

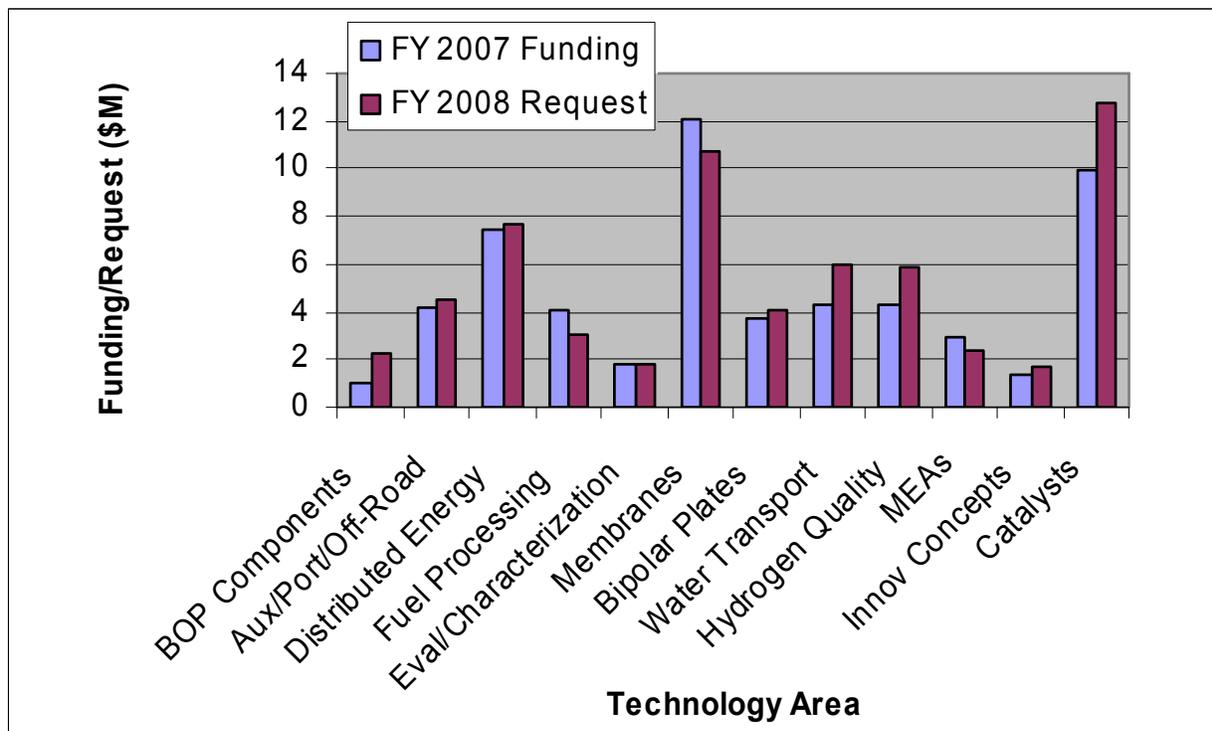
2007 Fuel Cells Summary of Annual Merit Review Fuel Cells Subprogram

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 Initiative. Overall, the R&D portfolio was judged to be well managed, appropriately diverse, and focused on addressing technical barriers and meeting performance targets. Progress was considered good. The current focus on partnering (industry, National Labs, 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 project with improved outcomes and deliverables. Many R&D projects in the Fuel Cell Subprogram were completed in FY06. New projects from the 2006 solicitation/lab call were kicked off in February 2007 and they were presented in a poster session but not reviewed. As a consequence, fewer fuel cell projects were reviewed this year at the Merit Review and Peer Evaluation. These new projects will be reviewed in FY08.

Fuel Cell Funding by Technology:

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



Majority of Reviewer Comments and Recommendations:

In general, the reviewer scores for the fuel cell projects were high to average, with scores ranging from 3.7, 2.8, and 1.8 for the highest, average, and lowest scores, respectively. The majority of the projects were reviewed by six to seven reviewers. The scores reflect the technical progress that have been made over the past year, relevance to the DOE Hydrogen Program, technical approach of the project; extent of technical transfer; and proposed future plans for the project. 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: Scores for catalyst projects 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 durability results from the non-precious metal catalyst projects are promising, but performance needs to be an order-of-magnitude better before this durability matters. The reviewers commented these efforts in alternative electrocatalysts represent a potential high pay-off option and should be supported in the future.

