating the effects of contamination on fuel cell performance; and 11) conduct outreach activities to disseminate critical data, findings, models, and relationships that describe the effects of certain contaminants on polymer electrolyte membrane fuel cell performance.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Effect of impurities on polymer electrolyte membrane fuel cell performance is critical to defining H_2 quality and fuel cell durability.
- Focus on fuel impurities.
- Very good – the compounds listed match the industry concerns. The data on methane and ethane at high concentrations combined with the Japan Automobile Research Institute data at low concentrations puts these compounds to bed.
- The selected impurities and overall objectives are relevant to the fuel cell application.
- Supports one barrier only, but is well focused on it.
- Project addresses DOE goal of increasing the durability of fuel cells by investigating the effects of impurities on performance.
- The project objectives are relevant to the DOE objectives.
- Contaminant effects can be a true barrier to fuel cell deployment and must be studied to understand levels, effects and mitigation.

Question 2: Approach to performing the research and development

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

- Literature search, analytical method, contaminant experimental studies, contaminant modeling is good valid approach.
- Very good – the approach to the testing is basically conventional. The benchmarking to the USFCC round robin demonstrated that the data is repeatable (multiple runs in the stand) and reproducible (the same results as seen at other labs involved in the round robin). It is surprising that this was not mentioned as it demonstrates a sound approach and a willingness to collaborate.

- Logical approach, but concern that it may be too broad to be fully accomplished by the available resources and time available.
- The choice of membrane electrode assembly loadings and membrane thickness are important for obtaining meaningful results for automotive fuel cells, but this project appears to have been ill-advised on the catalyst loadings and membrane thicknesses chosen.
- Evaluate effects of organic (methane, ethane, ethylene, aldehydes, organic acids, glyols) and cations on fuel cell performance degradation using conventional materials and catalyst loading (however, higher Pt loading on anode is unusual). Also low temperatures (80°C).
- Evaluation is integrated with model development.
- Focused only on membrane properties.
- Metal contaminants focus on automotive alloys.
- Concerns about duplication with other related projects within the group. It is suggested that the 3 groups working on impurities closely communicate to select the impurities to avoid duplication.
- Development of standard durability testing per impurity needs to be considered.
- Good approach to use prior work to define the contaminants of interest.
- Starting with methane and ethane may not have been the best choice since the effects are expected to be limited or zero, but this did serve to get the project started.
- It may have been better to use a known industry protocol, or at least a published testing protocol.
- Testing for contaminants just prior to the cell is a good refinement of a general approach.
- Cation testing based on metallic alloy constituents is a good starting point.
- Work to characterize the mechanical membrane properties is interesting.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.9** based on accomplishments.

- Measured CH_4, C_2H_6, and cation impurity effects on mechanical properties of membranes.
- Apparently literature search was not completed well, because the fact that CH_4 is a non-adsorbing impurity at polymer electrolyte membrane temperatures was missed.
- Spent significant time on impurities that were previously already known not to be detrimental.
- Outstanding – starting from scratch, developing test methodologies, getting test facilities on line, validating the facilities and methodologies and generating meaningful data in a year is excellent.
- The start-high-and-dilute is a good approach to look at the effects of the organic impurities and the team appreciated that there needs to be a reasonable and practical upper bound.
- The high loading and membrane electrode assembly configuration may distort the results especially related to the maximum concentration that can be observed.
- For the metal ions, the measurements of key properties are well targeted, but the use of Nafion 117 and complete metal ion contamination could provide erroneous data.
- Fuel cell relevant conditions for the measurements were not examined.
- Very good results and progress to date toward their objectives.
- The data showing the impact of the cations on the nitrogen permeability are very significant.
- This project appears on track to have a significant impact on overcoming the impurity aspects of the durability barrier.
- Established testing system and protocols.
- Evaluated effects of methane and ethane and ethylene (no effect).
- Established cations decrease membrane water content (expected) plus make membrane more brittle.
- It suggested to test catalyst coated membranes not only with Pt/Nafion but also other types of membranes and catalysts.
- Development of standard durability testing per impurity needs to be considered.
- Good results and good analytics on the contaminants studied.
- Good progress, although the project has far to go.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- Partners include FC Energy, and UT Hamilton Sundstrand.
- Participate in impurity working groups and publish results.
- Very good – the formal collaboration appears to be as expected. The current level of collaboration with Los Alamos National Laboratory, Hawaii Natural Energy Institute, University of South Carolina, Savannah River National Laboratory/Clemson University and Argonne National Laboratory is a very pleasant surprise.
- The team has the appropriate skill sets to address the impurity issues.
- The proposal team is interacting with industry groups to understand the priority items, but should ensure the levels and membrane electrode assembly construction meets industry direction and standards.
- Few but strong partners, and good collaboration indicated.
- Universities and industry involved (with industry providing data and test supports). However, no original equipment manufacturers are involved.
- Several universities are involved in characterization and modeling.
- Collaboration with others, Los Alamos National Laboratory and Clemson University, is highly recommended and seems to be lacking.
- Good team experience with industry and university participants.
- Good use of prior work by other stakeholders.
- A more extensive list of contaminants might have been chosen based on published hydrogen purity specifications and testing by others. If this is a coordinated effort with others, it would have been helpful to make everyone aware of that fact and why the contaminants were chosen.

Question 5: Approach to and relevance of proposed future research

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

- Contaminant Studies on chart proceeds for only 5 quarters – this should be extended and ongoing.
- Excellent – the focus on compounds and cations likely to be encountered in practical application is a demonstration of applied science and this directly supports the DOE effort to commercialize this technology.
- The proposed direction addresses the program objectives and they have the resources to address the topics.
- The team should ensure the impurity levels, and membrane electrode assembly materials and operating humidity are compatible with industry standards to prevent distortion of the effects of the various impurities and ensure the relevance of the work.
- Focus on key organic species is excellent, but selected organics should be chosen carefully. The choice of their standard membrane electrode assembly on which to carry out the impurity effect studies should revised. The impurity modeling could be a tour de force and result in a very valuable utility for the fuel cell community.
- Complete industry assigned generic list including halogenated organics.
- Complete cation studies.
- Characterize ammonia and H_2S.
- Begin modeling efforts.
- Suggest having a clear direction on mitigating strategies and testing several kinds of membranes, i.e., Pt alloy and membranes other than Nafion.
- Provide a plan clarifying the modeling efforts timeline and impurities downselection to avoid duplication with Savannah River National Laboratory/Clemson University.
- It is suggested to consider having *in situ* testing of cationic impurity effects on the performance of the fuel cell.
- Moving into modeling is a good transition towards full understanding of the contaminant effects on a micro level.
- The next set of contaminants will be important.

Strengths and weaknesses

Strengths
- Good approach with literature review, experimental, modeling, model validation.
- Current collaboration with other investigators.
- Strength and experience of the collaborators.
- Good definition of roles in the project.
- Input from industry regarding most useful contaminants to investigate.

- Gets hydrogen purity working group input.
- Good integration with model development.
- Good overall project plan and logical flow of development.
- Good outreach plan.
- Fuel cell testing capabilities.
- Builds on prior work.
- Good steady progress.
- Cation work based on metallic alloy contaminant possibilities.

Weaknesses

- Publication record to date is weak. There are no peer-reviewed publications, and most are presentations at workshops/meetings. Possibly early in project for significant publications.
- Significant work on CH_4 as impurity, but CH_4 effect on fuel cell performance has been well know by natural gas / polymer electrolyte membrane stationary fuel cell developers for a long time.
- Using too high of a catalyst loading on the anode.
- A potential weakness might be the lack of willingness to share preliminary or unpublished data with other investigators. If the DOE target deadlines are to be met with quality results, researchers will need to be less parochial with the data.
- Fuel cell measurements of the effect of organic impurities are performed with a membrane electrode assembly configuration that may significantly distort the results and behavior.
- Metals effect on the membrane looks at complete exchange and much thicker membrane than the current industry direction. This could distort the effects measured and provide a potentially erroneous direction for the impurity modeling.
- Mechanical measurements should be made under fuel cell type environments and reasonable upper bounds for the metal ion contamination.
- Limited material under investigation - conventional material for membrane only.
- Only lower temperature investigated. If higher temperature membrane materials are developed, this could diminish value of this study.
- No electrochemical characterization.
- Maybe not focused on most important contaminants.
- No publication.
- Collaboration with others within the center to avoid duplication.
- Cation loading may be higher than ever will be seen in use. A lower level, or lower levels, might be better to show the threshold of contaminant effects.
- No degradation seen yet with the gaseous contaminants used. It might have been better to try something with a higher rate of degradation to allow the team to hone their skills.

Specific recommendations and additions or deletions to the work scope

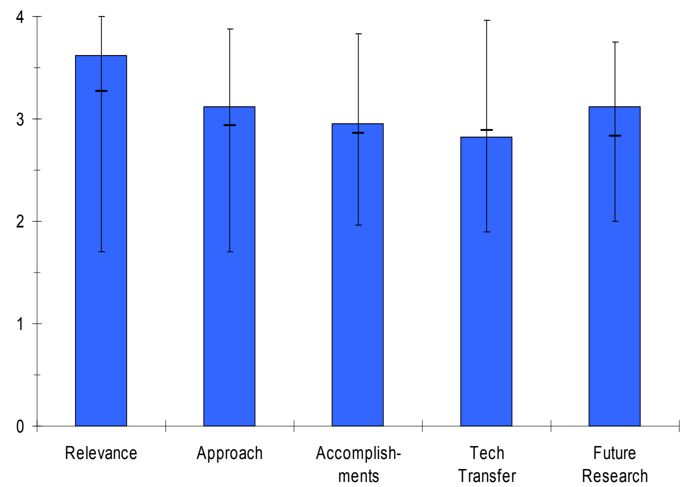
- Should publish results in more detail and in peer-reviewed journals.
- Impurity review should include more than UT Hamilton Sundstrand's database on electrolyzer contaminants.
- Continue as the program is planned out.
- The effects of relative humidity on the performance with various contaminants should be considered in the degradation reactions.
- The membrane electrode assembly characteristics on which they will base their impurity studies should be revised to better reflect state-of-the-art automotive membrane electrode assemblies. Suggest anode loadings of 0.05 mg-Pt/cm^2 and cathode loadings of 0.15 mg/cm^2, and membrane thicknesses of 20 microns since that will be more realistic as well as give greater sensitivity to the impurities.
- Should add additional materials.
- Look at higher temperatures and higher temperature membrane materials.
- Should look at lower contaminant level (more realistic).
- Suggest keeping the project; however, suggest testing several types of catalyst coated membranes other than Pt/Nafion based and creating mitigation strategies as the effects of each impurity are investigated.
- Continue the effort coordinated with the other contaminant research.

Project # FC-32: Subfreezing Start/Stop Protocol for an Advanced Metallic Open-Flowfield Fuel Cell Stack
James Cross; Nuvera Fuel Cells

Brief Summary of Project

The overall objective of this project is to demonstrate a polymer electrolyte membrane fuel cell stack meeting the Department of Energy 2010 cold start targets. The specific goals are 1) achieving -20°C cold start target respecting the energy budget; and 2) identifying electrochemical material freeze cycle aging models. The energy budget target of 5 MJ is currently exceeded by 12% but will be met with further optimization. The next generation 2010 material sets are in active development and are to be informed by forthcoming post-test analysis.

Overall Project Score: 3.1 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- Project is well focused on issues related to cold start and operation of fuel cells to meet DOE targets.
- Water transport within a polymer electrolyte membrane fuel cell stack is required for optimal fuel cell performance (and thus cost, durability, power density, etc.).
- Extensive work on freeze/thaw, cold start-up.
- An important area, but apparently already being pursued by all major fuel cell manufacturers.
- Demonstration of rapid start-up at freeze conditions is a critical performance parameter for automotive performance. The freeze start-up time may not be as critical for backup power, stationary power, or industrial motive power applications.

Question 2: Approach to performing the research and development

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

- Baseline system and performance and project metrics/goals (including quantitative where appropriate) clearly defined.
- Strong combination of theory and experiment.
- Stack design modification, testing and modeling for low temperature stack start-up.
- Energy budget optimization discussed, but hard to evaluate approach with information presented.
- Generally reasonable but several serious limitations.
- Inlet flows of air and fuel are at laboratory room temperature, which is not appropriate.
- Hydrogen flow heating value is not included in starting energy as it should be.
- The modeling approach also seems to have limitations associated with level of sophistication.
- Approach appears systematic but has a significant experimental weakness -- the reactants are introduced at ambient temperature. This is a major experimental error because the cell stack is artificially heated by the ambient reactants, and the humidity of the reactant gases will be very different at ambient temperatures than at subzero temperatures.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- Significant progress made.
- Have already demonstrated 2010 -20°C start-up goal.
- Significant progress was made in achieving start/stop energy goal with path to achieve the final goal.
- 50% rated power in 30 s from -25°C is an excellent accomplishment.
- While progress has clearly been made, it is of questionable value due to limitations in approach.
- Test results apparently are not yet reliably repeatable.
- The presentation stated that the project claims met the 2010 start-up target of 50% power in 30 seconds, but this target is not demonstrated since the testing used ambient reactants.
- The energy accounting did not take into account the use of ambient temperature reactants, and the value presented is not representative of the test system. The summary makes claims that are not consistent with a thorough research evaluation.
- The reviewer questioned the development of new stack technology with high performance, but that was not an objective identified by DOE in chart 3 and does not appear to be an objective of the program.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- Other team members appear to be engaged in materials characterization (based on presentation, roles did not come across clearly in printed slides).
- Degree of interaction between team members appears to be very limited. it is not clear how data from materials studies is impacting cell and stack studies and development.
- Strong collaboration between fuel cell stack original equipment manufacturer, membrane electrode assembly / gas diffusion layer component suppliers and academics.
- Interactions seem to be fairly limited.
- The program has several collaborators but the application is restricted to the design of the Nuvera fuel cell stack. The design-specific solution to rapid start-up of freeze does not benefit the complete fuel cell community but is a specific benefit to Nuvera.

Question 5: Approach to and relevance of proposed future research

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

- Proposed work should require more interaction between team members and results at next Annual Merit Review should demonstrate the impact of materials studies at the system level, particularly if progress made in understanding decay modes.
- Improved materials, installation of environment chamber, and development of 2D model are all needed for project success.
- Addition of controlled inlet flows will add much to the value of test results.
- Removal of mass, associated with higher operating design voltage, should help meet all goals.
- Several topics for proposed research will provide information to the fuel cell community. The development of an advanced stack does not appear to be consistent with the objectives of DOE. The advanced fuel cell stack will benefit Nuvera's business and will not be available to the fuel cell community.

Strengths and weaknesses

Strengths

- Freeze/start-up modeling already being correlated to stack start-up experimental measurements.
- Good technical capabilities.
- Good experience with similar experimental work.

Weaknesses

- Unclear how materials development will impact the project; little was stated about materials development approach.
- Too many limitations on results the way the program is currently being conducted.
- Experimental procedures used have yielded results that are inconsistent with real world operating conditions; the project principal investigator acknowledged the limitations of the experimental approach.

Specific recommendations and additions or deletions to the work scope

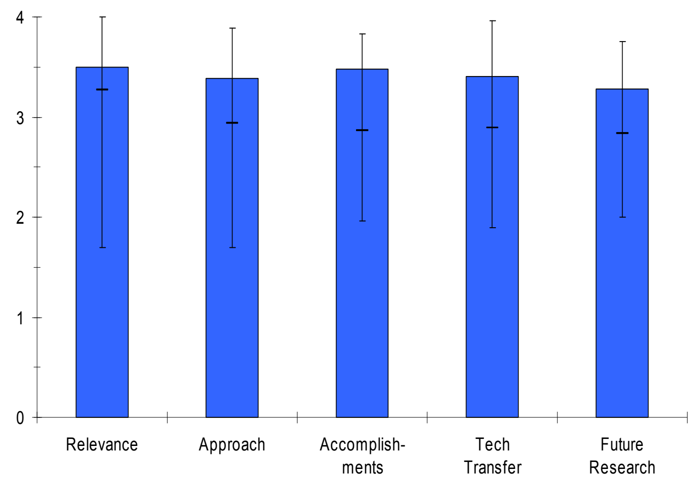
- Need to add an environmental chamber into stack testing.
- Carefully control inlet flows.
- Insert minimum repeatability into criteria before accepting test results as valid.
- Refocus program to meet DOE objectives at true, real freeze conditions.
- Delete new stack development activities that are not in the project objectives or include new stack in objectives.

Project # FC-33: Visualization of Fuel Cell Water Transport and Performance Characterization Under Freezing Conditions

Satish Kandlikar; Rochester Institute of Technology

Brief Summary of Project

Overall Project Score: 3.4 (5 Reviews Received)



The overall objectives of this project are to 1) gain a fundamental understanding of the water transport processes in the polymer electrolyte membrane fuel cell stack components; and 2) minimize fuel cell water accumulation while suppressing regions of dehumidification by an optimized combination of new gas diffusion layer material and design, new bipolar plate design and surface treatment, and anode/cathode flow conditions. The phase 1 goal is to establish a baseline system performance. This includes 1) a performance matrix for *ex situ* multi-channel and *in situ* fuel cell experiments; 2) freeze effects on performance and durability; and 3) microscopic study and models for water transport in the gas diffusion layer and parallel channels.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Water transport within a polymer electrolyte membrane fuel cell stack is required for optimal fuel cell performance (and thus cost, durability, power density, etc.).
- The overall objective is to understand and also gain fundamental information on the water transport and performance characterization in the polymer electrolyte membrane fuel cell stack under freezing conditions.
- The program is highly relevant to President's Hydrogen Fuel Initiative.
- Water management in the cell/stack is important to fill gaps of performance, freeze start-up capability, reliability.
- Work is highly relevant toward understanding many automotive fuel cell stack failure modes that relate to water management, including freeze start, and low cells during nominal conditions due to gas diffusion layer intrusion, transition region deficiencies and non-uniform plate features.
- Project attempts to derive fundamental knowledge that can be widely applied, regardless of material sets, cell design and operating conditions.
- Water flow characteristics in flow channels are important parameters to understand the design of fuel cell operating characteristics. Plugging of channels is a known cause of performance degradation that can become permanent. Much of this work is already in the open literature. The development of a model for water and gas transport in gas diffusion layers could be beneficial.

Question 2: Approach to performing the research and development

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

- Parametric studies could be very valuable.
- Well thought-out approach that gradually moved from parametric studies to *in situ* performance with water distribution.

- The technical approach is to use *in situ* combinatorial water distribution and current density measurement for water transportation. Neutron radiography technology is also used to study water transportation in the polymer electrolyte membrane fuel cell stack. The membrane is Gore membrane.
- Water management is one of the key problems for the polymer electrolyte membrane fuel cell stack performance. The project addresses this issue.
- Cell/stack water management depends on flowfield design configuration. It is not clear whether this characterization includes implications on flowfield design or excludes them. If it includes flowfield design implications, it is unclear how to optimize flowfield configuration.
- Approach seeks to find what "worst case" conditions are upon shutdown.
- Studies incorporate the contribution of gas diffusion layer mechanics and the manufacturing variations that can lead to plate non-uniformity.
- The use of a small channel width (with carbon-based plate style features) will limit application of results for some customers.
- Correlation of pressure drop characteristics to different types of two-phase flow is valuable. According to question responses, this can be adjusted for operation when water is being generated.
- Good use of visual techniques on channel phenomena.
- The approach is systematic and should develop a better understanding of water transport in the flowfields.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.5** based on accomplishments.

- Significant amounts of work shown on flow visualization under many operating parameters.
- Flowfield design with cross-channels (11 degree offset) good for separation of anode/cathode water content during neutron imaging measurements.
- Flow maldistribution measurements and modeling due to gas diffusion layer intrusion are good.
- The technical accomplishments from two universities are excellent.
- It is necessary to explain correlation between gas diffusion layer materials property and water management in the cell/stack.
- Project is in process of completing baseline evaluation, including flow maldistribution, two-phase flow mapping, and shutdown conditions that most stress freeze start.
- Some items still need to be studied, including the relationship of transition region features to pressure drop and flow maldistribution.
- Discussions with investigators revealed that flow maldistribution and gas diffusion layer intrusion have been researched with respect to plate/gas diffusion layer compression.
- Although capillary flow of water is covered, unclear whether gas permeation/diffusion is covered or whether water vapor diffusion is addressed.
- Good progress.
- Intrusion of the gas diffusion layer into the flowfield is commonly known as "tenting" and was resolved with more rigid gas diffusion layer structures by several researchers. The researchers appear surprised by this phenomenon. Researchers would benefit from expanded contacts.
- Slug flow characteristics are well understood by fuel cell industry and previously reported by Los Alamos National Laboratory. It is not clear what is new in the work reported at this review except for the very interesting neutron imaging data.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.4** for technology transfer and collaboration.

- This project has a close collaboration between an automotive original equipment manufacturer and universities.
- Addition of component supplier interactions might help.
- Good publication record to date.
- The joint team includes Rochester Institute of Technology, General Motors Corporation, and Michigan Technological University.

- The technology transfer and cooperation is very good between Rochester Institute of Technology and Michigan Technological University.
- List of collaborators is short, but each collaborator has made a solid contribution.
- Michigan Technological University is contributing capillary flow models; General Motors is contributing cell design, gas diffusion layer coating and knowledge base.
- Collaborators are clearly not limited to mere material and analytical inputs. Many other projects use "collaborators" in this sense and then those collaborators do not contribute to the direction of the research. That has been avoided here.
- Mix of industry and academics, but it is not clear what the fuel cell component experience is.
- Program would benefit from expanding contacts with fuel cell companies.

Question 5: Approach to and relevance of proposed future research

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

- Spatial variation and current density measurements would be valuable in a real original equipment manufacturer flowfield design.
- The future work is clearly stated in the slides, future work plan and directions are excellent.
- For gas diffusion layer characterization, it is not adequate to look at only contact angle and capillary number. Other considered parameters, such as mechanical properties, permeation/diffusion, etc. should be evaluated.
- Future work is consistent with what is stated in the approach.
- The problem here lies with the metric(s) for qualifying that a gas diffusion layer/plate design is "improved." A possible scenario is that the "worst case" condition for stack shutdown becomes worse, but the overall regime of mist flow increases. In such a case, is the design improved? There should be some way of clearly saying what an improvement constitutes if the familiar tradeoffs involved in water management are realized.
- The future plans are consistent with the program objectives.

Strengths and weaknesses

Strengths
- Automotive original equipment manufacturer provides access to most materials and significant amounts of beam time at the National Institute of Standards and Technology.
- The technology cooperation between two universities is good.
- Collaboration with strong industry partners.
- Use of imaging techniques to examine channel phenomena.
- Careful attention to and respect for true automotive ranges of operating conditions and modes.
- Realistic accounting for the way in which manufacturing variations and cell design influence water transport.
- Delivery of useful parameters for wide use (e.g., two-phase flow mapping and shutdown conditions that most severely challenge freeze start).

Weaknesses
- Flowfield design might not be applicable to all developers.
- Unclear what the working interaction between the project partners is, and appears most of the work presented was done by General Motors as a subcontractor.
- What is the role of General Motors in the project?
- Modeling capability, e.g., computational fluid dynamics.
- Thorough accounting for all transport mechanisms for all fluids was not fully realized in the presentation shown.
- Some ambiguity exists at the future decision points.
- Context limited by small channel width.
- Interesting testing using the neutron imaging.

<u>Specific recommendations and additions or deletions to the work scope</u>

- The project started in March 2007 – we should give the principal investigator and Co-principal investigator more time and then make additions or deletions.
- All transport processes (diffusion, permeation, capillary motion) should be accounted for in all pertinent phases and species. If any are missing, they should be added. It is impossible from this review to determine if there is more research that has already covered this.
- Unless investigators wish to examine wider channel widths, any suggestion of adding the measurement of gas diffusion layer thermal conductivity should be ignored. If wider channel widths are of interest, then, yes, thermal conductivity should be added.

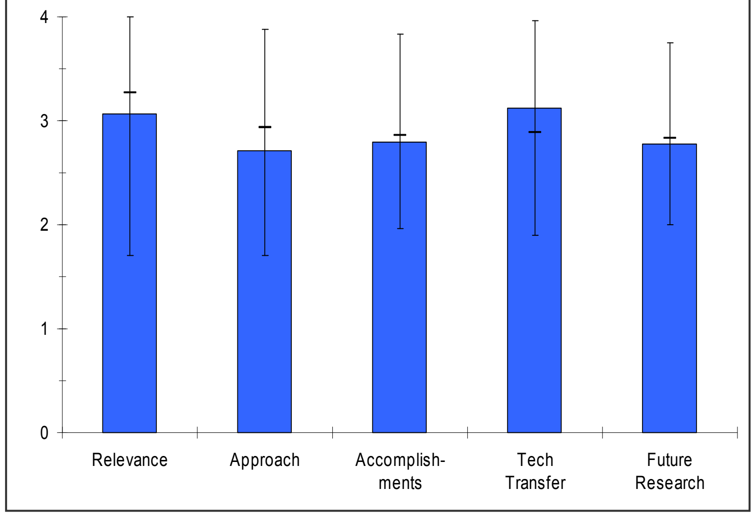
Project # FC-34: Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization

Vernon Cole; CFD Research Corp

Brief Summary of Project

The overall objectives of this project are to 1) develop advanced physical models and conduct material and cell characterization experiments; 2) improve understanding of the effect of various cell component properties and structure on the gas and water transport in a polymer electrolyte membrane fuel cell; 3) demonstrate improvement in water management in cells and short stacks; and 4) encapsulate the developed models in a commercial modeling and analysis tool. The fiscal year 2007 and 2008 objectives are to 1) perform baseline characterization for gas diffusion layer materials; 2) develop procedures for and begin gathering cell and stack-level diagnostic data; and 3) down-select model formulations and implement and test improved models for transport in gas diffusion layers, channels and across interfaces.

Overall Project Score: 2.9 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- Water transport within a polymer electrolyte membrane fuel cell stack is required for optimal fuel cell performance (and thus cost, durability, power density, etc.).
- Addresses a critical aspect of fuel cell operation and is using relevant cell designs for the modeling.
- The program is quite relevant to the DOE program objectives. Water transport is an important issue in fuel cells.
- Relevant, but likely that all major fuel cell manufacturers have their own approaches and solutions.
- Their work has limitations that somewhat limits the relevance.
- Water transport and management is extremely important to DOE, but Lattice-Boltzmann modeling is not necessarily the best approach.

Question 2: Approach to performing the research and development

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

- Experimental measurements, extensive characterization to be correlated with strong modeling component.
- Combining *in situ* and *ex situ* experimental measurement techniques.
- Use of current interrupt to measure resistance and predict flooding.
- The approach to gathering the data and modeling is based on relevant industrial designs for the cell configuration and is looking at multiple operating conditions.
- The project objectives are well designed for moving forward with obtaining the fundamental characterization of the materials under realistic conditions to develop the model.
- The approach is good; it combines modeling at different length scales to formulate descriptions of the various components with experimental data to produce validated models that can describe water transport in operating fuel cells.

- The combination of modeling along with experimental results for calibration is good. However, significant limitations.
- All work seems to be for steady flow while major problems are also associated with transients.
- Apparently, there is no multi-dimensional capability except within a specific flow channel.
- Results seem to be very configuration-specific.
- Principal investigator is trying to do too much with available funding.
- Principal investigator should focus effort on fewer subjects – would impedance testing be more useful than the current interrupt tests? Are internal resistance tests likely reflecting poor cell setup causing high contact resistance and thus providing erroneous results – more relative humidity range is desirable in testing.
- Tests have been primarily steady state – they will need to be transient in order to be useful.
- The freeze-thaw experiments need more work and should wait on preliminary modeling data.
- Much of the data presented has been well documented by others previously – not much new (innovative) data presented.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- Characterization of gas diffusion layer materials, model development.
- The team is making good progress against their objectives of characterizing the materials and developing baseline data.
- It is not clear if some of the information is an artifact of the cell design to propose flooding.
- Project has spent the first year setting up platforms for model development.
- Good understanding of the need to fully characterize the microstructure in the model formulations.
- Model development for water transport through the gas diffusion layer is ahead of schedule.
- The work is interesting but does not seem to be particularly useful. It is not likely to add much to the basic understanding of water distribution issues.
- Internal resistance use to infer water flooding not accurate since it is an indication of a poorly designed cell (could be an artifact of that).
- Current interrupt technique – only focuses on one frequency – impedance might be a better technique.
- Transport equations – he is only getting permeation but not accounting for diffusion – sounds like they are looking at it.
- What electrochemical model are they aligning with the flow model?
- How many different relative humidity ranges are covered?
- Much of the characterization work has been well documented by other researchers, so isn't a lot of this data already in the literature and can be applied to the models discussed in this program?
- Too much effort devoted to preliminary characterization and "extravagant" imaging techniques that do not provide much additional information to what is already known about gas diffusion layer materials.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- Currently no publications.
- Strong team with fuel cell original equipment manufacturer, component suppliers, academics.
- The team has good participants that should be able to provide industry relevant data and expertise.
- There are numerous collaborators involved in the project including a major fuel cell developer to guide the modeling effort using real world data and assumptions.
- Several good partners but little indication of interaction with other than one or two.
- The list of partners is extensive, but it is not clear what each of the partners is contributing to the project (other than Ballard).
- Cell and stack diagnostics should be the focus (rather than so much effort in unnecessary elaborate characterization).

Question 5: Approach to and relevance of proposed future research

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

- Unclear how modeling results will be verified.
- Little information presented on proposed future work.
- The future work is well directed at addressing the program objectives and moving the understanding forward.
- The presentation indicated that the future work includes studies of transient operation.
- Not clear that future work will add much to understanding.
- Don't focus on freeze-thaw early in the program – get baseline models established first (don't jump ahead of the game) then move onto different fuel cell operation.
- Lessen focus on extensive characterization and utilize existing data to establish baseline models.
- Why isn't some of this research being coupled with imaging observations (such as those done at the National Institute of Standards and Technology)?

Strengths and weaknesses

Strengths
- Experimental measurements, extensive characterization to be correlated with strong modeling component.
- Good use of analytical modeling and testing with relevant cell designs to understand the water management.
- Good team working on an important problem.
- Good presentation.
- Partners have excellent combined capabilities.

Weaknesses
- Small amount of results shown to date.
- Modeling not yet correlated to experimental results, and unclear exactly how this will be done.
- Use of current interrupt technique is inferior to a complete-frequency alternating current impedance spectroscopy measurement.
- Too many limitations to be very useful and probably duplication of efforts by other groups.
- Too much effort on unnecessary characterization.

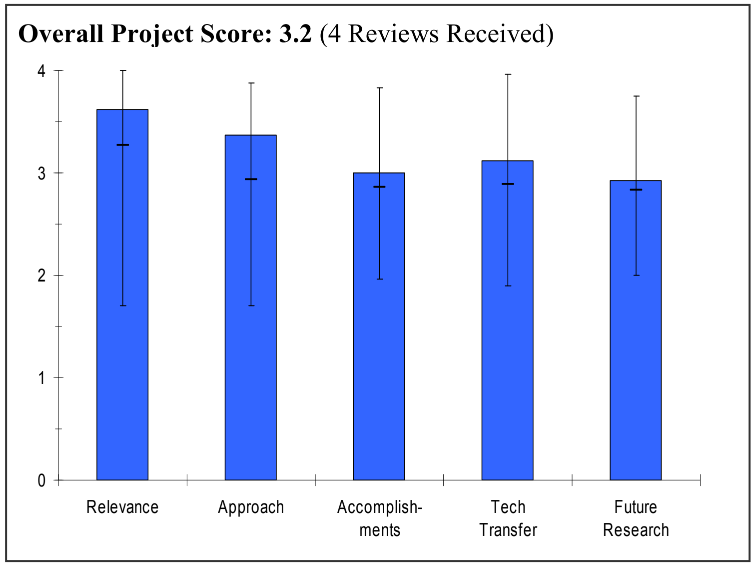
Specific recommendations and additions or deletions to the work scope

- Incorporate high frequency resistance /alternating current impedance measurements.
- Assess potential value of project as formulated.
- If project continues, add unsteady as well as multi-dimensional efforts – at least experimentally but also analytically if practical.
- Coordinate models and diagnostics with imaging techniques available at the National Institute of Standards and Technology.

Project # FC-35: Water Transport Exploratory Studies
Rod Borup; Los Alamos National Laboratory

Brief Summary of Project

The overall objective of this project is to develop an understanding of water transport in polymer electrolyte membrane fuel cells. The specific objectives are to 1) evaluate structural and surface properties of materials affecting water transport and performance; 2) develop new components and operating methods; 3) accurately model water transport within the fuel cell; 4) develop a better understanding of the effects of freeze/thaw cycles and operation; 5) develop models which accurately predict cell water content and water distributions; 6) work with developers to better the state-of-art; and 7) present and publish results.



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.6** for its relevance to DOE objectives.

- The project is highly relevant to the President's Hydrogen Fuel Initiative.
- The overall objective is to understand water transport in polymer electrolyte membrane fuel cells.
- Very good – the issue of the hydrophobicity of components changing with time has the potential to be a major durability issue.
- Good orientation towards overall goals.
- This project is relevant to the DOE objectives regarding performance, durability and unassisted start from freeze.
- Project seeks to provide original equipment manufacturers with fundamental knowledge regarding water presence in relevant material sets, using relevant operating conditions and standard cell designs.

Question 2: Approach to performing the research and development

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

- Neutron imaging, high frequency resistance, and alternating current impedance technologies are used to study water transport in the polymer electrolyte membrane fuel cell stack.
- The description of the technical approaches is excellent.
- Fair/good – I would expect that Teflon migration due to water transport, carbon oxidation changing the water contact angle and potentially pore structure changes due to freezing would be explored. I don't see this lower hanging fruit being discussed.
- Excellent consortium, in particular key industry partners.
- Solid measurements.
- As with any proper water transport project, this project seeks to link *in situ* phenomena with *ex situ* material characteristics.
- Modeling to be used for those aspects that are difficult to routinely address with experiments (e.g., water movement through gas diffusion layer).
- Operational stresses addressed (e.g., freeze).

- Lack of attention given to cell assembly and channel dimension effects. In a water transport project where mechanical, electrical, and – in some designs – thermal interactions between gas diffusion layer and plates/catalyst layers are important, these parameters must be known.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- The project started in 2007, the technical accomplishments are excellent.
- Fair/good – the modeling of droplet formation and separation is interesting. It is unclear how this actually addresses the issues.
- Good results and insights on water distribution and ice formation. Improvement of empirical understanding. However, transfer of methods/technologies missing.
- General trends should be elaborated.
- A considerable amount of work has been done with neutron imaging, but parameters such as gas diffusion layer type and compression have been left out, therefore making comparisons difficult if not impossible.
- Because contemporary rollable gas diffusion layers now have wide ranges of compressibility, compressing all gas diffusion layers to the same percent thickness will not lead to the same compression. Wide performance and water transport variations will result.
- Freeze study contains some trends that could be of use to developers with knowledge of gas diffusion layer parameters.
- CFD study could be more valuable if parameters were shared that were used to match experimental data (e.g., gas diffusion layer or catalyst layer flow resistance).

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- The technology cooperation among the principal investigator and co-principal investigators is good.
- Good – the list of collaborators is representative of the supply chain.
- Interaction with industry seems to have room for improvement.
- Wide, commendable range of collaborators among national laboratories, universities and membrane electrode assembly component suppliers.
- What is missing from collaborations is the dedicated assistance of a stack assembly original equipment manufacturer. The role of Nuvera is stated to be limited to assistance with the low-temperature conductivity testing. Either a greater role for Nuvera or the entry of a stack assembly collaborator should be sought.

Question 5: Approach to and relevance of proposed future research

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

- The future work plan and directions are excellent.
- Good/fair – the proposed work appears to be a rational follow on to the work to date. Consideration of some of the items noted in part 2 may be more relevant.
- Target orientation of future work not clear.
- Transient work utility will depend on ability to replicate the same relative speed of flow increases/decreases versus load up/downturns.
- Work that has already been done should still be related to cell assembly parameters, as well as gas diffusion layer characteristics.
- Assumption has been that neutron imaging shows ice when temperature is below freezing. In polymer electrolyte membrane, this can be debatable. Another technique that can distinguish water from ice would be helpful (e.g., MRI).

Strengths and weaknesses

Strengths
- The attempt to understand and potentially address a legitimate durability issue.
- Wide range of analytical access and experience.
- Wide range of collaborations with universities, component supplies and other National Laboratories.
- Experiments designed with relevance to the major stressors involved in fuel cell water management.

Weaknesses
- Too many subcontractors, the work and duties are not well-defined.
- It is unclear if the researchers are focusing on the probable physics of the problem.
- Attention to cell assembly information.
- Collaboration with stack original equipment manufacturers.
- Delivery of modeling parameters to possible customers.

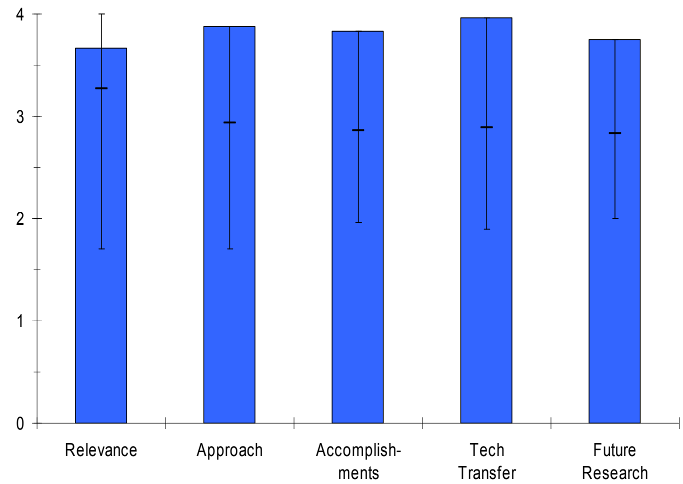
Specific recommendations and additions or deletions to the work scope

- Should delete a couple of subcontractors.
- I would suggest considering doing some research on the items in part 2.
- Consideration should be given to more advanced hardware selection, similar to that used in the Rochester Institute of Technology project. This would help provide more realistic heat transport in freeze experiments.
- Reporting of gas diffusion layer type and cell compression for every experiment.

Project # FC-36: Neutron Imaging Study of the Water Transport in Operating Fuel Cells
David Jacobson; NIST

Brief Summary of Project

Overall Project Score: 3.8 (6 Reviews Received)



This project aims to develop and employ an effective neutron imaging based, non-destructive diagnostics tool to characterize water transport in polymer electrolyte membrane fuel cells. The objectives of this project are to 1) form collaborations with industry, national laboratories and academic researchers; 2) provide research and testing infrastructure to enable the fuel cell/hydrogen storage industry to design, test and optimize prototype to commercial grade fuel cells and hydrogen storage devices; 3) make research data available for beneficial use by the fuel cell community; 4) provide secure facility for proprietary research by industry; 5) transfer data interpretation and analysis algorithms techniques to industry to enable them to use research information more effectively and independently; and 6) continually develop methods and technology to accommodate rapidly changing industry/academia need.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- Water and thermal management are important problems aligned with the program goals, though not the most critical questions facing the program.
- Very useful facility.
- Analytical instruments like this are critical to fundamental understanding of water management.
- Neutron imaging is an important tool for monitoring the distribution of water in a polymer electrolyte membrane fuel cell. The technique provides a window into the operation and stability of cell components.
- Although not "critical" to hydrogen economy, this project is highly relevant to water transport in fuel cells.
- Neutron imaging is a unique tool for studying water transport *in situ*.
- Project is extremely relevant to DOE objectives as it supports the water management projects and research at many institutions – the National Institute of Standards and Technology is developing the techniques allowing for direct water transport imaging in operating fuel cells, a critical issue for DOE.

Question 2: Approach to performing the research and development

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

- Uniquely well-poised to look at water management at the micro scale. Very good team to do the work with the special tools and the neutron source.
- Excellent user model – provides unprecedented opportunities.
- Very good.
- The approach combines experimental and modeling methods to better understand the distribution of water in the fuel cell. The development of test cells that permit the location of water within a cell is an important function.
- The facility is well-equipped and well-suited for water imaging in fuel cells.
- The National Institute of Standards and Technology appears to be committed to constantly improving their neutron imaging capabilities, which is a big plus.

- The developmental work during the past year has been great and the addition of high resolution imaging capability is very exciting and extremely relevant.
- Collaborative work is outstanding – since the facility is part of a user center, many fuel cell water management researchers have access to the capabilities at National Institute of Standards and Technology provided they can justify need in a proposal.
- DOE covers cost of the research and development necessary for fuel cell activities related to water management and access to the facilities is open to all organizations involved in fuel cell research. This is a very useful mechanism by which to conduct the research rather than limiting to only a few institutions/collaborators.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.8** based on accomplishments.

- Excellent method development, though in truth most of this is not from the last year.
- Able to discriminate the water to ice ratio in freeze tests.
- Confirmed purge effectiveness in repeated tests and gas effects on water transport.
- Validation of models helps theory groups.
- Lot of excellent work done by university groups.
- Good progress with enhancing facilities.
- This program is leading edge technology!
- The project is developing interesting data. The observation of water collection in the "lands" reveals the complexity of the internal operation of the cell. Data and model prediction provide insights into the design of future cells.
- Progress is not easy to assess as one is dealing with a tool rather than focused research and development task; in the future, projects such as this should be evaluated according to a different set of criteria, specific to a service facility (center), not a research and development entity.
- The service rendered by the National Institute of Standards and Technology to numerous customers appears to have been fully satisfactory.
- More data interpretation would be welcome.
- The addition of an environmental chamber is extremely beneficial for freeze/thaw studies.
- High resolution imaging of water transport is a tremendously useful development for nearly all fuel cell researchers already utilizing the facility at the National Institute of Standards and Technology.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **4.0** for technology transfer and collaboration.

- Working with very many groups and most all the key players. Would be hard to do better in this area.
- Very user-friendly procedure to get beam time
- Could use a few more international participants.
- Excellent and expanding list of collaborations
- An impressive list of collaborators (hardly surprising for a service center).
- Outstanding use of DOE funds for research and development and developing the necessary collaborations within the fuel cell community. Nearly all the fuel cell organizations conducting water transport research have made valuable use of this facility.
- The facility is an extremely important tool for water management studies and should continue to be funded as a baseline program that will benefit all researchers in the fuel cell community.