Membranes: The membrane projects were ranked average to above average. Virginia Tech and Colorado School of Mines ranked the highest among membrane projects. The use of heteropoly acids for proton conduction in membranes is a novel concept with high potential. A major issue continues to be immobilization of "polyPOM" in polymer materials. The Virginia Tech effort provides a new approach to formulate fuel cell membranes and showed significant progress in conductivity and swelling reduction. A cost of production study of most promising membranes was recommended for many of the projects. One outcome of the 3M stationary membrane activities is the correlation of lifetime with initial fluoride release rate that may enable a lifetime prediction capability.

Recycling: Two recycling projects were evaluated and each received an overall rating of above average. Pt (PGM) recovery is 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 CCMs and MEAs. Significant progress has been made by Ion Power in economic analysis and prototype process demonstration but more cost analysis is needed. BASF should implement a go/no go decision point before proceeding to build a recycling plant prototype.

Stationary: One stationary project (Battelle) was evaluated and its total score is above average. The data collection and analysis methods were considered thorough and systematic. Through the forklift market study, a good tool was developed for future implementation into different market segments. However, all costs to transition and operate new forklifts and other systems need to be included. The data and model from this project will be available to the public to promote technology transfer.

Analysis and Characterization: These projects were ranked average to above average and were noted to strongly support the fuel cell program objectives and goals. The NIST Neutron Imaging Project received the highest score throughout the entire fuel cell program. Correlating microstructure of MEAs with performance data would increase the value of the ORNL TEM characterization effort. Components such as membranes, GDLs, and catalysts from a working stack should be considered for study. The modelers in the fuel cell program were encouraged to validate their models with real world data, as previously suggested. Fuel cell manufacturers need to supply more experimental data to the modelers.

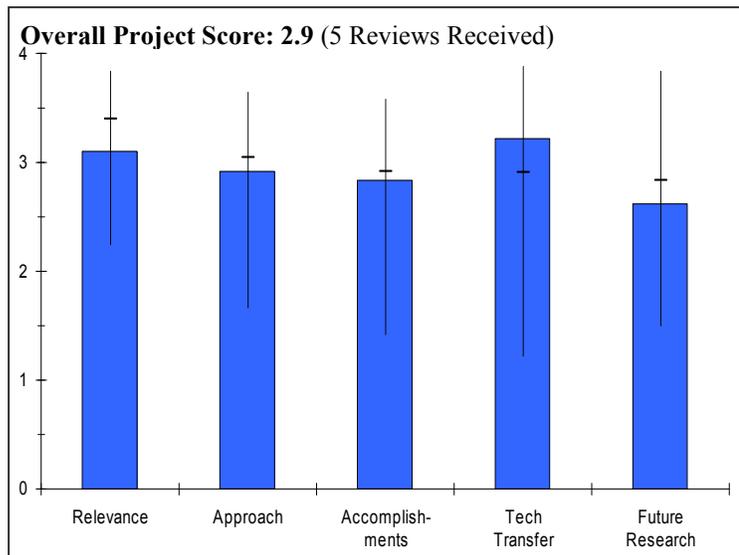
Portable Power, Auxiliary Power, BOP, and Fuel Processing: No projects in these technology categories were included in the Annual Merit Review and Peer Evaluation this year. Projects of this type were on hold and not funded until the middle of FY07.

Bipolar Plates: No bipolar plate projects were reviewed in the Annual Merit Review and Peer Evaluation this year. Two new bipolar projects were included in the poster session but they were not reviewed.

Cross Cutting: One cross-cutting project (National Center for Manufacturing Sciences) was rated with scores ranging from average to below average. The reviewers recognize the importance of manufacturing research and development in attaining cost targets for PEM fuel cell vehicles. Cost data and technical accomplishments must be presented in order to track progress in relation to cost targets and technical goals.

Project # FC-01: Fuel Cell Systems Analysis*Rajesh Ahluwalia; ANL***Brief Summary of Project**

The objectives of this project are to 1) develop a validated system model and use it to assess design-point, part-load and dynamic performance of automotive fuel cell systems; 2) support DOE in setting and evaluating research and development goals and research directions; and 3) establish metrics for gauging progress of research and development projects. The objectives for FY 2007 were to develop, document and make available versatile system and analysis tools consisting of GTool (stand alone code) and GTool_ENG (coupled to PSAT). The models were then validated against data obtained in laboratories and at Argonne's Fuel Cell Test Facility. These models may then be used by those of current interest, including FreedomCAR Technical Teams and DOE contractors.