Question 5: Approach to and relevance of proposed future research

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

- Looks suitable.
- Would like to see temperature-dependent measurements if possible.

- Very pertinent.
- Very nice work!
- It is not obvious that impedance measurements will distinguish between flooding of pores in gas diffusion layer, microporous layer or electrode. The sensitivity of the neutron imaging is on the order of 10 microns while a catalyst layer is typically less than 10 microns thick. This may be a difficult experiment.
- Planned addition of neutron detector(s) with even higher resolution, implementation of impedance spectroscopy and expansion of research onto hydrogen storage are all good ideas.
- With an advent of even better image resolution, the use of neutron imaging for mapping water in catalytic layers and membranes should also be considered.
- What additional improvements can be made after 10 micron resolution goal is met? This is very impressive, but it is unclear what the next goal will be.
- Little justification given for advantages of coupling impedance spectroscopy with water transport measurements.
- Continue emphasis on establishing collaborations with fuel cell community.

Strengths and weaknesses

Strengths
- Non-invasive water visualization. Great partnering at a rare facility.
- Most aspects.
- Develop leading edge analytical tools for fuel cell development.
- Creative application of neutron imaging.
- This is generally a strong and needed project.
- Extensive collaborations with numerous fuel cell researchers – this is important for the dissemination of critical observations in water management.
- The use of DOE funds to develop improved techniques is justified in that the National Institute of Standards and Technology facility is open to all researchers specifically for water transport studies related to fuel cells.
- The high resolution imaging of water transport is critical and thus demonstration of this capability should be a priority.

Weaknesses
- None.
- Limited access since there are too many users.
- Rather limited involvement of the National Institute of Standards and Technology in the "pre-neutron" and "post-neutron" phases of projects may be a weakness.
- None!

Specific recommendations and additions or deletions to the work scope

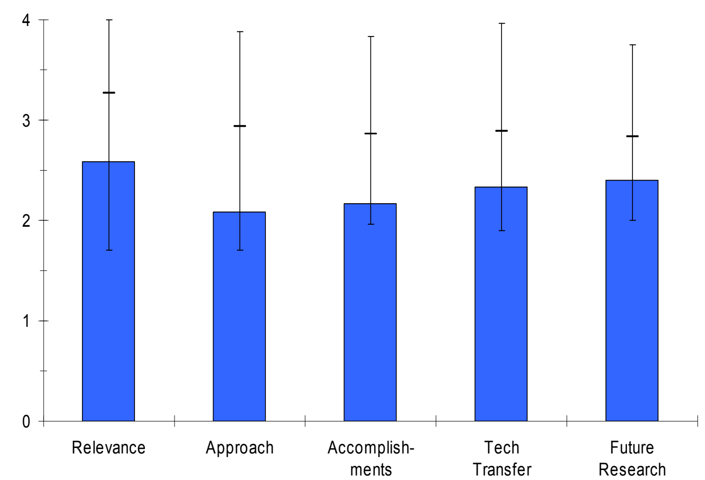
- Keep it up. Look for ways to measure temperature too.
- All in all, an outstanding project.
- Now that the resolution is good (10 microns), can the speed be increased to measure transients?
- Very limited interaction with the fuel cell industry. Program could benefit from industry inputs.
- Expansion of neutron imaging beyond "water transport" into, for example, catalytic layers and membranes, should also be considered.
- The authors should get more involved in the data interpretation and tie their catchy images to it.

Project # FC-37: Development of Thermal and Water Management System for PEM Fuel Cells
Zia Mirza; Honeywell

Brief Summary of Project

The objectives of this project are to 1) validate the performance of full-scale humidification devices sized for 80 kW fuel cells; and 2) design a full-size radiator to meet the 80 kW fuel cell cooling requirements. The Emprise enthalpy wheel and Perma Pure membrane module will be tested.

Overall Project Score: 2.3 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **2.6** for its relevance to DOE objectives.

- The relevance of this project has to be questioned if it could be delayed (or paused) for two years.
- The overall objective is development of thermal and water management systems for polymer electrolyte membrane fuel cells.
- The program is highly relevant to the President's Hydrogen Fuel Initiative.
- Units being tested are not being incorporated in current or future automotive fuel cell systems.
- Information generated provides no useful insight to original equipment manufacturers.
- Water management is critical to the President's Hydrogen Fuel Initiative.
- Technical gap of thermal and water management is cost, not performance.
- Stack technology is trying to decrease dependency on external thermal and water management (trying to eliminate external humidifier).
- A steady humidity of the input air is important for Nafion-based fuel cells.

Question 2: Approach to performing the research and development

This project was rated **2.1** on its approach.

- The approach proposed for this project appears to be sound, however the selection approach has to be questioned since neither of the two humidification systems operated satisfactorily and will have to be modified.
- Two system approaches, enthalpy wheel and membrane module are reasonable and good.
- The project is more toward development work.
- Novel technology is not being developed to overcome technical barriers.
- Comparative analysis of overall systems was not included.
- Design humidification system and radiator for 80 kW fuel cell stack use of an enthalpy wheel.
- It is unclear of technology downselection process.
- Down-selected components are not meeting cost targets.
- Two advanced humidity control systems are being studied.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.2** based on accomplishments.

- Granted it is very difficult to stop and restart a technical project such as this one, however the progress since the restart appears to be quite slow. Apparently since the restart no effort has been made on the radiator and the

initial effort in this area will be to revisit the past selection process. It seems that prototype equipment should already have been procured.
- Technical accomplishments are good.
- Testing was conducted on Emprise wheels and a Permapure membrane unit.
- Identified leakage in full-scale units.
- The limited data shown on Emprise wheel was suspect.
- No comparative analysis was shown between the two devices.
- Testing 80% complete, but enthalpy wheel leaks and needs a pre-cooler.
- Testing for design verification done.
- Limitations of both the enthalpy wheel and the membrane systems were identified and characterized.
- Which of these two systems is considered to be the best?

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.3** for technology transfer and collaboration.

- There appears to be little or no collaboration by outside organizations in this project. Clearly interactions with credible polymer electrolyte membrane fuel cell suppliers could benefit from humidification and heat rejection hardware.
- Partnered with Argonne National Laboratory, but no Argonne work in the presentation.
- DOE is a funding agency, what is meant to partner with DOE?
- Principal investigator does collaborate with component suppliers to solve component flaws.
- Better collaboration with original equipment manufacturers would be required.
- Argonne National Laboratory and FreedomCAR Fuel Cell Tech Team; no university or specific company.
- Collaboration indicated with Argonne National Laboratory.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.4** for proposed future work.

- Future plans are adequate, but appear to be drawn out and could be accelerated.
- The future work and plan are excellent.
- Future work includes evaluation of microchannel heat exchanger.
- Re-test humidification device. Radiator optimization.
- Radiator is not technical gap, it is design gap (packaging). Conventional radiator is the baseline.
- Future emphasis will be on the development of a full-scale radiator for an 80 kW polymer electrolyte membrane fuel cell system.
- Studies of advanced radiator technologies have been done.

Strengths and weaknesses

Strengths
- None.
- Project has a good focus.

Weaknesses
- Doesn't have fuel cell system developers or fuel cell companies involved in the project.
- Limited data presented.
- No system analysis presented.
- The technology is not state-of-the-art.
- No cost analysis done.
- Enthalpy wheel sealing.
- Project justification.
- Not much indication as to how the shortcomings of the humidity control systems will be overcome.

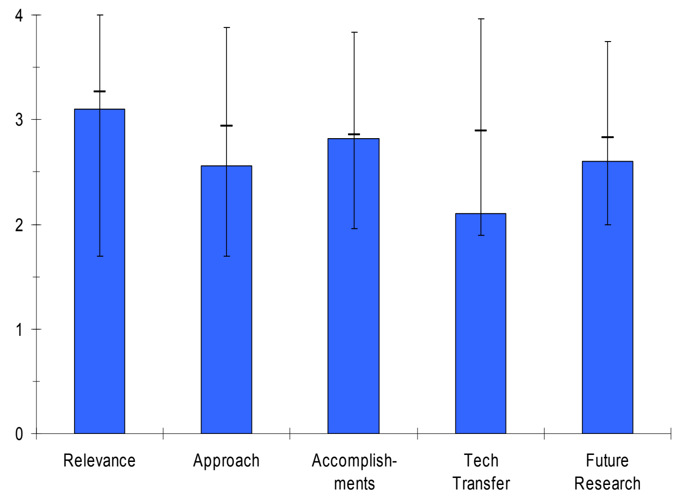
Specific recommendations and additions or deletions to the work scope

- Completion of this project should be accelerated as much as possible and completed in a timely manner in order to make the results of this study available as quickly as possible for the project to have any benefit at all.
- Need to work closely with fuel cell system developers or fuel cell manufacturing companies.
- I recommend discontinuation of this project.
- Enthalpy wheel needs a strong go/no-go decision point based on whether or not it can be sealed.

Project # FC-38: Low-Cost Manufacturable Microchannel Systems for Passive PEM Water Management

Ward TeGrotenhuis; Pacific Northwest National Laboratory

Overall Project Score: 2.7 (5 Reviews Received)



Brief Summary of Project

The overall objective of this project is to create a low cost, passive technology for water management in polymer electrolyte membrane systems. A 1-kW_e device has been designed and built at 22-kW_e/L power density and 4.2-kW_e/kg specific power. Testing is in progress. The primary cost driver for the device is powder rolled and annealed sheet. Current results indicate the powder rolled sheet will work and, therefore, cost projections will be met.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- Low-cost passive water management systems for polymer electrolyte membrane fuel cells are needed.
- Low cost materials for water and heat management are very relevant to the program.
- The project addresses the cost and manufacturability but needs to ensure the applicability to fuel cells.
- The project addresses an important issue.
- Because an anhydrous membrane is not likely, humidifiers will remain in fuel cell systems, and, therefore, this project maintains relevance.
- This project appears to be a design for manufacturing project. Humidification using porous media is well-established for fuel cells and the subject of several patents; therefore, the reviewer questions why this project is included in the DOE's fuel cell research and development activity.

Question 2: Approach to performing the research and development

This project was rated **2.6** on its approach.

- Passive low cost approach is good.
- Approach which requires saturated stack gas streams needs to be verified as an applicable approach.
- The design approach for cost and thermal and water management are appropriate.
- The team does not seem to have addressed in its approach possible issues with contaminant generation and transfer to the fuel cell as part of the overall approach.
- This innovative approach should yield promising results.
- Analysis to date has assumed that the exit stream from the stack cathode will be 100% relative humidity. However, throughout many operational modes on-board a vehicle, this assumption will not be true. For example, if someone drives two miles through the neighborhood to the store, there will not be enough water generated to reach 100% relative humidity. In this situation, the humidifier will likely dry.
- The low differential pressure required between two sides of the humidifier (< 102 mbar) dictates against placement downstream of compressor due to low stack pressure drop demand.
- Stack cathode exit stream (humidifier hot side inlet) will have to be expanded to near-ambient pressure, which will lower temperature and therefore, lower water transport.
- The approach follows several similar approaches in the literature and patents. The program did not discuss the solubility of reactants and inert gases in water. The approach should test the potential for crossover in the humidification device.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- Testing of single channel device with saturated gas streams does not verify that this is an applicable approach.
- The team has achieved several accomplishments in reducing the cost and improving the performance of the passive water management technology and in addressing the key barriers as they were identified.
- Progress is good and demonstrates feasibility.
- Good reporting of cost and weight for device.
- With tensile testing, a measure of durability against freeze/thaw has been shown.
- Strategy for manufacturing has been considered.
- Powder rolled material has improved bubble point, although not enough to avoid severe differential pressure limitations.
- A system-level cost analysis, perhaps using parts of TIAX or DTI reports, would have been helpful to compare a system with the humidifier to a system without it.
- Progress is consistent with objectives.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.1** for technology transfer and collaboration.

- Partners include Pacific Northwest National Laboratory, ADMA Products, Argonne National Laboratory.
- This project would benefit from interactions from a fuel cell original equipment manufacturer.
- The team would benefit from more integration with fuel cell testing and fuel cell requirements for the implementation of the device.
- PNNL did not clearly present the technology transfer and collaboration on the project.
- Lack of collaboration is hurting this project and collaboration is needed to provide experience and knowledge in automotive fuel cell systems.
- It is not clear what technology will be transferred if patents exist.

Question 5: Approach to and relevance of proposed future research

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

- Future plans need to include use of sub-saturated gases.
- The possibility and analyses of potential contamination transfer to the fuel cell should be examined to demonstrate the applicability of the device, in particular under real operating conditions where impurities could further enhance the corrosion of the steel materials.
- The principal investigator indicated that the device could potentially introduce droplets of water into the fuel cell that could contain metal ion impurities.
- The cost implications of any mitigation strategies for impurity problems should be examined.
- Future plans are logical and should advance the project.
- It is good that the investigators are interested in pursuing robustness to various operating conditions.
- Investigators should move quickly towards demonstration of the device in an automotive fuel cell system with realistic transient operation, to drive the project immediately to acknowledge problems implied with the cross-pressure limitation.
- Future work should be expanded to include non-automotive fuel cell applications.

Strengths and weaknesses

Strengths

- Good development of a material that could achieve the cost, manufacturability and performance targets.
- Focus on durability (freeze, etc.) is a good idea.
- Project is not just device-based, but has sought to improve a system component with a material improvement.

- Project has been responsive to feedback concerning cost/weight reporting and plans to eventually test a wide range of conditions.
- Strong experience in microchannel devices.

Weaknesses
- Water flow by capillary action limits the usefulness of this approach, as it requires a saturated fuel cell outlet.
- For transportation applications, outlet/inlet gas flows are not expected to be fully saturated; gas bypass is likely with realistic gas humidification – that amount of water on-board a vehicle is typically not available for saturated gas streams.
- Start-up time may prevent this technology from being used for transportation applications.
- Not enough consideration of the secondary effects of materials selection on the fuel cell nor of the potential issues that could increase the cost or limit the applicability of the solution.
- Model appears overly simplistic.
- The device has inherent limitations that will dictate against its use in an automotive fuel cell system.
- Assumptions regarding operation of an automotive fuel cell system need to be refined.
- Collaborations need to be developed with those who have system test benches and who know representative operating conditions.

Specific recommendations and additions or deletions to the work scope

- Need to demonstrate applicability for humidification with streams that are sub-saturated.
- Testing in conjunction with a fuel cell.
- Testing in the presence of fuel cell impurities that may affect the corrosion of the device both in the inlet and the outlet stream.
- Project should seek to immediately do system-level testing with transient conditions.
- If the device is not capable of withstanding realistic system-level environment, it should no longer address DOE automotive fuel cell targets.
- Researchers should research patent literature, particularly under the name Grasso.

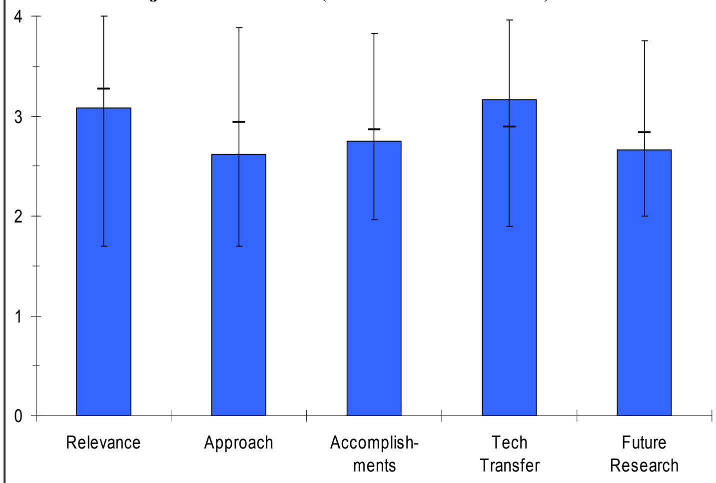
Project # FC-39: Development and Demonstration of a New Generation High-Efficiency 1-10 kW Stationary PEM Fuel Cell Power System

Durai Swamy; Intelligent Energy

Brief Summary of Project

The overall objective of this project is to develop and demonstrate a polymer electrolyte membrane fuel cell based stationary power system that provides a foundation for commercial, mass produced units that address identified technical barriers. The technical objectives are 1) 40% electrical efficiency (fuel to electric energy conversion); 2) 70% overall efficiency (fuel to electric energy plus usable waste heat energy conversion); 3) the potential for 40,000-hour life; and 4) the potential for $450/kW. Intelligent Energy will engage international partners and enter a demonstration phase with an International Partnership for the Hydrogen Economy country other than the U.S.

Overall Project Score: 2.8 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- The project certainly addresses its defined objectives.
- Project will provide important information and possibly an important product if they are successful in integrating an ethanol reformer and polymer electrolyte membrane fuel cell power system.
- The use of liquid feedstocks limits the applicability of this system though it would address some market niches.
- Although stationary systems can contribute to advancements in technology, the goals of this project may not be high enough to contribute significant advancements to stationary fuel cell performance.
- Actual accomplishments appear to exceed the goals and might contribute to advancements, if the accomplishments continue to progress.
- System has high potential and technical merit with many fuels. Work appears to meet/exceed stationary targets in efficiency and cost.
- Project team understands and is addressing appropriate barriers.

Question 2: Approach to performing the research and development

This project was rated **2.6** on its approach.

- Approach seems to result in significant progress, but it is difficult to evaluate on scientific merit with so little revealed information.
- Numerous cell, stack and system changes were implemented between "Baseline" and new version, yet the principal investigator did not present, or show an understanding of how the results were partitioned; so no understanding of the benefits of any particular change were learned.
- Sorbent-enhanced reforming has been tried by others (Air Products and Chemicals, for example) and large challenges on catalyst recovery and other issues surfaced. Principal investigator's modeling and experiment may fall short of predicting actual behavior of catalyst and sorbent in a full system under realistic cycling.
- It is not clear how the project is going to address durability and cost barriers, nor has total efficiency pathway (heat recovery) been discussed.

- The plan to test all combinations of stack design and fuel processing options seems unnecessary; the project should be capable of reducing the number combinations to save schedule and budget.
- General approach, to improve stack efficiency, reformer efficiency, power conditioning efficiency and reduce parasitic losses is a generally sound approach.
- Approach is sound and logical. The isolation of the fuel from the reformer with pressure swing adsorption and H_2 storage appears novel and could result in high purity H_2 at fuel cell inlet with elimination of costly CO/CO_2 cleanup processes. Is pressure swing adsorption impacted by reformer gas composition? Is a H_2 storage device necessary, and if so, what would it be?
- The principal investigator understands what is necessary to achieve the efficiency goals and the incremental improvements required to get there.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- Project seems to be on pace to reach specified targets.
- Principal investigator showed good improvement from their "Benchmark" fuel cell polarization, but it is not obvious how well the "Benchmark" unit was designed so it could be a representative state-of-the-art benchmark.
- The goal of a go/no-go decision by July 2008 is probably overly ambitious for the complexity of this integrated system project, where developments of reformer, fuel cell stack and power electronics are required.
- It appears that the bulk of the work to date has been related to fuel processing. The apparent lack of stack and system testing increases the risk of not initiating the demonstration in a timely manner and not achieving the project's goals.
- The work presented to date does not seem sufficient to support a system design finalization by January 2009.
- The project is meeting or exceeding its stack goals, but is not meeting its reformer goals.
- The project does not appear to be meeting its overall efficiency goals, although future gains may improve this situation.
- Intelligent Energy has made good progress. Meso Reformer may not be a major technical challenge. Fuel cell development appears to be an improvement and under control. Adsorption enhanced reformer achieved proof of concept. Data for polymer electrolyte membrane fuel cell performance showed no fuel composition, temperature or fuel utilization. It is difficult to assess real performance. Pressure swing adsorption unit has not been operated.
- Reasonable progress toward efficiency goal has been made, but definitely not there yet.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.2** for technology transfer and collaboration.

- Planning for future installations outside U.S., etc., and the number of engaged collaborators demonstrates significant integration with the fuel cell community at large.
- Collaborating partners are appropriate.
- The additional no-cost effort by Sandia National Laboratories to model six configurations is a plus.
- The project appears to be making good use of its partners to date.
- University / industry partnership.
- More input from users might be an improvement.
- Although electric utilities are being considered as partners, other industry user stakeholders, such as data center and office building developers, might be a valuable addition.
- Collaboration, including University of South Carolina, California State Polytechnic University, Pomona, and Sandia National Laboratories should be strong and effective.
- Working with Sandia National Laboratories and two universities is reasonable.
- Planning to demonstrate in an International Partnership for the Hydrogen Economy partner country.

Question 5: Approach to and relevance of proposed future research

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

- As often with industrial presentations, technical evaluation is difficult, but progress has been made toward stated goals and so the success in the future can be inferred.
- The identified issues regarding the potential abandonment of the heat recovery portion of the system and the possible switch to natural gas from liquid fuel are significant scope changes and represent appreciable schedule risk areas.
- The project does not appear to be meeting their current goals, but assumes that the decision to move ahead will be made.
- Good logical plans for future work: six combinations are being considered. Intelligent Energy is downselecting technologies within team and then engineer, test and demonstrate a new generation polymer electrolyte membrane fuel cell power system.
- Inclusion of go/no-go decision point is outstanding.

Strengths and weaknesses

Strengths
- Good single cell performance demonstrated; goals within reach for efficiency.
- Good fuel cell stack performance.
- Good group of collaborators with potential to eventually meet key project objectives.
- Solid approach to achieving gains.

Weaknesses
- Little information provided for meaningful technical evaluation.
- Too complex a scope for the schedule.
- The project seems to be lacking a rigorous approach to technology development and screening.
- The project does not address cost issues at all, and the presenter was unable to answer any questions regarding cost reduction approaches.
- Project goals do not appear to be a significant advancement over current fuel cell technology.
- The project does not appear to be meeting its overall goals.

Specific recommendations and additions or deletions to the work scope

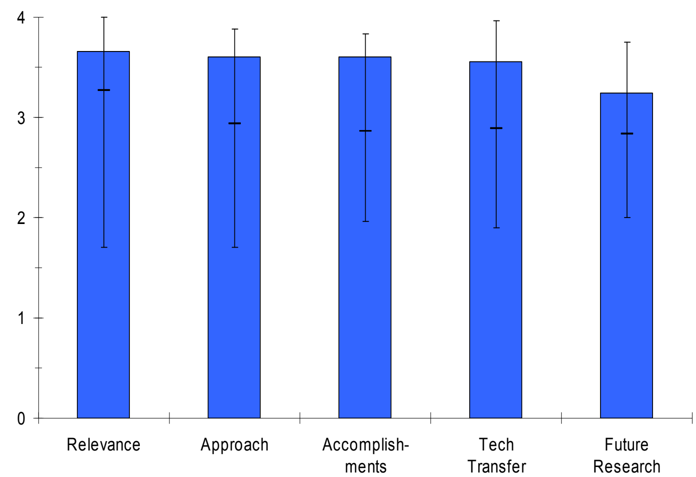
- If principal investigator has not already done so, look into the DOE funded sorbent enhanced reforming done by Air Products and Chemicals in the late 1990s.
- If the project continues past the go/no-go decision point, emphasis should shift to the durability targets.

Project # FC-40: International Stationary Fuel Cell Demonstration
John Vogel; Plug Power Inc.

Brief Summary of Project

The overall objective of this project is to develop, test, and validate a high temperature polymer electrolyte membrane, stationary reformate-based, combined heat and power, fuel cell system as the first demonstration of a modular, scalable design for a worldwide market. The technical objectives are 1) total system cost of less than $750 / kW in production volumes; 2) $\eta_{electric}$ = 35% (line of sight to 40%) and $\eta_{overall}$ = 85%; 3) system life of 40,000 hours; and 4) modular and scalable system and combined heat and power hydraulics concepts.

Overall Project Score: 3.6 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.7** for its relevance to DOE objectives.

- The program is well directed at the program objectives.
- Very relevant to the DOE program though not relevant to transportation.
- Supports DOE: total system cost of <$750/kW in production volumes; $\eta_{electric}$= 35% (line of sight to 40%); $\eta_{overall}$= 85%; System life = 40,000 hours.
- Very well aligned with DOE's stationary fuel cell activities.
- This project is highly relevant to the President's Hydrogen Fuel Initiative and the objectives of the Multi-Year RD&D Plan.
- It is very important that a commercial "win" be achieved in the not to distant future, to help sustain the supplier base and maintain momentum and support for fuel cells in stationary and more challenging applications such as transportation.
- This project is relevant to the Hydrogen Fuel Initiative and the Multi-Year RD&D Plan as it targets a number of key barriers to the successful application of stationary polymer electrolyte membrane fuel cells utilizing different fueling scenarios.
- The basic project building block is the 5-kW fuel cell module. From here, a system can ostensibly be scaled up for a variety of applications including backup power, peak shaving, and prime generation.
- The project includes at least two potential fueling options- electrolyzer and natural gas reformation.
- The project is also evaluating the interconnection of the 5 kW power plants with the electric grid and opportunities for utilization of waste heat from the polymer electrolyte membrane fuel cell.

Question 2: Approach to performing the research and development

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

- The approach to the technology validation seems well directed to making a commercially acceptable device that can meet residential needs for combined heat and power.
- The team is addressing the major technological barriers that will limit consumer adoption of the fuel cell in a realistic consumer environment.
- The project approach is clearly focused on delivering a 5 kW combined heat and power unit.
- Approach is well-documented; milestones are detailed and appropriate and aggressive.
- Not only are they addressing the technical targets, but also commercialization issues.

- The overarching approach is sound, spreading the developmental cost between the U.S. and EU, private and government sectors, and targeting specific residential combined heat and power applications as a drop-in solution.
- The presentation was somewhat vague and not comprehensive on how each of the technical barriers (durability, cost, and performance) is specifically being addressed.
- Little discussion is provided of alternative technical approaches should current avenues not prove out.
- This project overtly addresses key technical barriers of durability, reliability, electrical and combined heat and power energy efficiency, and cost.
- Project incorporates a completely passive natural water management system mode.
- The project is broad emphasizing a number of areas, but lacks a sharp focus on any one particular technical barrier and does not focus on a specific market niche.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.6** based on accomplishments.

- The team is making good technical progress against the objectives of the program.
- The major technical objectives of durability with the new materials in a fuel cell system need to be demonstrated.
- Three units have been built and are ready to ship to the delivery sites.
- Good progress. A high temperature polymer electrolyte membrane, stationary, reformate-based, combined heat and power fuel cell system has been developed based on commercial requirements.
    - Enabling membrane electrode assembly, stack, reforming and power electronics technologies have been explored, down-selected and developed.
    - Progress has been made toward achieving DOE technical targets; especially performance and system durability.
- Technical improvements are headed in the right direction to achieve efficiency and life.
- Higher efficiency inverters are being developed through the DOE Vehicle Technologies Program.
- There appears to be solid technical advancements with the cathode and inverter but otherwise technical accomplishments seem a little sparse at this point in the project (80% completed). Specifically, with regards to the stack, it appears only limited progress has been made.
- No hard data is provided on specific technical accomplishments vis-a-vis DOE durability, cost, and performance targets.
- No accounting is provided of technical accomplishments on the EU side.
- Clearly, technical progress is being made with regards to efficiency (42% without power conditioning). IR, open circuit voltage, falloff time, and conductivity have exceeded program requirements for unitized electrode assemblies and performance at 1 A/cm^2 is close to minimum criteria.
- There is insufficient information to determine progress towards durability, combined heat and power efficiency, and cost targets.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.6** for technology transfer and collaboration.

- The team has the skills to build and put in place the test units.
- The team is well coordinated with integration of the materials test, integration and build within a reasonable project plan to meet the demonstration objectives.
- Major collaborations with the EU, which is providing funds.
- BASF provides high temperature membrane and new cathode catalyst formulations.
- First of a kind collaboration between the DOE and the EU. Goal to develop “high-temperature” (PBI-based) fuel cell heating appliances for residential use worldwide. Executed through a U.S./EU consortium: Plug Power (U.S.)/(Netherlands), BASF E-TEK (U.S.), BASF (Germany), Vaillant (Germany), Domel (Slovenia), Bulgarian Academy of Sciences (Bulgaria), Gaia (Sweden), Imperial College (United Kingdom).
- Impressed with the consortium that has been assembled for this project.

- Broad collaboration especially on the European side with several different companies and academic institutions.
- Collaboration is narrow on the U.S. side with a notable absence being DOE laboratories.
- It is not clear as to the exact role of each of the participants. For example, which entity is going to help crack the barriers to entry in the boiler market (Vaillant)?
- No discussion of how intellectual property rights would be allocated and shared to protect each entity's achievements but still expedite commercialization.
- The project only has a minimal amount of partners for testing, power conversion / electronics, and refueling options (electrolyzer). There are no other fuel cell industry, laboratory, or university partners. As a result, it is unlikely that significant technology transfer will occur.

Question 5: Approach to and relevance of proposed future research

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

- The future work is well-designed to meet the remaining engineering tasks to necessary to put the three demonstration units into place and monitor their progress.
- The system will be tested for 6 months in Europe by the end of the first quarter of 2009.
- Well-conceived management milestones.
- Planned work is consistent with goal of completing demo next year.
- Limited discussion is provided as to other commercialization avenues should the residential boiler replacement market not pan out.
- No discussion is provided as to other potential technical paths should further progress toward the technical goals not be achieved under the current strategy.
- It is indicated the technology is modular and "scalable" but little discussion was provided on specifically how it may make the technology amenable to other potential applications.
- The broad scope of the project inherently permits significant flexibility to adjust to future market opportunities. For example, to use the basic 5 kW fuel cell building block to scale up to different applications and accommodate different fueling options. However, the broad scope also hinders strongly focusing on a specific market application that could be achieved in the near term and lead to a commercial foothold.

Strengths and weaknesses

Strengths
- Good project team to do the integration and put the systems into place.
- Worked on one of the key materials degradation processes in the catalyst corrosion.
- Addresses a market that could be ready for near-term deployment.
- Overall consortium strategy with EU is interesting and refreshing.
- Project appears strongly focused on commercial applications.
- Focusing on a 5-kW building block that provides inherent commercial flexibility.
- Broad scope of project looking at variety of key technical barriers and fueling options.

Weaknesses
- The longer-term durability of the components, in particular the new catalyst and support was not shown.
- Technical progress to date is somewhat limited.
- There is no collaboration with DOE national laboratories, universities, and only one other U.S.-based company.
- The project does not provide a solid discussion of contingencies should the current technical and business approach not be entirely successful.
- No specific near term commercial application is targeted.
- Limited number of project partners especially with regards to the fuel cell system itself.

Specific recommendations and additions or deletions to the work scope

- Is a longer testing period for the demonstration units need to really demonstrate the applicability of the units?
- Involve National Laboratories to help resolve durability issues.

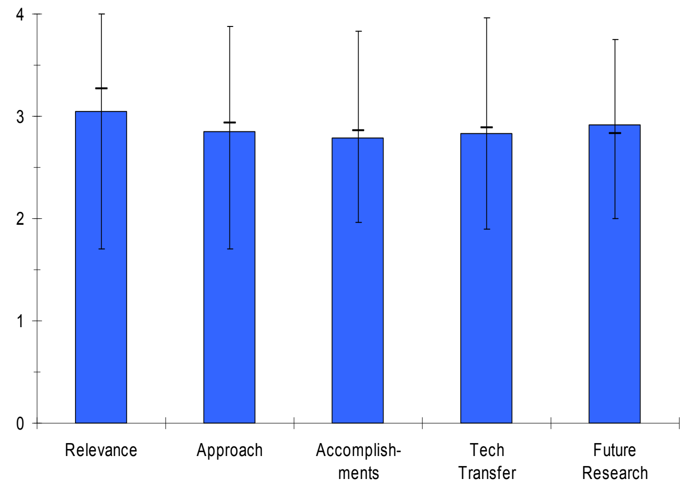
- Clearly delineate intellectual property agreements (if they haven't been already) to enhance commercialization prospects.
- Work with U.S.-based home energy suppliers to determine if options exist in the U.S. for the proposed technology.
- Establish collaboration with the National Lab(s) or universities to help solve most difficult membrane/electrode issues.
- Conduct downselection process to identify and have focus on a specific near term market opportunity such as a backup power. Develop partnership with commercial entities that can facilitate breaking into this market.

Project # FC-41: Intergovernmental Stationary Fuel Cell System Demonstration
Rhonda Staudt; Plug Power Inc.

Brief Summary of Project

The objective of this project is to design and produce an advanced prototype polymer electrolyte membrane fuel cell system with the following features 1) 5-kW net electrical output; 2) flex-fuel capable (liquefied petroleum gas, natural gas, ethanol); 3) reduce material and production cost while increasing durability; 4) increase electrical efficiency over the current alpha design; and 5) increase total efficiency by incorporating combined heat and power. Plug Power will also show a path to meet long-term Department of Energy objectives, including 1) 40% system electrical efficiency; 2) 40,000-hour system/fuel cell stack life; and 3) $750/kW integrated system cost (with reformer).

Overall Project Score: 2.9 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- Stationary systems that are flex-fueled are reasonably aligned with the Hydrogen vision.
- A meaningful demonstration of implementation of fuel technology is very relevant. It should encourage other potential first users to pursue deployment of this important technology.
- The overall objective is to design and produce an advanced prototype polymer electrolyte membrane fuel cell system with many different functions such as flexible fuels.
- The program is highly relevant to the President's Hydrogen Fuel Initiative.
- Not to be judged from the presentation.
- Shows a path to meet long-term DOE objectives.
    - 40% system electrical efficiency
    - 40,000 hour system / fuel cell stack life
    - $750/kW integrated system cost (w/ reformer).
- Pursuing path to efficiency and durability as established by DOE targets.

Question 2: Approach to performing the research and development

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

- Approach thus far appears to be well-planned, which is necessary for a small company.
- Clear and well-defined steps to approach targets have been established.
- Breakdown of various components is well understood and mapped out.
- Unclear why ethanol was chosen as a fuel.
- The proposed approach appears to be sound and when successfully completed should achieve the desired DOE objectives. The proposed tasks are reasonable and well-defined.
- The project is not research and development; it is primarily system development and integration. The approaches are excellent.
- Only vague general statements.

- Approach may be too ambitious. Flex-fuel capability – liquefied petroleum gas, natural gas, ethanol may be difficult but possible with an autothermal reformer. What about guaranteed output power no matter the fuel? Can fuel switch be done quickly without major modifications?
- Good work plan for a fuel flexible system.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- Despite short funding period, quiet a few accomplishments have been met.
- Stationary community has finally recognized issues of start/stop on stack durability.
- Interesting cost analysis has been performed.
- This is a fairly new project.
- Completion of the first task indicates good progress being made.
- The program started August 2007, so far, the accomplishments are good.
- Nothing substantial.
- Modest progress. Completed mostly only conceptual efforts. However, a realistic direct manufacturing cost reduction plan was apparently obtained.
- Determined that continuous operation is financially advantageous.
- Significant analysis and thought has gone into conceptualization of the design.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- Collaborations exist but at this time it is premature to judge relationships fully.
- Based on work to date, it appears to be sufficient.
- Appropriate partners for this project have been identified and are in the process of being brought onboard.
- Partnered with Ballard and Army's Construction Engineering Research Laboratory, excellent cooperation. The system may be used for the Department of Defense facilities.
- Unclear.
- Collaboration is strong and effective. Ballard and the Construction Engineering Research Laboratory bring excellent test and technical strengths.
- Collaborations are really limited to the demonstration sights. Additional, diversified subcontractors might help accelerate improvements.

Question 5: Approach to and relevance of proposed future research

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

- Future research is well described and logical.
- Depends on some criteria coming together so some risks exist.
- A good plan for future work is in place in sufficient detail.
- The future work and plan are clearly stated in the slides and also excellent.
- Unclear.
- Plug Power planned future work is well conceived, but ambitious.
- Go/no-go decision next year.

Strengths and weaknesses

Strengths
- Key player in this area.
- Strong Team.
- Good Plan.

Weaknesses

- Inclusion of ethanol seems to be an unnecessary step – perhaps liquefied petroleum gas is sufficient as primary first step.

Specific recommendations and additions or deletions to the work scope

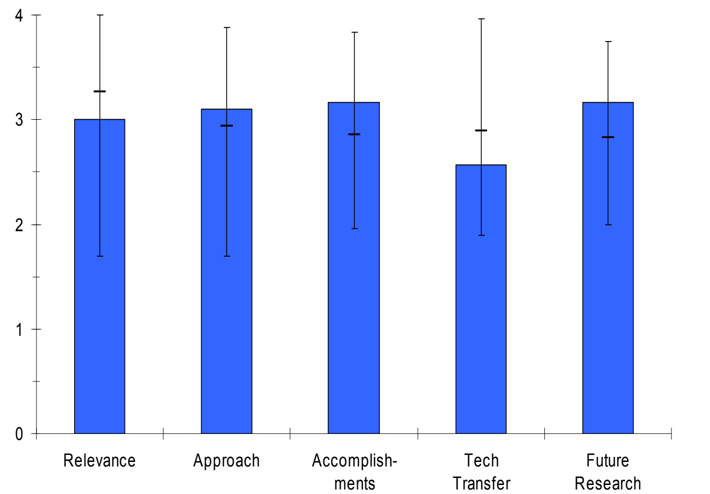
- Consideration of focusing solely on liquefied petroleum gas.
- The project started August 2007, wait for the next year review to decide recommendations.
- Generate and present clear results.

Project # FC-42: Stationary PEM Fuel Cell Power Plant Verification
Eric Strayer; UTC Power

Brief Summary of Project

The objectives of this project are to 1) evaluate the operation of a 150 kW natural gas-fueled polymer electrolyte membrane fuel cell; 2) assess the market and opportunity for utilization of waste heat from a polymer electrolyte membrane fuel cell; 3) verify the durability and reliability of low cost polymer electrolyte membrane fuel cell stack components; 4) design and validate an advanced 5 kW polymer electrolyte membrane fuel cell system; 5) conduct demonstrations of polymer electrolyte membrane technology with various fueling scenarios; and 6) evaluate the interconnection of the demonstration 5 kW power plants with the electric grid.

Overall Project Score: 3.1 (3 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.0** for its relevance to DOE objectives.

- Project addresses the evaluation and advancement of stationary polymer electrolyte membrane fuel cells.
- Relevant to the DOE program objectives though not necessarily relevant to transportation.
- Durability is a critical characteristic for base load stationary power applications.
- The project is also addressing cyclic performance for backup and intermittent power implementations.

Question 2: Approach to performing the research and development

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

- Approach seems to move project towards stated targets.
- The approach is clearly focused on developing a commercially viable fuel cell generator.
- UTC Power performance targets are well documented.
- While the approach appears to be working towards addressing the identified barriers, there needs to be a clearer presentation of the linkages between project activities.
- There was very little discussion regarding approaches for reducing cost.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.2** based on accomplishments.

- Goals have been achieved on schedule for evaluating the technology.
- Progress appears to be good in the three enabling fundamental technologies – a low cost membrane electrode assembly, evaporative cooling, and a strategy to mitigate the effects of O_2 in the anode chamber on startup after a shutdown.
- The advanced stack with the above features is under test.
- Progress against targets is well-documented.
- Progress is being made in most areas, though there are a few open issues that need to be addressed, most notably end-cell degradation effects.
- UTC presented little technical information beyond final performance (which is typical of presentations from industry.)

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.6** for technology transfer and collaboration.

- It is unclear whether collaborators provide more than simply pre-built components.
- Key suppliers/developers and independent test organization are identified that contribute to the project.
- It could be inferred how the project partners participated in a meaningful manner, but the project presentation does not clearly identify the partners' activities and contributions.

Question 5: Approach to and relevance of proposed future research

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

- Project seems to be well-planned and there are paths for improvement.
- After the test program and data are evaluated, the final design iteration will be completed.
- It is unclear which technology set (baseline or advanced) is being incorporated into which future demonstration.
- As with the project approach, there needs to be a clearer presentation of the linkages between future project activities.

Strengths and weaknesses

Strengths
- Shows progress and makes the technology look more promising.
- Clear market-driven focus.
- UTC Power has the system development experience to complete the work and is focusing on important issues.

Weaknesses
- Unclear if durability issues will prevail against the technology.
- There was no presentation of approaches and progress relative to cost reduction.

Specific recommendations and additions or deletions to the work scope

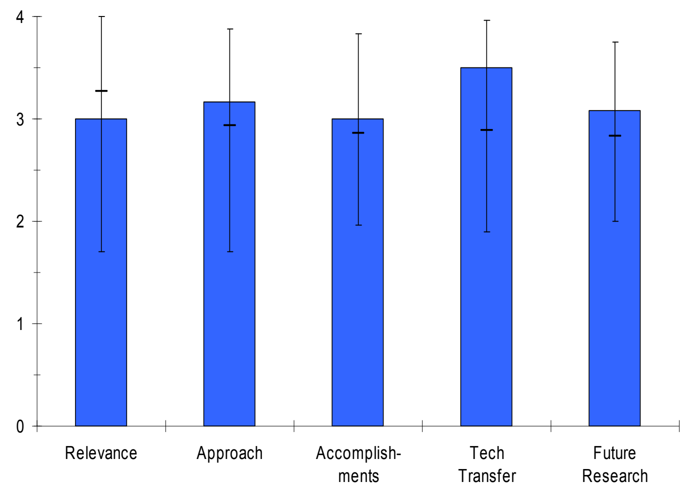
(None provided by reviewers.)

Project # FC-43: Diesel Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power
Dan Norrick; Cummins

Brief Summary of Project

The objectives of this project are to 1) demonstrate on-vehicle and evaluate a solid oxide fuel cell (SOFC) auxiliary power unit with integrated on-board reformation of diesel fuel; 2) develop a transparent method of water management for diesel fuel reformation; 3) develop controls to seamlessly start, operate, and shutdown the solid oxide fuel cell auxiliary power unit; 4) evaluate hardening the solid oxide fuel cell auxiliary power unit to enable it to operate reliably in the on-highway environment; and 5) develop the overall system for performance, size, cost, and reliability targets.

Overall Project Score: 3.1 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.0** for its relevance to DOE objectives.