**Question 1: Relevance to overall DOE objectives**

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

- Project, while not directly vital to the Program's success, provides a useful check on the progress towards the final objectives (such as system efficiency and cost) and warrants continued support.
- Provides operating conditions, strategies, models and insight that can assist and guide other Program projects. For example: models are used for Program's cost studies, water & thermal management project, and air compressor projects.
- Understanding of system-level implications is critical to understanding of DOE high-level targets and to prioritization of specifications/development tasks for R&D.
- A purpose of this project is to create a "paper" fuel cell system in order to provide quantitative insights into fuel cell engineering. ("Paper" in this case means a computer model that simulates an actual fuel cell system in intent if not in practice.)
- This project could be valuable, potentially, as a resource for discovering engineering data that are inconsistent with other data.
- The work is directly relevant to the President's Initiative.
- The work supports the fuel quality work and will help extrapolate the cell data being generated by LANL, HNEI, JARI, etc. to evaluate the effects of changes in cell design and catalyst loadings.

Question 2: Approach to performing the research and development

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

- Generally a solid approach, but would benefit from more validation.
- Perhaps too much extrapolation of some models (e.g., membrane water uptake and conductivity at temperatures higher than available data, CO limit outside data range). Again, please validate.
- Modeling work needs to address durability and failure root causes better.
- MatLab compatibility is a good choice for wide usability.
- The absence of uncertainty (sometimes called "error") analysis is a significant weakness. The data used to build the model should have an indication of the uncertainty of the data – perhaps the standard deviation of a

distribution if a result was arrived at statistically. This information should be preserved and propagated through the model in the standard fashion to provide error bounds for predictions of the model.

- The concept of collecting and compiling the open literature test data in one area would be very helpful.
- Using the working model to complement the efforts of NREL and LANL is a plus.
- Is the model to be used to make extrapolations that will later be validated by LANL, HNEI, JARI, etc?

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

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

- The project has delivered on their objectives. Program "barriers" do not apply to this system-based model development.
- Durability prediction is just scratching the surface. Funding level is not consistent with major effort required in this area.
- Decision to use 3M NSTF catalyst and PFSA membrane as reference system may limit applicability of results (for instance water transport, optimum operating temperature) to other MEA/Catalyst systems.
- Not clear that any breakthroughs are being enabled by this activity. Incremental progress towards goals, which are better addressed by developers.
- The purpose of the project is to provide quantitative insight to members of the fuel cell development community. Lacking in the project is feedback from the community as to how this insight affected their decisions and how their ultimate experience compared with the initial predictions.
- The measure of technical accomplishment would be how well the model compares with real-world experience. Some of the slides (e.g., 16-19) make interesting predictions, but without comparison of theory with experimental data, one cannot tell how great the accomplishment might be.
- The model is timely for the hydrogen quality effort, which is a key point in the evolution to a hydrogen infrastructure.
- The evaluation of the 3M membrane and catalyzing technique is helpful.

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

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

- Good interactions with other Program projects (TIAX cost study, Honeywell BOP programs, H₂ quality programs) and FC Tech Team.
- Future work includes durability models. Perhaps this can be tied into LANL's continued durability experimental effort.
- Good interaction with component developers
- Explore use of test data from other test labs (universities).
- Unclear that the developers are using the model, or that DOE is using input from model to revise/prioritize specifications of components or materials.
- The project has many industry partners, which is one of its greatest strengths.
- The project could be strengthened by additional feedback from its partners – how model influenced decisions, how model comported with real-world results, and how model was refined based on such information.
- The interaction between ANL and 3M appears to be very good.
- The use of LANL and U of SC data also appears to be very good.

Question 5: Approach to and relevance of proposed future research

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

- The future research plan correctly includes developing models and understanding derived from the Program's impurity studies (H₂ quality and air impurities). I strongly recommend focus on impurity effects on reduced catalyst loading electrodes that are required for FC commercialization.