- Addresses auxiliary power unit application.
- Highly relevant to DOE mission.
- The development of solid oxide fuel cell-based auxiliary power units is critical to reducing the environmental impact of auxiliary power units.
- The project appears well designed to address most substantial issues related to heavy-duty vehicle auxiliary power unit development.
- There is not sufficient focus on durability aside from shock and vibration tolerance.
- Shows path to reducing truck emissions in prospect of anti-idling laws. Also auxiliary power units will lead to lower diesel fuel consumption. Project will become more important as price of diesel continues to increase.

Question 2: Approach to performing the research and development

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

- Standard approach of analysis and design/sub-system test and development/laboratory testing/on-vehicle evaluation.
- Very good approach matrix to develop the auxiliary power unit.
- Good approach to use existing packaging design and size.
- Tightly integrated packaging of reformer and solid oxide fuel cell.
- Approach is rational and properly staged.
- Use of existing engine-based commercial auxiliary power unit platform/constraints is helpful for integration into vehicle.
- It is not clear how the project is going to address cost reduction or thermal cycling performance.
- Excellent understanding of barriers.
    - Waterless reforming of ultra low sulfur diesel fuel.
    - Transient operation of solid oxide fuel cell system.
    - Power density, specific power (W/L, W/kg).
    - Shock and vibration tolerance.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.0** based on accomplishments.

- 17% net efficiency does not come close to the DOE 2010 target of 35%.
- Catalytic partial oxidation improvements appear to sacrifice efficiency.
- Good results for system design, fuel cell components and balance-of-plant.
- No indication how Cummins will harden system for improved sulfur tolerance.
- Good progress on opening operating region for catalytic partial oxidation, but a wider range of conditions is still needed.
- Little progress on anything but reformer development.
- The project team has addressed system demand and packaging issues.
- More information regarding transient performance, solid oxide fuel cell sulfur tolerance, and power density are required.
- Approach is well-organized. Selection of current collection approach is very critical for this solid oxide fuel cell design. Could be costly and ineffective if not correctly done. Tube power density needs to be increased as much as possible. Dry catalytic partial oxidation is best reforming approach but system efficiency of 17% is low. Only 500 h catalytic partial oxidation testing to-date. Transfer switch to shore power is good feature.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.5** for technology transfer and collaboration.

- Partnership between Cummins, Protonex and International Truck and Engine.
- Collaborations utilize all partners' strengths to advance the technology.
- Excellent team covering all aspects of system development and demonstration.
- The project team encompasses and has engaged all pertinent participants.
- Collaboration is excellent. Excellent team skills/subsystems. Cummins Power Generation (project lead), Protonex, LLC (solid oxide fuel cell power module), International Truck and Engine (vehicle and installation). Cummins is already in truck auxiliary power unit business.

Question 5: Approach to and relevance of proposed future research

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

- Future work shows how system will be finished, integrated and tested.
- No path apparent to reach DOE efficiency targets.
- Future work weak. No mention of demonstration. It appears that all work is on H_2 pump, which is not really a pump.
- There remains much to be done in this project, but the proposed future work should address all issues.
- Future work is largely appropriate relative to the work to date and overall objectives.
- Planned future work is well-conceived: fabricate and test hot zones – build single modules and 4-module sets – test modules in furnace and in insulation packages – optimize bundle performance.

Strengths and weaknesses

Strengths

- Operation on diesel with no water makes for simplified system infrastructure requirements.
- Tightly integrated team.
- Cummins is well-positioned given their experience with engine-based commercial auxiliary power unit products to understand the technical and functional requirements of a solid oxide fuel cell-based auxiliary power unit.

Weaknesses

- System efficiency limits the application of this project to small niche markets.

- Overall system gross efficiency is not much better than IC engine. How will this concept ever gain acceptance!
- System could be designed to improve fuel utilization and stack efficiency to more than 60% on diesel with redesign. Advanced concepts have been overlooked or neglected to improve system efficiency.
- Somewhat slow progress to date.
- A clearer understanding of how the project is addressing issues related durability and performing relative to DOE power density targets is required.

Specific recommendations and additions or deletions to the work scope

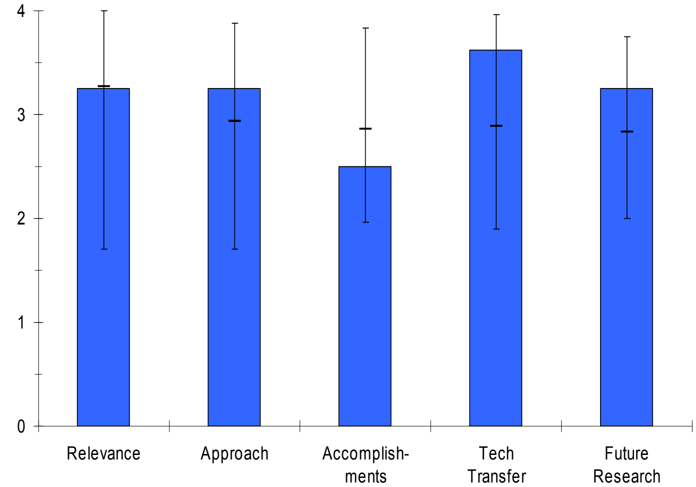
- Need to explore methods to improve catalytic partial oxidation and system efficiency.
- Add wider range of operating conditions to testing of catalytic partial oxidation reformer, including the effect of higher concentrations of sulfur in diesel fuel on performance and durability of catalytic partial oxidation reformer and solid oxide fuel cell stack.

Project # FC-44: Solid Oxide Fuel Cell System Development for Auxiliary Power in Heavy Duty Vehicle Applications
Gary Blake; Delphi

Brief Summary of Project

The objectives of this project are to 1) develop auxiliary power unit system requirements and concepts with major truck original equipment manufacturers; 2) design, develop, and test the needed subsystems for the approved concept; and 3) build and demonstrate a diesel-fueled truck auxiliary power unit system. Delphi is preparing the on-truck installation using a modified natural gas auxiliary power unit in an integration enclosure. Delphi is on target for meeting timing and budget and is committed to introducing solid oxide fuel cell diesel technology in full-scale production for heavy-duty truck applications.

Overall Project Score: 3.0 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- The project is relevant, but the payoff in terms of fuel and emissions reductions is not quantified.
- The development of solid oxide fuel cell based auxiliary power units is critical to reducing the environmental impact of tractor trailers and the reliance of tractor trailers on carbon-based fuels.
- The project, in principle, can address issues related to heavy-duty vehicle auxiliary power unit development, but project objectives are very high level and lack clarity.
- Shows path to reducing truck emissions in prospect of anti-idling laws. Also auxiliary power units will lead to lower diesel fuel consumption. Project will become more important as price of diesel continues to increase. Fuel cell genset should be lower cost than diesel genset no matter the driver/truck behavior/use pattern.

Question 2: Approach to performing the research and development

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

- This is a typical design, build, test project.
- Good plan to include thermal cycling effects on system performance and durability.
- Excellent understanding and description of requirements.
- The approach lacks specifics regarding how the project will address development issues.
- The lack of a road test represents a risk area.
- Excellent understanding of barriers.
    - Sulfur remediation.
    - Reformer operation.
    - Stack sensitivity – carbon issues.
    - Catalyst plugging.
    - System pre-combustion / combustion.
    - System integrated electrical efficiency could be 30-35%.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.5** based on accomplishments.

- On target for schedule and budget.
- No performance data were presented, just "projected" efficiency data.
- Nice demonstration of projected efficiency of future Delphi solid oxide fuel cell.
- Though the presentation stated that the project is 50% complete, it appears that a large majority of the tasks were not yet complete.
- There was insufficient discussion regarding how the project is progressing against required system characteristics.
- The switch from a catalytic partial oxidation reformer to an "endothermic" reformer represents an appreciable change to system architecture and a program risk that was not adequately discussed.
- Progress has been slow/delayed. Delphi is developing one of highest performing solid oxide fuel cells in world developed under Solid State Energy Conversion Alliance program. Delphi is developing reforming technology for Diesel/JP-8 solid oxide fuel cell applications for the Department of Defense. In solid oxide fuel cells, the water is created on the anode side that is where it is needed – ideal fuel cell for fuel reforming applications to produce H_2.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.6** for technology transfer and collaboration.

- Excellent support from the ultimate customer, truck original equipment manufacturers.
- Excellent team covering all aspects of system development and demonstration.
- The project is largely an in-house effort, but appropriate system requirements have flowed down from end users.
- Collaboration is excellent. Excellent team skills/subsystems: Delphi, Paccar, Volvo Truck, and Electricore, Inc. Delphi is already in automotive business. Excellent market understanding and presence.

Question 5: Approach to and relevance of proposed future research

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

- Logical and according to plan.
- Good plan, but with little time remaining.
- There appears to be a substantial amount of work remaining, but it is appropriately structured.
- Planned future work indicates complete understanding of how to complete this project successfully.
- Finalize the Subsystem Requirements Document and Development Plan.
    - Complete the solid oxide fuel cell auxiliary power unit hardware design and build.
    - Design subsystem test fixture.
    - Begin subsystem testing and development iterations.
    - Build a system for DOE.

Strengths and weaknesses

Strengths
- The team.
- Integrated team.
- Understanding of system issues.
- Delphi is an experienced solid oxide fuel cell developer who understands what is required to develop a system.

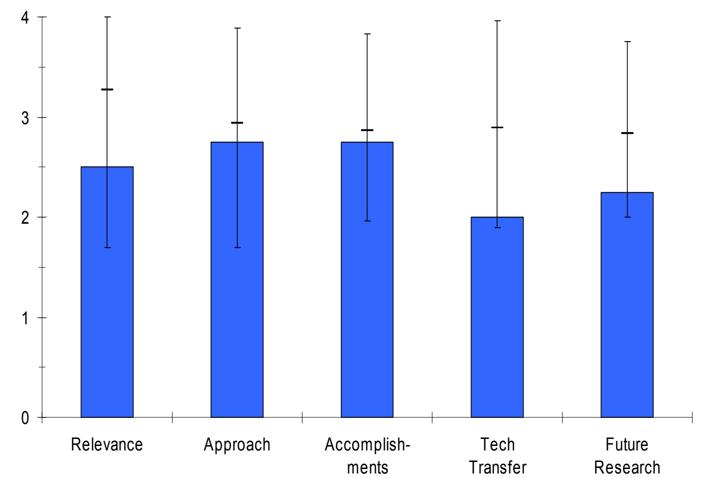
Weaknesses
- Project started with focus on partial oxidation reforming, but has switched to a vastly different design utilizing steam reforming at a very late stage in the project.
- Lack of progress, with the exception of paper studies.
- The approach and discussion of progress lack specifics.

Specific recommendations and additions or deletions to the work scope

(None provided by reviewers.)

Project # FC-45: DMFC Prototype Demonstration for Consumer Electronic Applications
Chuck Carlstrom; MTI Micro Fuel Cells

Overall Project Score: 2.6 (2 Reviews Received)



<u>**Brief Summary of Project**</u>

The objectives of this project are to 1) benchmark energy density of 600 Wh/L; 2) demonstrate prototypes; 3) develop pathways to low cost for initial market entry; 4) demonstrate continual operation of 1,000 h; and 5) accelerate codes, standards, and regulations to allow shipping and airline passenger cabin usage. Prototype energy density was demonstrated to be on path to system targets. There was also success on the regulatory road map.

<u>**Question 1: Relevance to overall DOE objectives**</u>

This project earned a score of **2.5** for its relevance to DOE objectives.

- Portable power systems will not directly support the Hydrogen Fuel Initiative; the project has some aspects that could support the advancement of fuel cells thereby providing tangential value to advancing the Hydrogen Fuel Initiative.
- Relevant.

<u>**Question 2: Approach to performing the research and development**</u>

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

- Mobion technology has been developed for very low power, portable applications.
- The mostly passive Mobion technology has advantages regarding balance-of-plant issues (fewer components, less system complexity, etc.).
- The energy density produced is not significantly higher than lithium batteries. The project primarily represents an engineering approach to a system that is not likely to be commercially competitive. Significant increases in energy density would make this project more compelling.

<u>**Question 3: Technical accomplishments and progress toward project and DOE goals**</u>

This project was rated **2.8** based on accomplishments.

- The reported performances were only modestly compelling compared to lithium batteries. The next generation of Mobion technology is a little more interesting, but still not demonstrated. The arbitrary choice of several refills/cartridges in projecting an energy density makes the true performance versus weight characteristics impossible to completely evaluate.
- Good progress towards stated goals.

<u>**Question 4: Technology transfer/collaborations with industry, universities and other laboratories**</u>

This project was rated **2.0** for technology transfer and collaboration.

- Really not particularly relevant. The community gains little in terms of understanding or scientific advancement for a publicly funded project.

- Not very clear.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.3** for proposed future work.

- It is very hard to judge what the substance behind the future plans is. The demonstration of the next generation system with higher energy density and cartridges is obviously a step forward.
- Difficult to assess.

Strengths and weaknesses

Strengths
(None provided by reviewers.)

Weaknesses
(None provided by reviewers.)

Specific recommendations and additions or deletions to the work scope

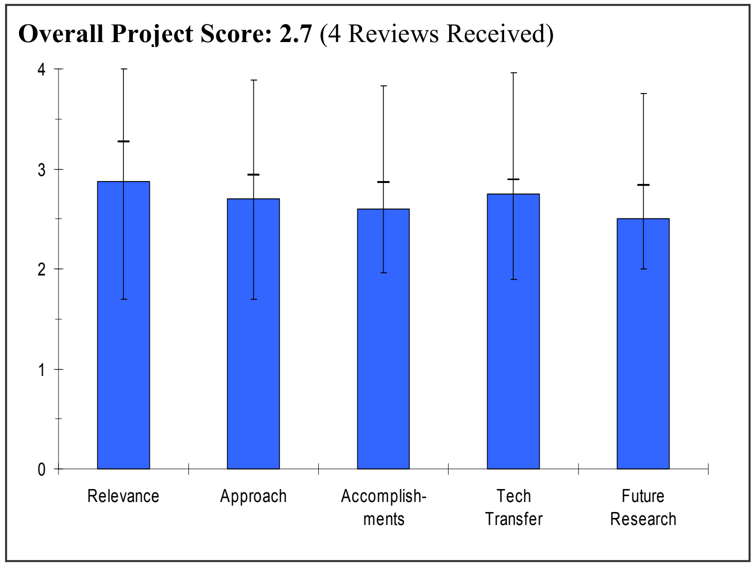
(None provided by reviewers.)

Project # FC-46: DMFC Power Supply for All-Day True-Wireless Mobile Computing

Brian Wells; Polyfuel Inc.

Brief Summary of Project

The objectives of this project are to 1) build a direct methanol fuel cell laptop power supply with a significant advantage over lithium ion batteries; and 2) fully integrate this power supply into a laptop computer. A radical departure from conventional active systems is required to realize competitive power density. PolyFuel's intention is to license any arising intellectual property to electronics original equipment manufacturers. PolyFuel has identified a novel method of membrane electrode assemble construction with a new membrane and gas diffusion layer structure.



Question 1: Relevance to overall DOE objectives

This project earned a score of **2.9** for its relevance to DOE objectives.

- The main objective of the project is to build a direct methanol fuel cell system for a laptop computer application.
- The cost for a direct methanol fuel cell system is too high to be used for a laptop computer application.
- The project is indirectly relevant to the President's Hydrogen Fuel Initiative.
- Fuel cell introduction into the electronics portable power market is an excellent way for the public to increase its familiarity with and acceptance of fuel cell systems in other markets, such as vehicular.
- Portable power systems won't directly support the Hydrogen Fuel Initiative, but the project has some aspects that could support the advancement of fuel cells thereby providing tangential value to advancing fuel cells.
- Relevant.

Question 2: Approach to performing the research and development

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

- PolyFuel is a research and development company for membrane electrolytes while the project involves system integration and manufacturing.
- The power density and energy density are key issues for electronic portable power. These are being aggressively addressed through innovative approaches.
- Development of a direct methanol fuel cell system without active water recovery is beneficial for balance-of-plant issues. Engineering of membranes and gas diffusion layers to remove water is a reasonable approach. The control system strategy seems logical although a deep level of detail is not possible in such a review. An analysis comparing active water recovery systems that can operate at higher temperatures and have higher cell efficiency (although increased balance-of-plant losses and a larger footprint) would have been useful.
- The energy density is not significantly higher than lithium batteries. The project primarily represents an engineering approach to a system that is not likely to be commercially competitive. Significant increases in energy density are necessary to make this project more compelling.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.6** based on accomplishments.

- The single cell performance is not good as Nafion 117 single cell performance. The direct methanol fuel cell system problem is balance-of-plant. The project focuses on single cell research and development.
- The water recovery approach appears to be producing excellent results in terms of fuel cell power density, stability, and operational lifetime.
- Differences in single cell and stack performance suggest that significant issues remain to be solved.
- Performances reported are not compelling for laptop applications because of other advantages of lithium batteries over fuel cells in these applications.
- Substantial shortcomings in terms of implementing technology effectively in the platform considering the funding level.
- Good progress.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.8** for technology transfer and collaboration.

- The project may not be able to transfer technology.
- The collaborations with others on the project with regard to membrane electrode assembly development appear to be quite effective.
- PolyFuel indicates its intention to license its intellectual property to electronics original equipment manufacturers.
- Reasonable team for commercial development of these systems. However, little is learned by the community from these highly proprietary projects.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.5** for proposed future work.

- Find a system integration and manufacturing company to support the project. The direct methanol fuel cell is too expensive to be used for a laptop computer application.
- The future work is targeted at the remaining issues with the system.
- Not clear how future objectives will be met (i.e., presentation does not have any details).

Strengths and weaknesses

Strengths
- Innovative approaches.
- No active water recovery needed.

Weaknesses
- PolyFuel does not have the necessary experience for system integration and balance-of-plant for a direct methanol fuel cell system.
- Energy densities not compelling; no route was presented toward achieving compelling energy densities.

Specific recommendations and additions or deletions to the work scope

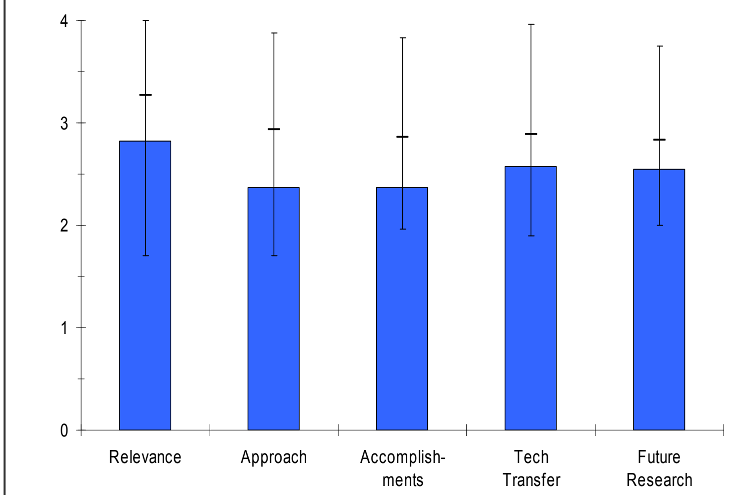
- Find a system integration and manufacturing company to support the project.

Project # FC-47: Fuel Cell Research at the University of South Carolina
John Van Zee; University of South Carolina

Brief Summary of Project

The objectives of this project are to 1) develop novel materials (e.g., Nb-doped) for improved corrosion resistance and improved fuel cell components; 2) develop a fundamental understanding of performance and durability loss induced by fuel contaminants; 3) develop a fundamental understanding of the degradation mechanisms of existing gaskets and the performance of improved materials; 4) develop a fundamental understanding of acid loss and acid transport mechanisms in polybenzimidazole systems, and predict performance and lifetime as a function of load cycle.

Overall Project Score: 2.5 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **2.8** for its relevance to DOE objectives.

- Project works to develop components and/or make measurements to support modeling.
- Project covers many topics, but none are addressed with the proper methodology.
- Improved fuel cell durability, cost, and performance are relevant goals.

Question 2: Approach to performing the research and development

This project was rated **2.4** on its approach.

- Project consists of 4 different/separate approaches.
- Unclear why project is developing non-carbon electrocatalyst supports for direct methanol fuel cell anodes.
- Probably don't need to evaluate silicon gaskets for polymer electrolyte membrane environment as most developers have eliminated those from consideration.
- Polybenzimidazole work supports limited number of applications and developers.
- CO impurity work supports other modeling work that has been requested.
- Catalysis work is improperly benchmarked, both rotating disk electrode and direct methanol fuel cell data.
- Impurity work seems to be repetitive with other DOE projects and with previous literature.
- If the gasket work is focused on so few materials, then *in situ* testing would be appropriate at an earlier point.
- Projects tend to cover well-studied areas. Difficult to see progress toward defined targets.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.4** based on accomplishments.

- Significant data produced for H_2 quality team.
- Possible good progress with non-carbon supports.
- Evaluation of silicon and ethylene propylene diene methylene terpolymer (EPDM) gasket materials already accomplished by industry.
- Project needs to re-evaluate the first two topics with serious attention to what has already been done. Benchmarks must be more accurate.

- Gasket topic includes many simplistic leaching experiments so far, and provides little insight.
- Work on Ti catalyst supports interesting, somewhat novel. Many small projects underway, which were covered with little detail. Hard to see any focus.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.6** for technology transfer and collaboration.