- Systems analysis and hydrogen quality support activities are poorly defined. Need to focus on specific deliverables.
- End-of-Life modeling is potentially a very useful task, but details are missing. Scope of EOL modeling is probably inconsistent with available funding for 2008.
- Future work is primarily support/exercise activity, not directed research towards system simplification or component specification.
- Proposed future research includes new models for end-of-life analysis and fuel impurities. The PI does not explain how building such models would affect the course of the research program to overcome technical barriers.
- The proposed future works makes sense and is relevant. Specific examples would have been helpful.

Strengths and weaknesses

Strengths

- The project has solid modeling expertise.
- Good stack and system mechanical system simulation. Materials behavior and electrochemical behavior prediction needs more work.
- Good collaboration with developers and suppliers.
- Distribution of model should help industry make consistent projections.
- Captures much of the relevant physics for traditional system, steady-state operation.
- The PI cites several collaborators, though it is unclear if they use the model for engineering or rhetorical support (e.g., in PowerPoint presentations).
- The start of using lab and field data from multiple sources.
- The start of using the model to support other efforts like fuel quality.

Weaknesses

- The project will still benefit from increased validation of results, especially on potential impact of impurities.
- Many in the audience were confused by the impurity results shown as a function of "recycle ratio". As the PI no doubt is aware, the actual driver was the H₂ purge rate. This would be communicated more clearly if it was referred to as such (perhaps defined as purge H₂ rate/electrochemically-consumed H₂).
- Durability prediction needs to be strengthened.
- This is primarily a paper study.
- Insufficient emphasis on game-changing configurations (elimination of major components or simpler control algorithms).
- Transient phenomena?
- Apparent use of the same sets of data to both create and to validate the model, thus confusing validation with data fitting. This weakness could be corrected by more clearly identifying the sources of data, showing that separate and independent sources were used for model construction and validation.
- Absence of uncertainty analysis. This weakness could be corrected by more clearly showing error bars in the data used to construct the model and confidence bands in the model predictions.
- Lack of demonstrated impact. This weakness could be corrected by showing that the model had value in influencing engineering decisions, correctly predicting real-world experience, or critically evaluating inconsistent data sets.
- Objectives that stress management goals (setting goals, establishing metrics) rather than engineering goals (making accurate predictions, reducing the need for expensive experiments). (One does not need a computer model to "gauge progress of R&D projects" or to "set and evaluate R&D goals and research directions.")
- The apparent lack of validation of extrapolation of the model.
- The leveraging of complementing activities from projects would be an asset.
- As an aside, the presentation has a number of acronyms (e.g., CEM, ORR, EWH, etc). A page defining the acronyms would be helpful.

Specific recommendations and additions or deletions to the work scope

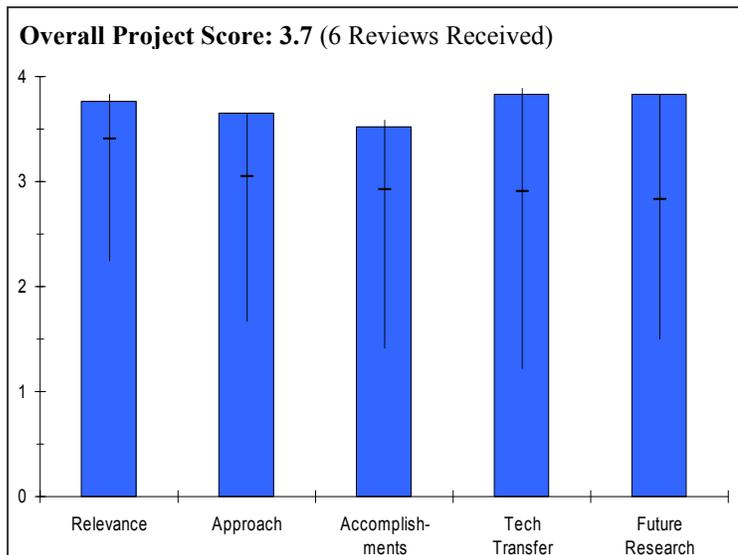
- Prioritize impurity modeling. Hydrogen side followed by air side.
- System model should be used to determine how a change in material or device specification could allow for major changes to system complexity or control.
- Need focus on transient designs/off-design points, which are harder to get data for in power plants.
- Is a comparison of the 3M materials to the DuPont and Gore materials envisioned?
- Does ANL plan on only using the published LANL and U of SC data, or include the data being generated by HNEI, JARI, Clemson, U of CT?
- Has ANL considered requesting these labs to run specific points to validate the model?
- Are alternate cell designs/materials going to be modeled?
- What type of radiator is being modeled? What would be the effect of modifying the radiator design?