- Unclear what collaborations exist other than H_2 quality team.
- The gasket topic involves many companies.
- Other topics have no obvious involvement from others, only the intention.
- Principal collaboration is with the University of South Carolina National Science Foundation project, which is the same organization. Things are just beginning, so that may be changing.

Question 5: Approach to and relevance of proposed future research

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

- Solid extension of approach on impurity work.
- Developing accelerated durability tests for gasket materials and predictive modeling of degradation is a good path.
- Future work not discussed for task 1 and task 4.
- Future work not stated specifically enough in all the topics.
- Durability of catalyst supports was not addressed at all, but should be.
- The future presented was an extension of the past.

Strengths and weaknesses

Strengths
- Topic areas selected are of interest to the hydrogen fuel cell community.
- Some principal investigators have relevant expertise.

Weaknesses
- Four largely unrelated projects with no interconnection.
- Evaluation of materials seems incomplete compared to literature standards, including poor benchmarking.
- The funding level is high enough at a university that the amount of data generated is less than expected in each topic.

Specific recommendations and additions or deletions to the work scope

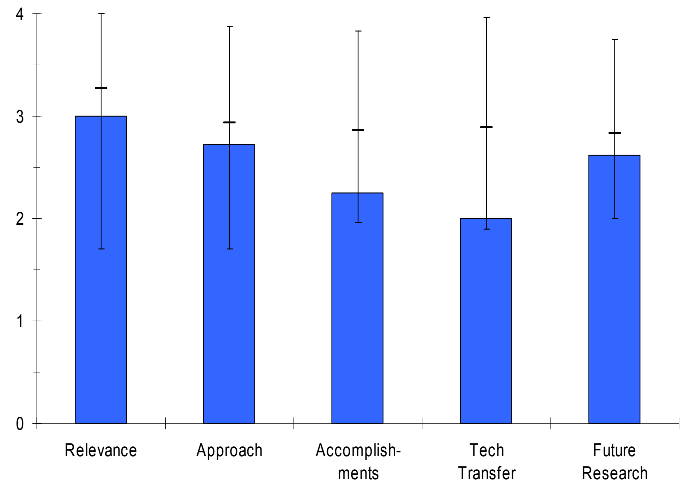
- Need to evaluate non-carbon supports for the oxygen reduction reaction on the cathode where carbon corrosion problem exists.
- Perhaps the scope should be narrowed from four to two topics that show the most success. I am not sure yet what those would be. It would be better to evaluate such disparate topics separately.
- The DOE might consider that future funds focus on one or two well-defined tasks that explore alternatives to existing technology. An example might be instead of redoing the very extensive literature on effects of fuel impurities on fuel cell performance, explore sensible approaches that allow fuel cells to live in a "dirty" world. "Fuel filters" come to mind.

Project # FC-48: Novel PEMFC Stack Using Patterned Aligned Carbon Nanotubes as Electrodes in MEA
Di-Jia Liu; Argonne National Laboratory

Brief Summary of Project

The objective of this project is to develop a novel aligned carbon nanotube-based membrane electrode assembly and fuel cell with 1) improved efficiency; 2) reduced Pt usage; and 3) simplified stack design. Argonne National Laboratory prepared and characterized the structure and activity of two transition metal-functionalized and one Pt-decorated aligned carbon nanotube samples as electrode catalysts. A transfer method to apply the aligned carbon nanotube layer to the membrane electrolyte with nanotube orientation intact was also developed. The catalyzed aligned carbon nanotube-based membrane electrode assembly with intact carbon nanotube alignment was fabricated.

Overall Project Score: 2.5 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.0** for its relevance to DOE objectives.

- The approach does not appear to offer a solution to carbon corrosion or Pt nanoparticle dissolution, the two main electrode durability issues.
- Methods of manufacturing and catalyzing the carbon nanotubes will prevent reduction of cost significantly.
- The project appears to be focused on meeting the DOE targets for electrocatalyst platinum loading and durability using a novel aligned carbon nanotube-based membrane electrode assembly.
- Durable, low cost, high performance fuel cell membrane electrode assemblies address many relevant targets.
- If the project works, there will be a contribution to the DOE objectives on cost, since plate forming should be reduced and the gas diffusion layer eliminated.
- Considerable development is likely needed before DOE objectives on performance and durability are achieved.

Question 2: Approach to performing the research and development

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

- Approach has many or all the disadvantages of carbon black supports.
- There is no expected advantage of surface area or specific activity over standard Pt/C supports.
- The concept of using oriented nanotube supports to improve mass transport is incorrect. The alignment is secondary by far to the length and spacing of the support rods. The porosity of the layer is what matters and that does not require alignment of the rods to make high porosity.
- Improved conductivity of the supports is not required for improved fuel cell performance.
- The high temperature and chemical vapor deposition processes for growing and catalyzing the aligned carbon nanotubes will be very difficult to scale up cost-effectively for anything other than small batch samples.
- The high surface area of the aligned carbon nanotubes is wasted since the catalyst particles are isolated far from one another.
- The approach is adequate to accomplish the project's objectives.
- Figuring how to utilize carbon nanotubes in fuel cell electrodes is a worthy effort.
- The original approach to eliminate gas diffusion layers and allow a flat plate was promising, but this has been somewhat foiled by cell architecture issues. Tests are now run with gas diffusion layers and flow fields.

- Investigators have been diligent in developing various methods of creating Pt/aligned carbon nanotube materials. It would be interesting to see if a more "3M-like" technique could be attempted, but it would be understandable if the hydrophobicity of the aligned carbon nanotubes was a problem.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.3** based on accomplishments.

- Principal investigator has spent its efforts on developing methods for growing and catalyzing the aligned carbon nanotubes, and has not had time yet to seriously evaluate whether the approach can help overcome the DOE barriers A, B, and C it claims to address.
- The benchmark membrane electrode assemblies used to compare their performance are very sub-standard and not representative of state-of-the-art performance.
- The investigators should be trying to make fundamental measurements of the catalyst surface area and specific activity under H_2/O_2 at 900 mV using the DOE/General Motors recommended protocols.
- Trying to make membrane electrode assemblies is premature until they can show even one single kinetic improvement or durability improvement of their catalysts.
- The project team has made good progress toward achieving its objectives.
- Growing carbon nanotubes is a well-known process. Some success in making electrodes was apparent. However, there was no demonstrated performance improvement. Other attributes would have been lower cost or enhanced durability. However no data was presented to support those goals.
- Performance test with 0.6 mg Pt/cm^2 loading has shown a similar IR-corrected result to a BASF benchmark.
- More appropriate benchmark would aid the presentation of the work.
- Considerable progress has been made in optimizing dispersion and testing different means of fabrication. Further optimization could be considered in terms of placing more Pt near the triple-phase boundary.
- Mass activities are an order-of-magnitude lower than DOE objectives.
- Non-Pt work demonstrates low open-circuit voltages.
- Investigators' pursuit of single cell test was an excellent response to prior feedback.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.0** for technology transfer and collaboration.

- What collaboration has been identified is attributed to helping train the sponsoring organization investigators.
- A technology transfer process has not been enumerated, and there are no industrial collaborators.
- This is a carbon nanotube activity, and there are many experts in this area who could add real value.
- Low amount of collaboration indicated, besides initial consulting with Plug Power and training by Los Alamos National Laboratory.
- Lack of collaboration has not caused egregious mistakes, however, collaboration with a partner like 3M would help explore if there is any possibility of increasing at least the specific activity via vacuum techniques (other than those already attempted here), or increasing the electrochemically active area, which is low.

Question 5: Approach to and relevance of proposed future research

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

- The investigators should focus more on making fundamental rotating disk electrode measurements, getting advice from Nenad Markovic's team on how to do this, before trying to make and test membrane electrode assemblies. If they cannot achieve the expected gains in activity or durability under potentiostat cyclic-voltammetry cycling, they should not go on.
- The proposed future work is likely to be effective in improving the technology.
- Need for further optimization of catalyst synthesis.
- Need for further optimization of cell design.
- No mention is made of non-Pt work.
- Project needs to get back to investigating whether the gas diffusion layer can be eliminated.

Strengths and weaknesses

Strengths
- Strength and experience of the Argonne National Laboratory staff.
- A novel approach is pursued to improve electrocatalyst durability and platinum loading.
- Significant progress has been made toward meeting the DOE targets.
- Of innovative stack concepts that DOE has funded, this concept has the best chance to be amenable to automotive operation.
- Original premise could create considerable cost benefits if realized.
- Good approach to catalyst synthesis and optimization.

Weaknesses
- Concept is flawed that this approach will help overcome any of the three barriers claimed.
- Well-known now to original equipment manufacturers that graphitic-type carbons do not have adequate corrosion resistance.
- There are no industrial collaborators to facilitate technology transfer.
- Much of the activity to date was test sample preparation. There also needs to be considerable focus on sample testing, because it is likely that procedures for "standard" membrane electrode assembly might miss details when testing this new form of electrode. For example, if durability is the real goal, then accelerated durability testing needs to be done, with less regard for voltage performance. Argonne National Laboratory needs to think about how to reach their goals.
- Compromise forced on gas diffusion layer and flowfield presence to facilitate testing, leaving issues about pressure drop and flow fields embedded in the nanotubes largely unexplored.
- More comparable benchmark membrane electrode assembly should be shown.
- Low mass activity and low electrochemically active area.
- Catalyst utilization is likely low.

Specific recommendations and additions or deletions to the work scope

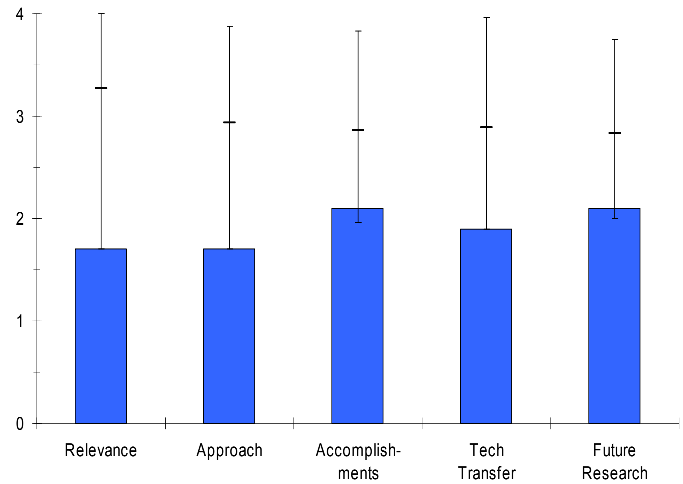
- The Argonne National Laboratory investigators' time and resources would be better spent working on some other fundamentally critical problem.
- Involve one or more industrial collaborators to facilitate easier technology transfer.
- The testing procedures for new fuel cell membrane electrode assemblies need to be written and enforced. We need to get away from showing just one or two "best" results but show results from a group of carefully controlled duplicated samples, and then talk about statistical data analysis before comparisons are made.
- Non-Pt work is not successful and distracts from the main goals of this project. It should be deleted.
- Attempts to test without gas diffusion layers or flow fields should be given higher priority. Given that cost objectives will not likely be realized through catalyst reduction, these kinds of tasks may still be able to deliver towards DOE cost objectives.

Project # FC-49: Detection of Trace Platinum Group Metal Element Particulates with Laser Spectroscopy
Stuart Snyder; Montana State

Brief Summary of Project

The objectives of this project are to 1) develop laser-induced breakdown spectroscopy to detect and quantify the presence of PGM nanoparticles in very dilute aqueous suspensions; and 2) apply laser-induced breakdown spectroscopy to determine the presence and mass concentration of PGM in water reformed in the stack of polymer electrolyte membrane fuel cells. The presence of nanoparticles of PGMs in this water is an indication of polymer electrolyte membrane fuel cell degradation. This work supports the polymer electrolyte membrane fuel cell field trials conducted at Montana State University-Billings to test and characterize the durability of polymer electrolyte membranes.

Overall Project Score: 1.9 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **1.7** for its relevance to DOE objectives.

- There is a need to understand degradation in polymer electrolyte membrane fuel cells, however, there is no indication that Pt is dissolving and leaving the fuel cell.
- It could be useful for researchers to know whether Pt nanoparticles are being emitted by the cell as opposed to Pt in solution.
- Relevance is not clear from the presentation.
- Detecting nanoparticles in stack product water does not help enable the President's Hydrogen Fuel Initiative – this has not been seen as a problem.
- Not clear how this technique contributes further to understanding degradation in fuel cells. Metal species are detected, but with little additional insight to previous effluent analyses.
- This program could be potentially relevant to overall DOE objectives if only pure precious metals will be used as cathode/anode catalysts in polymer electrolyte membrane fuel cell. Giving that the activity of pure noble metals is not high enough to meet the DOE activity goals on the cathode side (720 $\mu A/cm^2$ and 0.44 A/mg Pt) and that bi/multi-metallic systems have much more potential to be used as cathode materials, it would be desirable to develop methodology how to detect both precious and non- precious metals.

Question 2: Approach to performing the research and development

This project was rated **1.7** on its approach.

- The approach as stated is misguided. Pt does undergo dissolution in an operating polymer electrolyte membrane fuel cell. However, it re-precipitates within the cell or stack. This process is local (i.e., within the membrane electrode assembly) and the Pt never leaves that environment. There is no opportunity to see Pt in the produced fuel cell water. Even if Pt were in the water it would be in the ppb range.
- Work to date for nearly 2 years has focused on palladium.
- If the issue is platinum in the cathode exit water, then project should be refocused to establish platinum detection.

- The presentation does not adequately discuss the correlation between amount of PGM detected in the cathode exhaust water and membrane electrode assembly degradation.
- The approach seems reasonable enough if you accept the premise that measuring trace PGM levels in water is of value.
- This project adds no unique capability to fuel cell degradation analyses.
- The program should be improved to have impact on the DOE mission. It is surprising that a calibration method is developed first for Pd, which most likely will never be used as the oxygen reduction catalyst.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.1** based on accomplishments.

- Work to date is on Pd. Palladium is not a typical catalyst in a polymer electrolyte membrane fuel cell. Studies should be one Pt and Pt-metal binaries only.
- Individual tests are not as important as long-term continuous testing to see the impact of duty cycle on dissolution of Pt and/or to see if the catalyst ions are in the water all the time.
- The technique has been demonstrated with palladium.
- Work with platinum does not seem to have been done yet.
- The principal investigator has shown that Pd can be detected with this technique.
- Project succeeds in detecting palladium, but there is no demonstrated added value over previous analytical techniques.
- The authors demonstrated that the laser-induced breakdown spectroscopy method is capable for *in situ* monitoring a relatively small amount of Pd and that provides on-site support of polymer electrolyte membrane fuel cell field degradation studies.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **1.9** for technology transfer and collaboration.

- Collaborations should be expanded to other fuel cell original equipment manufacturers and tests should be run on automotive duty cycles.
- Plug Power is a team member, but its role is not clear.
- Technique has been applied on Plug Power unit.
- Connection to partner goals not effectively demonstrated.
- This is a weak part of this program and the authors must have much closer contact with the groups that are focusing on the design stable and active catalysts.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.1** for proposed future work.

- Appears to be one-year project.
- Future work limited.
- Beginning work with platinum is long overdue.
- Principal investigator plans to calibrate device for Pt detection too.
- There does not seem to be a path forward to make the process viable.
- Much more effort should be on detecting Pt during extended operation. The program must focus on the development of detection of trace amount of alloying components (usually 3d elements).

Strengths and weaknesses

Strengths
- Novel in-field technique could be feasible.
- Detection of palladium was accomplished.

- This is an innovative method that might be useful in replacing classical analytical tools for detecting small amounts of metals in very dilute aqueous suspensions. Even more importantly, an *in situ* method can provide valuable information in real-time operation.

Weaknesses

- Project very limited in scope.
- Project evaluating incorrect fuel cell electrocatalysts.
- Project has not proven that Pt can be detected or that Pt passes out of the fuel cell during operation.
- There is no evidence this technique is needed for fuel cell systems or explanation how the results for the analysis would be used.
- Technique is not truly an in-line test, samples must be taken from system.
- No specific advantage was demonstrated.
- The project is providing only partial information about total degradation of cathode/anode materials (a lot of materials can be trapped in the membrane); and as such it is difficult to justify how relevant the program is.

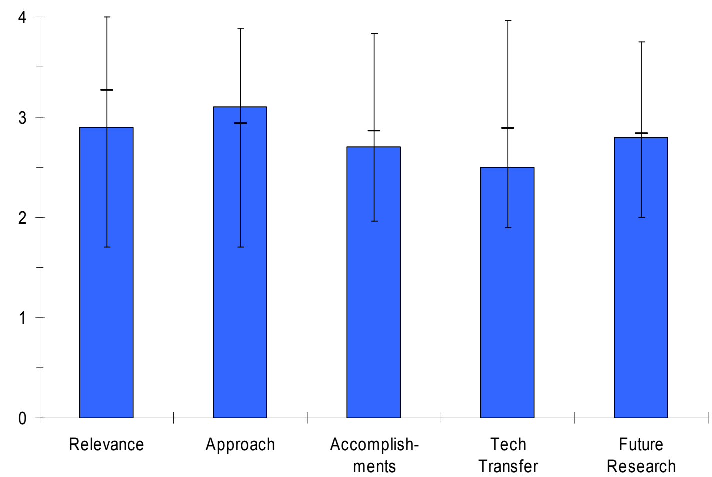
Specific recommendations and additions or deletions to the work scope

- Project could use expanded collaborations with catalyst developers.
- Project should also evaluate effect of automotive duty cycle on catalyst dissolution.
- Need to prove that Pd/Pt loss to fuel cell water is a problem before continuing project.
- Not clear where project fits in with fuel cell research needs.
- The program should be extended, and the method must be applicable or the detection of non-noble metals as well.

Project # FCP-01: Light-Weight, Low Cost PEM Fuel Cell Stacks

Jesse Wainright; Case Western Reserve University

Overall Project Score: 2.8 (5 Reviews Received)



Brief Summary of Project

The objectives of this project are to 1) demonstrate edge collected stack design capable of >1 kW/kg (system level); 2) develop low cost, injection molded stack components; 3) verify stack performance under adiabatic conditions; and 4) accelerate stack development by incorporation of multiple cell level sensors within the stack coupled with computation fluid dynamics modeling. A combination of molded plastic components and direct fabrication via printing will be used to yield a stack with a very low parts count.

Question 1: Relevance to overall DOE objectives

This project earned a score of **2.9** for its relevance to DOE objectives.

- This project addresses a fuel cell design approach with potential for portable power-type applications.
- Very good – this is a novel cell design. This would certainly work with low power, low voltage applications. Has any thought gone into scale up for large stack power/voltage applications?
- New stack concepts are relevant and although some advances are interesting, the potential to displace current configurations is low.
- The value in the program is in the new concepts that will emerge coupled with the modeling results for edge collection.
- New polymer electrolyte membrane fuel cell/stack designs that increase stack power density and decrease part counts can potentially enable this technology. This particular design has issues with achieving the same areal power densities observed with conventional designs.
- The proposed cell/stack design has several issues that make it not applicable to the automotive application, which is the main thrust of the DOE program.
- Innovative cell stack designs might lead to lower costs and higher performance.

Question 2: Approach to performing the research and development

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

- Approach based on a unique design that should be low-cost and amenable to high-volume, straightforward manufacturing.
- The primary technical challenge is to obtain performance comparable to conventional designs. Early single-cell testing is marginal, however design refinements and improvements may result in enhanced performance.
- Very good – this approach appears to leverage the printed circuit board industry technology. It unclear how reactants are supplied.
- The actual approach is good, especially the modeling. The team needs to continue in the mode to assess fluid dynamics and thermal management.
- The overall approach, which includes modeling, cell and "stack" part development, and testing is a good approach.
- This innovative end-connected design could result in lower costs and higher performance, but the results remain to be seen.

- The approach is both innovative and methodical, encouraging that the prototype will be indicative of an implemented design.
- Stack design appears to be something that can be manufactured and fabricated – no show-stoppers.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.7** based on accomplishments.

- Progress has been relatively slow due, in part, to staffing problem, which the principal investigator stated are now resolved.
- There is much work left to be done and the ultimate success of this project is still in the balance.
- Very good – performance is reasonable compared to conventional polymer electrolyte membrane units.
- The results are interesting and may yield direction towards new cell designs, in particular the in-plane thermal and electrical mechanisms as a function of current density, connectivity, area, and gas fluid dynamics (all relating to performance and fuel utilization).
- Due to difficulties with staffing, this project has been significantly delayed.
- Little progress in the first year and a half of this project, but a no-cost extension has been requested.
- Some prototype components have been fabricated as exemplars.
- No stack has been assembled, as yet.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.5** for technology transfer and collaboration.

- Good collaboration with Endura Plastics to make the molded plastic parts.
- Specific contributions of plastics molding firm were not identified (may just be a supplier).
- Good – collaboration is limited for applied science, but adequate for basic science. Collaborating partners would suggest applications.
- Appropriate for this stage of the program.
- Need an interaction with a cell / stack developer.
- This partnership is an industry / university collaboration.
- More stakeholder collaboration could be an improvement.

Question 5: Approach to and relevance of proposed future research

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

- Future plans are not specifically identified, but the task statement indicates the work remaining to be done.
- Very good – future research includes scale-up.
- This reviewer feels the engineering elements of the concept should be focused on more than the actual success of the stack builds. The principal investigator should work on very small systems of a couple to a few cells, and then assess and evaluate the key attributes of such cells.
- There are significant remaining barriers in increasing the achievable current density with this design.
- Without knowing the source of the very low current densities resulting from the use of diagnostic techniques, it is difficult to know what path to pursue toward improving the current densities.
- Stack assembly and testing is yet to come and is needed to illustrate the value of the design.

Strengths and weaknesses

Strengths

- Unique design approach.
- Investigator appears to be thinking outside of the box.
- The principal investigator is a solid contributor.
- Uniqueness.

- Innovative approach.
- Good engineering.
- Methodical progress.

Weaknesses
- High risk project, but potential high payoff if successful.
- Unclear as to the final power class (x<1 kW, 1<x<20 kW, or x>20 kW).
- Unclear as to the voltage class (i.e., target number of cells in a stack).
- No mention of durability testing.
- Very academic in approach from a practical applied engineering perspective.
- The principal investigator did not present a clear vision on how to achieve the necessary current densities.
- No stack or sub-stack as yet – single cell only.

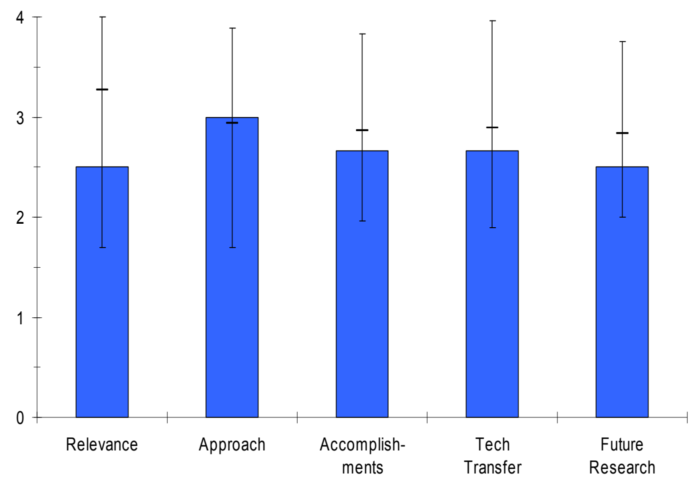
Specific recommendations and additions or deletions to the work scope

- If weaknesses are addressed a fuel cell manufacturer might have serious interest in the resulting technology.
- Additional research team members might accelerate the project.

Project # FCP-02: Platinum Group Metal Recycling Technology Development
Larry Shore; BASF

Brief Summary of Project

Overall Project Score: 2.7 (3 Reviews Received)



The objectives of this project are to 1) determine commercial practicality of cryo-grinding membrane electrode assemblies and the utility of the process for varied membrane electrode assembly architecture and materials; 2) define unit operations for Pt recovery from membrane electrode assemblies, integrate them into a process flow diagram, and estimate process economics; 3) identify apparatus/materials of construction for a pilot plant (1 kg/day) and full-size (1,000 tonne/year) operation; and 4) develop a rapid process control method to determine Pt remaining in leached membrane electrode assembly residues. Pt recovery of >98% is achievable from milled membrane electrode assemblies using an oxidative leaching process. The process has been shown to work will all types of membrane electrode assemblies and electrocatalyst compositions.

Question 1: Relevance to overall DOE objectives

This project earned a score of **2.5** for its relevance to DOE objectives.

- Platinum recovery from a variety of fuel cell types will be necessary to ensure economical supply.
- Recycling of the precious metals is very important, but the reviewer questions whether it needs government funding.
- Pt recycling has already been demonstrated to be economically viable – DOE should reduce funding effort on these projects because the industry will drive higher yields and efficiencies once the market becomes a large enough player.

Question 2: Approach to performing the research and development

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

- Approach avoids solvents and has little waste. The method is applicable to many types of catalyst coated membrane and diffusion media catalysts. Slide 15 presents some issues with larger batch sizes, and it is unclear why the ratio of surfactant to sample was changed.
- Approach appears very viable and should prove to be financially attractive.
- It is doubtful that cryogenic approaches will ever be cost-effective.
- It is doubtful that the principal investigator will combine many of the washing/ leaching, etc., steps into one unit and still achieve high yields and efficiencies.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.7** based on accomplishments.

- Procedure has been developed to a high level of Pt recovery. Cost analysis should be presented in some form, even though the details are proprietary.
- Accomplishments are impressive; however, the expenditure required to get there seems high.

- It is highly doubtful that BASF will achieve a single apparatus for leaching, filtering, washing, neutralization and solids drying to simplify the process.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.7** for technology transfer and collaboration.

- Samples were obtained from many sources, although the work seems to be in-house.
- Collaborations are limited due to proprietary issues.

Question 5: Approach to and relevance of proposed future research

This project was rated **2.5** for proposed future work.

- Goals are reasonable for a project that is ending in March 2009; cost models should be released.
- Priority should be given to the cost analysis, which is on the list of future work.

Strengths and weaknesses

Strengths
- Platinum is recovered with high yield, and the process produces little waste.
- Research has been successful.

Weaknesses
- Economic viability was not specifically demonstrated.

Specific recommendations and additions or deletions to the work scope

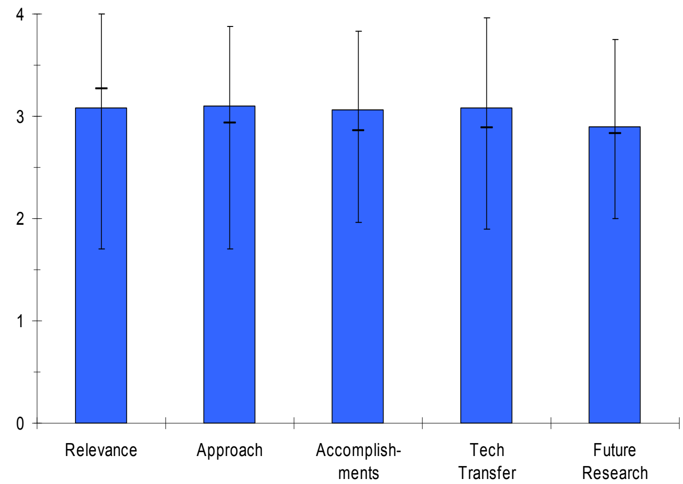
- Complete the cost analysis and document the results.

Project # FCP-03: Platinum Recycling Technology Development
Stephen Grot; Ion Power, Inc.

Brief Summary of Project

The objectives of this project are to 1) assist the Department of Energy to demonstrate a cost effective and environmentally friendly recovery and re-use technology for PGM containing materials used in fuel cell systems; and 2) use new processes that can also separate and recover valuable ionomer materials. Recovery and separation work at scale-up has been demonstrated and good recovery rates are being achieved. The recovered polymer can be remanufactured into fuel cell membranes. The effective removal of trace amounts of PGM from diffusion media needs more development.

Overall Project Score: 3.1 (6 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- Recycling addresses issues with cost and availability of Pt.
- 100% fit to general goals.
- Catalyst recycling will be driven by the economic interests of the recycler. Funding this work may not have an impact on that.
- The ability to recycle Pt and ionomer, as well as the ability to fabricate stacks with recycled materials, will be market-driven and should not be a topic for government research.
- There are no clear DOE objectives regarding how much cost savings should be realized with recycling.
- Platinum recovery is key to the future of polymer electrolyte fuel cells.

Question 2: Approach to performing the research and development

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

- Approach to recycle Nafion as well as the Pt is a good idea and will reduce impact of fuel cells on the environment and improve economics.
- Good approach; however, reference membrane electrode assembly tests are not up to date: 300 mA/cm^2 @ 0.7 Volts is not the correct measure.
- The principal investigator needs to show that use of the recovered, degraded membrane does not compromise durability through lifetime tests and fluoride release rate measurements.
- Approach to recycle Nafion as well as the Pt is a good idea and will reduce impact of fuel cells on the environment and improve economics.
- Methodology for cost analysis for recycling process was not shown. Directed Technologies, Inc and TIAX use rigorous analyses for their cost estimates. The same discipline should be applied here.
- Given project assignment, approach to fabricate stack from recycled materials is interesting. Good comparison to look at recycled catalyst and ionomer individually.
- Good thought to compare oxygen reduction reaction for fresh catalyst to recycled catalyst.
- Process seems to be relatively inexpensive.
- Ionomer recovery in parallel to platinum is attractive.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **3.1** based on accomplishments.

- Demonstrated recycled Nafion quality by making a refurbished membrane electrode assembly with it and showed good performance and durability of the membrane electrode assembly.
- Demonstrated remanufactured membrane electrode assemblies in a 5-kW stack, remanufactured membrane with new catalysts that perform as well as a new membrane and catalyst – recycled catalysts have lower activity.
- Need more work to recover Pt from gas diffusion layer.
- Cost analysis completed.
- Good results with a good portion of common sense, i.e., simply recover the noble metal but not the catalyst and use the electrolyte elsewhere.
- In addition to recovering Pt and ionomer, catalyst support is recovered and reused. This degraded material may be the reason for the observed low performance and may not be a viable approach. What about just recovering the PGM?
- Oxygen reduction reaction curves are very different from those presented in catalyst projects. Protocol not described as to whether the current/voltage sweep was done *in situ* or *ex situ*, or if *ex situ*, whether it involved a rotating disk electrode. Experiments should have been done by those familiar with electrocatalytic techniques.
- Reasons not shown for decreased performance for recycled catalyst in the GENCORE stack. No failure analysis reported.
- Previously reported Pt recovery of 96% requires batch operations and, therefore, some labor intensity.
- Procedure works well for recovering Nafion.
- Precise analysis of PGM recovery is not provided.
- Evaluation of Pt activity is confusing as the mass activity is stated to be "good," but the performance per surface area looks poor and the cells made with the recovered catalyst perform poorly.
- Additional processing of Pt appears necessary.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- Plug Power participation was key to the project.
- Convincing consortium.
- It is a benefit that the program involves membrane electrode assembly manufacturers and system integrators.
- Long list of competent collaborators assembled.
- Degree of coordination unknown.
- Plug Power task is clear. Other collaborator contributions are unclear, besides those that are material inputs.
- Role of external partners unclear; work seems to focus on Ion Power technology alone.
- Oxygen reduction reaction activity data from the university partner are low quality.

Question 5: Approach to and relevance of proposed future research

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

- Project is scheduled to be completed in August.
- The project is 90% complete, but rather than focusing the remaining time on recovering the PGMs from the diffusion media, the principal investigator should try to show that the recovered catalyst can be used without performance loss.
- Short note given on removing Pt from diffusion media.
- Despite short remaining duration of project, no notes were provided as to what could be done to enhance recycling process to decrease cost / increase volume.
- No plan was given to address how recycled Pt activity could be improved.
- The goal of increasing PGM recovery from diffusion media is reasonable for project that is ending in August 2008.

Strengths and weaknesses

Strengths
- During the past year, a clear approach was adopted to fabricate a stack from recycled components and test it.
- Appropriate comparisons were made in the course of assembling recycled test articles.
- Ionomer is recovered completely and can be used in a fuel cell.
- Process is cheap relative to the PGM cost.

Weaknesses
- Cost analysis given without detail.
- Failure analysis for low catalyst activity in both *ex situ* and GENCORE was not performed.
- Original recycling process does not appear applicable to high volume.
- In general, low amount of information shown for the different tasks in the project.
- Topic matter will be addressed by market economy.
- PGM recovery process seems incomplete.
- Cost analysis for ionomer recovery versus production needs to be addressed.

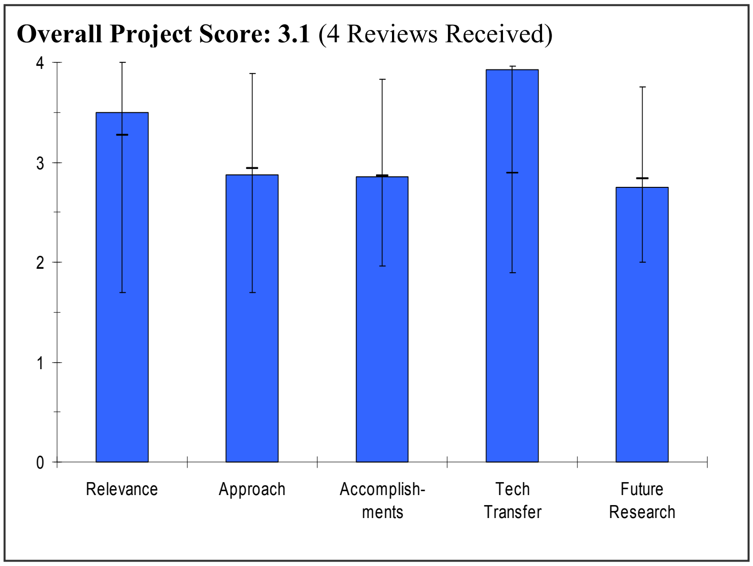
Specific recommendations and additions or deletions to the work scope

- Pt recycling efforts from DOE should be suspended due to Pt prices and expectation of market-driven incentives to recycle Pt.
- Deeper disclosure of experimental information and parameters.
- Greater focus on improving recycling process and cost analysis.
- Low oxygen reduction reaction activity of recovered Pt should be elucidated.

Project # FCP-04: Component Benchmarking Subtask Reported: USFCC Durability Protocols and Technically-Assisted Industrial and University Partners

Tommy Rockward; Los Alamos National Laboratory

Brief Summary of Project



This project provides Los Alamos National Laboratory technical assistance to fuel cell component and system developers as directed by the Department of Energy (DOE). This project is expected to include testing of materials and participation in the further development and validation of single-cell test protocols with the U.S. Fuel Cell Council. This project also covers technical assistance to the U.S. Council for Automotive Research (USCAR) and the USCAR/DOE Freedom Cooperative Automotive Research (FreedomCAR) Fuel Cell Technology Team. This latter assistance includes making technical experts available as questions arise, focused single cell testing to support the development of targets and test protocols, and regular participation in working and review meetings.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.5** for its relevance to DOE objectives.

- Component Benchmarking is important.
- Component benchmarking critical to the President's Hydrogen Fuel Initiative.
- Important to understanding of water transport and freezing in membrane. Understanding the relative protocol results is also valuable though has less impact on actual progress.
- Project provides assistance to other highly relevant projects for DOE objectives.
- Examples such as water transport studies on 3M's nanostructured thin film electrode, conductivity measurements under freeze conditions, and capability to conduct the FreedomCAR durability protocols all prove relevance.

Question 2: Approach to performing the research and development

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

- Sharing technical assistance is of importance, but there is no focus on the approach.
- Develop standard testing protocols.
- OK though not highly precise in isolating water content in membrane or certain in identifying meaning and source of changes in conduction of protons to membrane temperature.
- Approach is to assist fuel cell component developers, to establish baselines for durability protocols, to compare durability protocols from other international organizations, and to determine whether US Fuel Cell Council protocols are appropriate, all of which are needed.
- Limited space for presenting data here, so questions remain as to how water content was evaluated in conductivity under freeze studies, or to what extent alternating current impedance or other techniques could have been used to break down voltage losses during protocol comparisons.
- Unknown if study of Cabot supports is with reference to alloy catalyst. If so, that can be valuable.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.9** based on accomplishments.

- If interactions are the figure of merit, then a lot has occurred. Evaluating how much technology transfer has occurred is difficult.
- Developed a number of useful testing protocols.
- Moderate progress. What is done is valuable but relative to budget, progress as presented seemed fair but not exceptional.
- Water results are in good agreement with others results, but not ground-breaking.
- Correlation of protocols is useful.
- For this project, a considerable amount of work likely happens that cannot be reported here.
- Slides show that the project is likely helpful to developers. It is impossible from what is shown here to evaluate whether the 3M water transport assistance has been thorough in looking at different cell configurations, sensitivity to cell thermal characteristics, sensitivity to different gas diffusion layer parameters, or sensitivity to cell design (channel width, transition regions, etc.).
- The work done to critically examine the US Fuel Cell Council cycling protocol is excellent. This is the kind of feedback required to be sure the correct protocols are written.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.9** for technology transfer and collaboration.

- Since the subtask reported, US Fuel Cell Council Durability Protocols and Technical-Assistance to Industrial and University Partners, is one of tech transfer and collaborations, a high score is merited.
- Excellent interactions with all major players.
- Excellent by design.
- This project is entirely built on collaborative efforts.
- Collaborations exist with membrane electrode assembly suppliers, such as 3M, as well as other government entities.
- Los Alamos National Laboratory is being useful in facilitating National Institute of Standards and Technology neutron imaging studies on behalf of developers.

Question 5: Approach to and relevance of proposed future research

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

- There is no proposed future research?
- Not clear what will be done in future, however task should continue.
- Probably flexible and that may be as it should be.
- Although not clearly stated in the same manner as other projects, the future work does appear to be appropriate.
- Project is intent on continuing support of industrial collaborators.
- Project is focused on continuing critical examination of established durability protocols, and for those protocols that are valid, establishing baselines for known material sets.

Strengths and weaknesses

Strengths
- Assistance is being provided.
- Connectivity to other groups, dissemination of information.
- Utility in providing assistance to developers.
- Examination of protocols. Investigators do not make the assumption that US Fuel Cell Council protocols or those from other sources are appropriate.

- Ability to set baselines assists most projects funded by the DOE by providing a comparison at the membrane-electrode assembly level.
- Safety standards are set that can be useful to other laboratories, even those with experience with hydrogen.

Weaknesses
- Difficult to evaluate how effective is the assistance.
- Cost effectiveness and depth of analysis.
- In the specifics of some of the collaborations, it is difficult to assess whether experimental techniques are thorough. Most of the work is likely represented in reports from other projects.

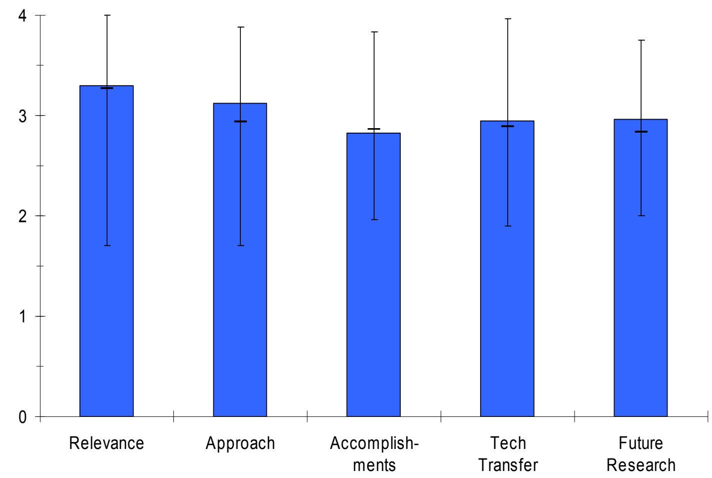
Specific recommendations and additions or deletions to the work scope

- This category is difficult to evaluate for this project, since the resource allocation between tasks is not clearly represented.
- Without knowing the weighting of different budget items, perhaps more resources should go towards evaluating protocols and serving as a common experimental source for FreedomCAR durability testing than towards the hosting of workshops. Again, though, without knowing how much is devoted to each task, it is unfair to comment further.

Project # FCP-05: Low Cost, Durable Seals For PEM Fuel Cells

Jason Parsons; UTC Power

Overall Project Score: 3.0 (5 Reviews Received)



Brief Summary of Project

The objective of this project is to develop advanced, low cost, durable seal materials and sealing techniques amenable to high volume manufacture of polymer electrolyte membrane stacks. The project goals are to 1) improve mechanical and chemical stability of seals to achieve 40,000 hours of useful operating life; and 2) obtain a material cost equivalent to or less than the cost of high performance silicones in common use. Material properties meet most ultimate program goals – FCS2 is expected to meet all program goals.

Question 1: Relevance to overall DOE objectives

This project earned a score of **3.3** for its relevance to DOE objectives.

- Supports DOE targets, goals, and objectives.
- Durability – Improve mechanical and chemical stability of seals to achieve 40,000 h of useful operating life (stationary fuel cell target; 5000 hrs with cycling is transportation target).
- Low cost, efficient and durable seals are important to the overall objectives of commercializing fuel cells.
- Funding level may be excessive for narrow scope of topic.
- Very few materials seem to have been considered.
- Very relevant project.
- Seal materials are a long neglected part of the DOE fuel cell subprogram.
- Seals contribute directly to fuel cell durability, both with respect to the durability of seals themselves, but also in how they interact with other components, particularly membranes.
- Although the seal design itself may fall into the domain of original equipment manufacturer development, there is very necessary materials development that needs to be done since silicone seals have known failure modes.

Question 2: Approach to performing the research and development

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

- Approach is sound and logical to complete objectives.
- The fundamental materials approach and testing methods developed for the program are well suited for the evaluation of the seal materials for applicability to the fuel cell.
- Some addition of longer-term fuel cell testing and testing of the seals in conjunction with fuel cell membranes may be needed.
- Given the limited number of materials tested, it seems that the testing should have been advanced to the in-cell level within a year.
- Approach is very good. All the engineering steps that are needed are being taken. The weakness of the project is that the supplier of the seals is not sharing the chemical details of what is in the seal material. This makes it hard to do durability studies. This issue should be resolved.
- The *ex situ* testing accounts for tensile strength, compression set, and rupture under different environments (air and humidity).
- In general, looking for more durable materials, but with the same manufacturing ease as silicone, is the right idea.