Project # FC-02: Neutron Imaging Study of the Water Transport in Operating Fuel Cells

David Jacobson; NIST

Brief Summary of Project

This project aims to develop and employ an effective neutron imaging based, non-destructive diagnostics tool to characterize water transport in proton exchange membrane (PEM) fuel cells. The objectives for FY 2007 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 prototypes to commercial-grade fuel cells and hydrogen storage devices; 3) make research data available for beneficial use by the fuel cell community; 4) provide a secure facility for proprietary research by industry; 5) transfer data interpretation and analysis algorithm techniques to industry to enable them to carry out research more effectively and independently; and 6) continually develop methods and technology to accommodate rapidly changing industry/academia needs.

**Question 1: Relevance to overall DOE objectives**

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

- PI developed tools that are useful for fuel cell developers.
- The benefits of the project are not clearly quantified.
- Very relevant as this technology and future advancements will be critical in solving the water management-stack issues.
- The project is critical to the design of components in which water management is key.
- This tool offers insight into water management within PEM fuel cells.
- Does not offer direct impact, but it can provide insights that may result in important improvements.
- This project is relevant to the DOE program. The development and use of new techniques to characterize fuel cell components and systems that provide complementary data to that available from other techniques is important. The presentation showed nice results from GDLs.
- NIST neutron imaging work is highly relevant to the DOE program objectives.
- Being able to visualize water movement and transport within an operating fuel cell is important in developing a better understanding of the conditions inside a fuel cell.

Question 2: Approach to performing the research and development

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

- Neutron scattering has been the most effective approach for *in situ* water transport study.
- The tools are clearly being widely used, but it was not clear how the work impacted the programs of collaborators.
- Most significant advancement in analytical non-destructive testing in many years.
- Facilitating better resolution and cross-sectional analyses to study water is appropriate.
- NIST has a dedicated beam line for neutron imaging of fuel cells and fuel cell components.
- Tomography and radiography are used to image the cell, the latter being emphasized allowing transient data to be collected.

- The use of modeling is enabling more powerful interpretation of their results.
- Have shown excellent results, to date, however further elucidation will require improved resolution, which is planned.
- Project is to make neutron imaging available to the fuel cell community and to facilitate taking and analysis of the resultant data. The new cell designs and data acquisition techniques will enable more efficient use of this facility to generate data. It would help in the future if the presenter indicated the ultimate sensitivity and resolution capabilities of his experimental setup.
- The approach that NIST is taking to grant access to the neutron source is good, namely externally reviewed proposals selected by a Program advisory committee.
- Improving the capabilities of the facility in anticipation of the needs of the user community is very good.

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

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

- It was not clear how the data collected agree with expectations based on literature or modeling.
- There was no explanation for the knee in the through-plane water gradient.
- Outstanding – the new detector and the new beam line are evidence of the accomplishments from this group.
- The new detector predicted to be available this fall will enhance this technique even further.
- Would like to see more publications – but this is not a NIST issue, it is a user responsibility.
- They have achieved a 10x improvement in spatial resolution.
- A 40% reduction in time-of-measurement has been achieved.
- Radiography is being used to study stacks with temporal resolution.
- Showed a lot of interesting results in the past year.
- A lot "bang" for DOE's bucks here.
- The use of neutron imaging to characterize water transport will provide much needed information. This effort was relatively new and did not have many results so the presentation came across as a bit naïve. As this program progresses, it should generate a plethora of new results.
- Significant progress appears to have been made since the 2006 AMR.
- Spatial resolution was improved to 25 μ and NIST expects another factor-of-two improvement this fall.
- The addition of a freeze chamber is an important accomplishment for 2007.
- Increasing the intensity of the neutron beam is also an important accomplishment because it reduces the time for imaging to the same resolution.

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

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

- The NIST tools have been widely used and NIST has developed tools to meet collaborator's specific needs.
- Excellent.
- At least 50% of the beam time is being used for non-IP research.
- Allowing excellent collaboration with both universities (via peer reviewed beam time requests) and industry.
- The number of collaborators is very impressive.
- Effort appears to be in its infancy. To ensure the best use of this facility, the PI needs to take additional steps to ensure more researchers know that the facility is available and its capabilities.
- Collaborations are in evidence. About half are for proprietary collaborations and half for open collaborations.
- Open collaborations advance the science of fuel cells to the benefit of the entire community.
- Proprietary collaborations may actually advance the technology even faster than open collaborations but benefit only one company or a small group.
- The balance of proprietary and non-proprietary work appears to be right.

Question 5: Approach to and relevance of proposed future research

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

- Sound future plans include going to higher resolution, utilizing AC impedance and freeze studies.
- If appropriately equipped, the PI should include some modeling to compare to data.
- New detectors to enhance the resolution are the most important "next step" in which this group could engage.
- New techniques.
- Spatial resolution down to 1 micrometer.
- *In situ* conductivity measurements by EIS.
- Freeze/thaw studies.
- Additional imaging using cold neutrons.
- Very good; proposing useful future steps.
- A reasonable path forward was presented which is dependent upon outside users expressing interest in using the facility. The addition of cold neutrons, with enhanced water sensitivity, will improve the quality of data available using this suite of techniques. The planned freeze/thaw studies provide interesting data.
- Greater resolution down to less than 1 μ will facilitate the study of water formation and transport within the electrode structure.
- Freeze chamber studies are very important to understand the damage mechanisms at work during freezing conditions.

Strengths and weaknesses

Strengths

- The PI has met user demands.
- The PI has shown continual improvement of methods.
- Team is strong.
- Collaborations excellent considering this is outside the DOE.
- Commitment is there at the NCNR.
- State-of-the art world class facility being funded by a Federal/private partnership.
- Excellent.
- Unique tool with interesting capabilities and results.
- Continuous improvements in resolution and capabilities (e.g., freeze).
- Demonstrating the challenges of water management in traditional PEM fuel cells.
- Application of new techniques to fuel cell problems.
- NIST has the capability to assist researchers to achieve the maximum value from the available beam time by training/assisting researchers in operational techniques and by assisting in data analysis and interpretation.
- The use of internal NIST support to increase the resolution down to sub-micron level is admirable.

Weaknesses

- There was no demonstration of a fundamental understanding of the impact of materials on water vapor transport i.e., lots of results but few explanations.
- There was no validation of results with models or literature data.
- None but it would be valuable to have an independent fuel cell expert engaged with the non-proprietary activities in the development of the technique.
- The following are minor.
- Modeling needs to be strengthened it appears to lag behind the experimental work in terms of quality.
- EIS may be too slow to get time-resolved proton conductivity while imaging, it might be better done ex-situ with reference to a few *in situ* well defined points.
- Not a lot of this work has been published in the literature yet.
- Half the requests for beam time are not able to be accommodated.

Specific recommendations and additions or deletions to the work scope

- Compare results with models or literature data obtained by other methods.
- Work to differentiate between vapor phase and liquid water.
- Increase the funding.

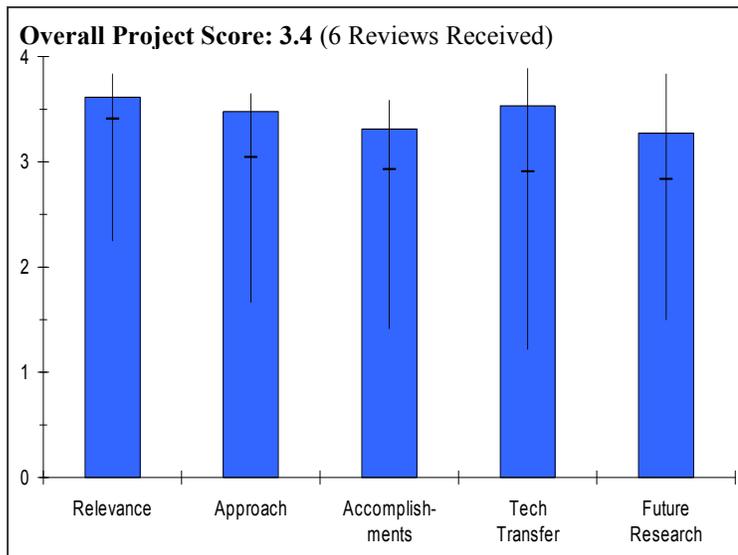
- Bring in a fuel cell expert.
- Obviously we need more of this, but it sounds like this beam line is maxed out. If possible, provide more beam time.
- Take "snapshots" during freezing process (to capture water movement) and during start-up (if possible) from freeze.
- The project needs to investigate new routes to advertise its existence. The addition of an additional project to investigate transient phenomena during startup, shutdown, and load-following would be beneficial.
- Are there any other strategies to increase productivity of the neutron source so that more requests for beam time can be accommodated?
- Three-dimensional effects are likely to be important in larger fuel cells so the ability to visualize water transport in three dimensions is important. Some effort is justified in trying to develop appropriate imaging technology that can be implemented at the NIST facility.