- It would be preferable for a test looking for migration of organics to have different levels of humidity.
- Work should include *in situ* testing that seeks to examine failure of the seal under reductive / oxidative conditions, as well as failure of the membrane as a consequence of interaction with seal.
- Resistance test would also be useful. This can be done by molding the seal onto a gas diffusion layer / polymer electrolyte membrane / gas diffusion layer sandwich and then checking that resistance is sufficiently high.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.8** based on accomplishments.

- Good progress has been made.
- Initial data from short-term aging and testing is encouraging. Both FCS0 and FCS1 meet or exceed all minimum program goals. Both also meet or exceed most of the ultimate program goals. FCS1 shows notable improvements in elongation and cure temperature.
- The seal materials address the key barriers.
- Additional testing in fuel cell environment with wet/dry cycling and polymer electrolyte membrane materials would be beneficial to ensure the applicability of the materials.
- The team has addressed key concerns of leaching of impurities, reaction or changes in the materials in contact with various fuel cell impurities.
- Long-term degradation tests have not yet been performed incorporating all aspects of operating fuel cell stacks. Such tests should be completed as soon as possible to validate the material downselection. The progress would be easier to evaluate if data were presented versus the original materials used.
- Very good progress but lifetime predictions are a worry. Pinhole failure or tearing is a big issue.
- Of the three materials of interest to the program, results have been reported for only one – FCS0.
- FCS0 results only cover a part of the *ex situ* battery of tests.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **2.9** for technology transfer and collaboration.

- Collaboration is strong and effective. UTC Power is a leader in research and collaboration.
- The team has the skills necessary to develop and characterize the seals for fuel cell environments.
- The team has participants who can commercialize the technology.
- Interactions with other institutions not specifically highlighted.
- The fact that the supplier is not sharing the formulation details with the customer is unacceptable for such a program.
- Collaboration scheme is rigorously thought out.
- Each collaborator has a definite set role in the project.
- Of all projects at the review, the collaboration strategy is best mapped out in this presentation.
- The proprietary nature of Henkel's material formulations is a disadvantage.

Question 5: Approach to and relevance of proposed future research

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

- Excellent. FCS2 expected to meet all program goals. First full-size parts expected by end of Q1FY09.
- The future plans for continued testing and validation of the material are appropriate next steps.
- The authors indicate the need for in-cell testing, and that should be the main goal for such a limited-term project at the halfway point.
- Future plans include accelerated durability testing. The need for formulation details is critical here.
- There should be more *in situ* testing.
- Any *in situ* testing would be welcome, whether a large cell or a small cell.
- There is not enough time to go beyond standard seal testing to genuinely capture the effects of fuel cell environments and membrane electrode assembly interactions.

Strengths and weaknesses

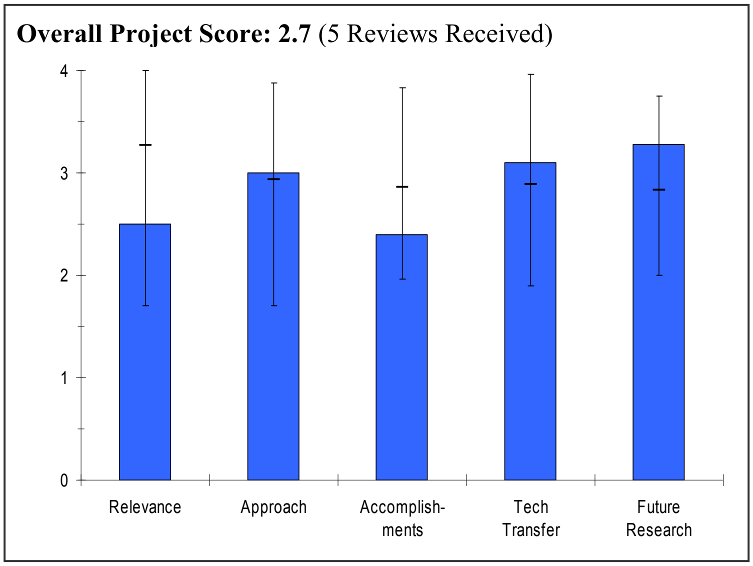
Strengths
- Strong team with good expertise in fuel cells and adhesive and seal materials.
- Candidates for the seals seem to have been identified.
- Excellent engineering/testing results in good progress.
- Clear motivation from the start: a seal that processes like silicone, but is more durable than silicone. This is one of the few projects that can be clearly stated in one sentence.
- Well-organized collaboration.
- Good sense of which *ex situ* measurements to use.
- It is the only project in the DOE fuel cell subprogram that is investigating a very critical area.

Weaknesses
- Some more fuel cell testing of the materials to ensure applicability would be useful.
- The number of materials screened is limited, and either there should have been more materials investigated or more progress on the few investigated.
- The lack of information on the seal material formulation is unacceptable because accelerated durability testing cannot be performed without this information.
- Need a chemist on the program.
- Lack of *in situ* experimentation.
- Some time appeared to have been spent developing techniques, which probably should have mostly existed before beginning the program.
- Time is now running short for going beyond what was planned.
- Original test plan may not have accounted for resistance failures and seal interaction with polymer electrolyte membrane/gas diffusion layer failures.

Specific recommendations and additions or deletions to the work scope

- Funding level seems high for so few materials examined, especially since the materials are based on existing formulations.
- *In situ* testing for polymer electrolyte membrane failure due to interactions as well as failure of the seal itself.
- Resistance testing with gas diffusion layer / polymer electrolyte membrane / gas diffusion layer sandwich.

Project # FCP-08: Research & Development for Off-Road Fuel Cell Applications
Richard Lawrance; Idatech



Brief Summary of Project

The objectives of this project are to 1) have Toro measure loads and report vehicle modifications and specifications; 2) report on shock and vibration profiles and lifetime; 3) complete shock and vibration of fuel cell system; 4) have Donaldson measure contaminants and develop air filter; 5) install a polymer electrolyte membrane liquid fueled system in a golf course maintenance vehicle. The critical assumptions for this project are that the fuel cell system can 1) physically fit into the vehicle; 2) can provide the required energy during field testing and 3) function under applications' shock and vibration loads. Potential solutions include 1) modifying the vehicle; 2) improving controls and response; and 3) incorporating shock and vibration test results.

Question 1: Relevance to overall DOE objectives

This project earned a score of **2.5** for its relevance to DOE objectives.

- The value in this effort – especially taking an electric vehicle and converting it to a fuel cell-powered one, will facilitate how such technology will be practical for such mobile devices, especially with liquid fuels.
- Funding is appropriate, but should not be at the expense of other critical technical issues.
- Demonstration of fuel cell stacks in a near-term application allow assessment of readiness levels and can potentially provide important feedback to the materials development projects within DOE.
- This project addresses air filtration and shock and vibration issues of fuel cells operating in off road applications.
- Golf carts are not the most robust off road application possible. It is unclear that the lessons learned on the golf carts will be adequate to address the more robust applications.
- The project relates to DOE objectives, however fits more under the Technology Validation subprogram.
- Good niche market.
- Although the DOE program has moved away from liquid fuel reforming, in a niche market this may be a better fit, and stack experience can support the program.

Question 2: Approach to performing the research and development

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

- The approach is practical and simple so as to minimize complexity.
- The team appears to be using standard off-the shelf components – but with their integration engineering.
- Practical application with respect to the mode of transportation and the fact that real units will be built and tested.
- The principal investigator is well established as one who can develop such practical applications.
- Quantifiable goals for the air quality and shock and vibration barriers would help in the progress assessment.
- The dynamometer and shock and vibration testing will provide valuable data on real-world operation of small-scale (2-3 kW) fuel cells for small off-road vehicle applications.

- Use of the fuel cell vehicle in a real-world golf course maintenance application could produce users that are comfortable with fuel cells, which may translate to an expanded early adopter market for fuel cell highway transportation vehicles.
- Good engineering.
- Good project plan.
- Good coordination with vehicle manufacturer.
- Better coordination with users might be helpful.

Question 3: Technical accomplishments and progress toward project and DOE goals

This project was rated **2.4** based on accomplishments.

- It looks as if good progress has been made even with the limited funding – this is due to the expertise of the principal investigator.
- Some data would be helpful, in particular the vibration data and air filtering, to name a couple.
- No data or information is provided on the air filter development.
- How did IdaTech conclude that compressed hydrogen is unacceptable for maintenance vehicles?
- Insufficient information is provided to assess the progress in modifying the fuel cell systems.
- The project team has completed packaging of the fuel cell for the golf course vehicle.
- Dynamometer and shock and vibration testing should commence shortly to provide data.
- Much of the progress in developing the fuel cell and installing it in a golf cart has been accomplished through leveraging with project partners rather than with DOE funding.
- No final hardware yet.
- Concept is good, but implementation remains to be seen.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.1** for technology transfer and collaboration.

- The team seems to be collaborating well.
- Current source and properties of air filter should be described.
- Current and future role of Toro, if any, should be described.
- The project partners have enabled progress in securing a vehicle, designing an air filter, and providing shock and vibration profiles.
- Project partners with more robust off-road applications for the fuel cell should be considered.
- Good coordination with vehicle manufacturer.
- Project appears to be based on sound principles of user preferences, but other stakeholders, such as property owners, could be a valuable addition to the team.
- While the concept appears to be marketable, user, and property owner feedback will be vital to confirm this.
- Adding users and property owners to the project would be an enhancement.

Question 5: Approach to and relevance of proposed future research

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

- The future proposed testing and development looks appropriate based on the objectives of the program.
- This reviewer would like to see more of the performance characteristics and the process layout/controls.
- Plan to complete the project is plausible
- A description of the planned shock and vibration testing would have been helpful.
- Testing on dynamometer and in real-world application will provide valuable data on the operation and additional research needs for fuel cells in off-road applications.
- Deployment of hardware is vital to accomplishment of the goals.
- Acceptance by the team and users and property owners remains to be seen.

Strengths and weaknesses

Strengths
- Lawrance is a very credible engineer, especially for applications like this one.
- Demonstration for near-term application of transportation fuel cells.
- This project has leveraged the project partners to extend the value of the DOE funding.
- A fuel cell has been installed in a golf cart vehicle and is ready for real-world testing.
- Manufacturer input and feedback.
- Solid design.
- Good niche market.
- High value application.

Weaknesses
- Limited funding.
- Weak presentation.
- The golf cart application may not provide sufficient data to produce a fuel cell that can be used in more robust off-road applications. Golf courses are usually paved; thus, dust and shock and vibration issues may not be adequately assessed on golf courses.
- No working hardware yet.
- No users or property owners on the project team.

Specific recommendations and additions or deletions to the work scope

- Show more of the system layout and controls and lessons learned going forward.
- Perform efficiency comparison and cost/benefit analysis of the fuel cell powered vehicle versus the standard Toro Workman e2065 vehicle.
- Quantify barriers and results.
- Include partners with more robust off-road applications for the fuel cell vehicle.
- Include testing of the air filtration system.
- Reviewer suggests to moving this project to the Technology Validation subprogram.
- Add landscape managers, workers and decision makers to the team.
- Add property owners and decision makers to the team.

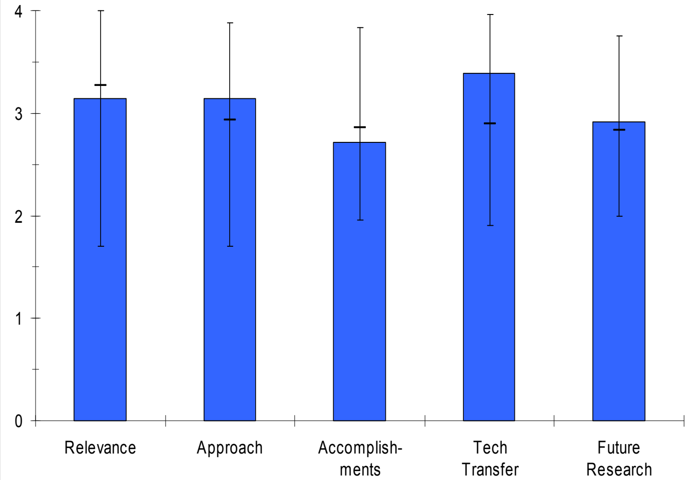
Project # FCP-09: Market Opportunity Assessment for Direct Hydrogen PEM Fuel Cells in Pre-automotive Markets

Kathya Mahadevan; Battelle

Brief Summary of Project

The overall objective for this project is to assist the Department of Energy in developing fuel cell systems by analyzing the technical, economic, and market drivers of polymer electrolyte membrane fuel cell adoption. The objectives of 2007 include 1) economic analysis of near-term markets in the federal and portable market sector; and 2) state and local agencies of emergency response market engagement. This includes 1) development of a candidate user database; 2) market engagement through targeted e-mailing of educational material and by facilitating teleconferences on polymer electrolyte membrane fuel cell applications and installations; and 3) conference presentation at venues frequented by the user community.

Overall Project Score: 3.0 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

This project earned a score of **3.1** for its relevance to DOE objectives.

- This project presents a survey of potential first-user applications among Federal government users.
- While the topic itself is relevant, the presentation did not fully assess market opportunities or production potential. As presented, the project only partially supports DOE goals and the President's Hydrogen Fuel Initiative.
- Relevant to the DOE program objectives.
- The general methodology and results to date are highly valuable in helping DOE provide relevant market signals to industry.
- Well-rounded approach to early market assessment that supports fuel cell market development.
- This project strongly supports the Hydrogen Fuel Initiative and the objectives of the Multi-Year RD&D Plan.
- It is evident that the first market opportunities for polymer electrolyte membrane fuel cells will be niche scenarios with less demanding cost and durability requirements than automotive applications. It is important to seek out and crack these opportunities while technology progresses on the challenges facing broader applications for fuel cells, due to the need to keep the supplier base engaged and in the game.
- Market analysis is essential in defining technical goals and 2012 targets.

Question 2: Approach to performing the research and development

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

- The comparison of first-use fuel cell applications with conventional, traditional power sources is interesting, but the approach does not present a compelling argument for a transition to fuel cell technology. Perhaps the problem is that the argument for the Federal government to lead a transition to fuel cells is more qualitative than quantitative.

- The presentation did not include any real breakthrough findings. During the course of its work, Battelle sought information from federal agencies but does not appear to have built on the data they were provided by otherwise preoccupied program managers, project members, and others.
- Market analysis techniques appear to be robust and through.
- The principal investigator used a multifaceted approach in identifying markets in two of the main early areas for polymer electrolyte membrane fuel cells. There are other early, small format markets as well, and using this approach will be very valuable.
- Primary research, particularly contact with potential users, is critical to understanding market needs.
- Stack life as a proxy for reliability may not be sufficient in early years of market development. System reliability, particularly for early systems, is a function of more than just stack life.
- Use of levelized hydrogen cost could downplay the impact of fueling infrastructure capital costs on decision processes for forklift applications.
- Approach is logical and well implemented following classical market analysis and early adopter conventions.
- In discussions with the principal investigator, it became evident that not a lot of follow up with respect to the earlier phases of this project (which focused on commercial niches as opposed to Federal and portable power) had been conducted. In other words, the project would benefit by fully understanding the results from the past with regards to fuel cell adoption in the commercial sector. Reconnecting with the decision makers in the commercial market that were previously identified as attractive opportunities by Battelle could help guide future project activities.
- To encourage adoption, there would be value in further support in the areas that have been identified as attractive near- and mid-term opportunities for polymer electrolyte membrane fuel cells. Even if the economics and technical attributes are there for specific applications, adoption of a new technology often requires considerable extra support and follow up.
- Another promising strategy for the future may be to facilitate the establishment of demonstrations for the applications that have been identified as most economically attractive.
- Approach is sound and logical. Methodology includes: market segmentation and identification of near-term applications; characterization of markets; identification of market and user requirements; selection of likely near-term markets using rating criteria; identification of lifecycle cost data for incumbent and polymer electrolyte membrane fuel cell technologies; and market penetration modeling and opportunity analysis.

<u>Question 3: Technical accomplishments and progress toward project and DOE goals</u>

This project was rated **2.7** based on accomplishments.

- The progress this year in this project appears to be fairly limited – a lot of effort has been expended in this project but the results thus far could be considered obvious to an informed audience. Perhaps the value of this project is the addition of statistical confirmation.
- There was no apparent breakthrough to provide possible paths forward for hydrogen and fuel cells. While using extensive efforts to locate and survey activities, the project can leave a reviewer wondering just how in depth the collaboration really was.
- Analysis of the market opportunities that were identified in the project objectives have been completed.
- The results of the study can influence or at least validate some of the decisions on market positioning taken by the fuel cell developers.
- The methodology (slide 5) provides a good algorithm for industry to relate their capabilities and motivations into a plan for product development. Of particular note is the use of a Bass model in the market penetration step and judgment in the market opportunity analysis.
- The life cycle assessment for the Federal and portable power applications represent important groundwork for further work in aiding fuels cells to intelligently grow in the marketplace.
- Of particular note is the important message (slide 17) to DOE and the industry of the critical need for reliability data for the Federal Aviation Administration market segment. There are other market segments that need that as well.

- The project is addressing the barrier of early market identification, though it is difficult to ascertain overall progress against plan for this five-year project.
- The project has identified several areas in the Federal sector and portable power where polymer electrolyte membrane fuel cells can make a strong business case. Areas for further improvement including reliability have been identified.
- The business case for these areas has been elucidated laying the groundwork for further market adoption activities.
- Solid, consistent technical results and presentation therein.
- Good progress. Completed analysis of federal markets – October 2007; submitted draft reports. Completed analysis of portable markets. Conducted two state and local emergency response stakeholder teleconferences.

Question 4: Technology transfer/collaborations with industry, universities and other laboratories

This project was rated **3.4** for technology transfer and collaboration.

- Many participants have contributed input and information to the survey activity.
- While using extensive efforts to locate and survey activities, the project can leave a reviewer wondering just how in depth the collaboration really was.
- Collaboration took the form of extensive interviews with fuel cell developers and potential customers of the technology.
- The principal investigator collaborated well with US Fuel Cell Council in polling the industry for information.
- Excellent use of outside resources.
- There has obviously been extensive contact with potential adopters of the technology in the Federal and portable power markets, however there has been little collaboration with other firms specializing in market analyses and transformation. Other firms experience might have provided additional insight with regards to market opportunities and next steps to further facilitate adoption.
- Besides the National Renewable Energy Laboratory, there has been no other overt collaboration with national labs nor universities
- Collaboration is strong and effective. Demonstrated ability to gather and analyze information.

Question 5: Approach to and relevance of proposed future research

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

- Future plans appear to be reasonable to complete the project.
- As presented, the project could have focused more on the real challenges to market potential rather than an almost-cursory survey.
- Project is wrapping up and the objectives have been met.
- Fuel cells applications in wastewater treatment does represent a future market, but there are other similar niches that may be better to apply this effort towards.
- The project is winding down; therefore the proposed future work seems in line with the time remaining.
- Proposed future research for polymer electrolyte membrane fuel cells in wastewater treatment and data center markets makes sense. Combined heat and power in some applications may make sense and data center markets are highly attractive but do require extreme reliability.
- Would recommend that if this project or a similar one continues in the future that increased effort be placed not only on identifying other new market opportunities, but maximizing success in the ones already identified. Working closely hand and hand with potential adopters to tip the scales and achieve successful adoptions.
- Principal investigator needs to complete market opportunity assessments for fuel cells in wastewater treatment and data center markets. Suggest inclusion of biofuel opportunities. Also similar study should be done for small solid oxide fuel cell.

Strengths and weaknesses

Strengths
- Despite a limited presence within and with Federal and other hydrogen and fuel cell programs, Battelle provided a well-organized and well-prepared document even though the discussion of market opportunities could have been improved.
- The study was very thorough.
- The principal investigator has a solid foundation for market analysis, and a detailed understanding of fuel cell market issues.
- Over all, this reviewer (with 14 years of fuel cell market entry analysis) thinks that this was an impressive effort.
- The project is well conceived and executed with good use of potential customers and industry participants.
- Very relevant to the Hydrogen Fuel Initiative and needs to breech the market for polymer electrolyte membrane fuel cells.
- Solid, methodical analysis that has done a good job identifying attractive opportunities and laying out business cases.

Weaknesses
- For a reviewer somewhat familiar with ongoing federal H_2 / fuel cell programs, the project offered little new knowledge, at best.
- It would be valuable to make this model generalized and available to users; the sooner the better.
- Hydrogen cost treatment could underestimate the impact of fueling infrastructure capital costs on decision process for forklift applications.
- Should incorporate other firms with market analysis and transformation expertise to enhance effectiveness.
- Develop deeper relationships with key decision makers in the areas of identified opportunities.

Specific recommendations and additions or deletions to the work scope

- Project results would have been improved if the project had assessed or included unique strategies to advance implementation including the use of tax incentives or other early adapter strategy potential.
- It would be useful to extend this work to activities that can enable very small fuel cells in applications that translate to retail market space.
- Should go deeper in the future as opposed to broader and try to achieve some real market adoption successes with entities already showing interest in polymer electrolyte membrane fuel cells.
- Similar study should be done for small solid oxide fuel cells.