Project # FC-03: Microstructural Characterization of PEM Fuel Cell MEAs

Karren More; ORNL

Brief Summary of Project

The objectives of this project are to 1) identify high-resolution imaging and compositional/chemical analysis techniques for characterization of the material constituents comprising proton exchange membrane (PEM) fuel cell membrane electrode assemblies (MEAs); 2) apply these analytical and imaging techniques for the evaluation of microstructural and microchemical changes to MEA materials during life-testing; and 3) elucidate microstructure-related degradation mechanisms contributing to PEM fuel cell performance loss. The objectives for fiscal year 2007 were to develop innovative methodologies to prepare samples for microstructural analysis of MEA constituents; apply state-of-the-art electron microscopy techniques for the analysis of MEA materials; and collaborate with industry, academia, and national laboratories to make these techniques available for MEA processing and/or life-testing studies.



Question 1: Relevance to overall DOE objectives

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

- PI has demonstrated capability in providing key diagnostic and analytical support necessary for the critical assessment of MEA materials under development by other program participants.
- Very relevant and timely.
- Project is addressing the critical failure modes.
- This project will support the MEA durability and cost effectiveness that are relevant to the Hydrogen Program vision and the DOE objectives.
- Should be very relevant, but the amount of conclusive results produced here appears quite limited.
- The investigator has developed a technique that can be used for quantifying the degree of order in catalyst particles, which can be used for correlations with performance and degradation.
- The project has confirmed known degradation trends (e.g. faster decrease of catalyst surface area at higher RH).
- Identifying characteristics that are stressors for degradation is crucial towards meeting the lifetime targets in the FreedomCAR Fuel Cell Technology Roadmap.
- Using the knowledge obtained from this project can accelerate fuel cell technology developments by eliminating efforts on non-ordered catalyst particles.
- The development of investigative techniques and the determination of lattice structure of alloyed catalyst are relevant.
- The determination of the degree of catalyst agglomeration with time is also relevant.

Question 2: Approach to performing the research and development

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

- PI's diagnostic examples were thorough and clearly presented.
- PI's examples demonstrated the relevance of the chosen analytical techniques to the requested tasks.
- Approach is unmatched anywhere and invaluable.

- She is using the most advanced microscopy tools available and leveraging the National Lab resources very well.
- The project integrates with other research areas in the catalyst and electrolyte polymers development fields.
- Further analysis of the technical barriers and system parameters were expected.
- The project's technical feasibility will be greatly enhanced with design modification to include correlations between the catalyst microstructure and its electrochemical performance.
- Need to characterize the changes to the carbon support, as well as the changes in catalyst. For example, the effect of RH on the surface area losses may be (directly or indirectly) due to degradation of the carbon supports.
- If ionomer on the carbon is problematic, then consider some alternative techniques (e.g., is it possible to remove ionomer with alcohol solution?).
- The project is simple and elegant in concept – it focuses on a very important technique for characterizing catalyst particles (z-contrast imaging), and then proceeds to draw correlations using performance and degradation tests when possible.
- The characterization of catalyst particles following degradation has assisted in understanding the mechanisms of catalyst agglomeration (re-precipitation and coalescence instead of ripening).
- Approach needs to begin focusing on sub-surface characteristics if possible. Questions regarding whether particles represent Pt skins over bulk Pt_xM , and whether the sub-surface ordering is important should be addressed. It is unclear from the presentation whether it is possible for ORNL techniques to explore this.
- The evaluation of the structure of the various alloyed catalyst mixtures will help with the development of robust, durable formulations.

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

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

- The quantity and "new" technical content of the PI's accomplishments were affected by changes in the projects being supported.
- PI demonstrated capability to adjust to new demands, and development of new techniques required by the changes to project scopes (e.g., "Microstructural Characterization").
- Very appropriate.
- Addressing the most critical components in an analytical approach but also using solid state chemistry fundamentals to guide her.
- Her continued progress on this over the last year was excellent.
- Hope she does not go off on tangents with the "so many" proposed technical solutions. Focus on the existing MEAs and the most relevant possibilities.
- The project certainly shows progress toward the overall project and DOE goals.
- The technical accomplishments will be more significant if more interaction between the collaborating parties was realized.
- Not much in terms of new conclusions here. For example, superior cyclic stability of Pt-Co has been shown and no real conclusions derived (yet) from the difference in alloy order.
- Establishing the link between performance and particle order is the most important achievement for this project this year.
- Establishing that the mechanism of the particle size increase allows for some particle population in the original particle size regime, is another important contribution.
- Project needs to begin identifying a clear link between catalyst particle order and degradation. There is enough data to hint at such a link, but no more.
- The development of the techniques is very important.
- The mapping and evaluation of Pt-Co is useful. The start of work on other alloys is also useful.

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

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

- PI has demonstrated excellent interaction with industry and national labs.
- The collaborations are well established leading organizations.

- Expand the availability of the user center.
- The project encourages the collaboration with industry, academia, and national laboratories to make the advanced characterization facilities and equipments located at ORNL available for interested users free of charge.
- Assistance with relating the physical and chemical behaviors of catalysts, electrodes, etc. to their microstructure may be provided to the invited users.
- Limited, but understandable due to limited budget.
- This project is entirely dependent upon collaboration for the acquisition of materials, so therefore, the degree of collaboration is high.
- Collaboration is on all levels: industry, academia, national laboratories.
- The collaboration with other national labs, academic labs, and industry is to be commended.

Question 5: Approach to and relevance of proposed future research

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

- PI should maintain an aggressive interaction with the other project PIs and (continue to) identify projects that would benefit from PI's diagnostic expertise.
- Karren is focused and doing what needs to be done. Driving this activity to fundamental solid state science is where she needs to go.
- Would like to see her use catalyst materials which are not just "conventionally accepted" catalysts from suppliers. Would like to see the use of new catalyst materials from various groups around the country.
- The project plans to establish further collaborations with industries, universities, and national laboratories to support microstructural characterizations of catalysts and catalyst supports, etc. The project, however, does not consider possible alternative paths.
- Not clear, is the intent to work on as-received catalyst (and postulate how different materials affect performance) or is the intent to focus on changes in the catalyst after use in fuel cell?
- While the future work section acknowledges the *post-mortem* utility of the microstructural imaging, there should also be a focus on linking durability to the beginning-of-life microstructural characteristics as well.
- Catalyst support characterization should be expanded beyond carbon. Although carbon may satisfy the stationary market, its ability to satisfy automotive needs is doubtful. Projects that incorporate metal carbides and metal oxycarbides (e.g. FCP-29 at PNNL) should be included in catalyst support characterization.
- The investigators should consider whether their techniques can be used for GDL, membrane, or interfacial characterizations as well.
- The continuation of further collaboration should be commended.
- This effort appears to be to establish ORNL as a center of excellence. If so, this would be wise.
- It would have been helpful to indicate what alloy catalysts ORNL plans to review next.

Strengths and weaknesses

Strengths

- PI has consistently demonstrated ability to provide excellent diagnostic and analytical support to Hydrogen Program projects.
- Talented group.
- Outstanding resources.
- Motivated.
- State-of-the-art microstructural characterization equipment and facility.
- Skilled staff capable of the operation of this equipment.
- Excellent analytical tools available.
- A focused and simple strategy to develop an analytical technique that can reveal information about catalyst degradation.
- Intense collaboration with industry, academia and national laboratories.
- Wide customer base for the information generated: automotive, stationary, portable and other markets.
- Wide acceptance of the fundamental data. The data interpretation is sound and logical.

- This activity appears to be positioning ORNL to support industry using tools that are expensive and often unavailable to the small fuel cell companies. This effort is to be applauded.

Weaknesses

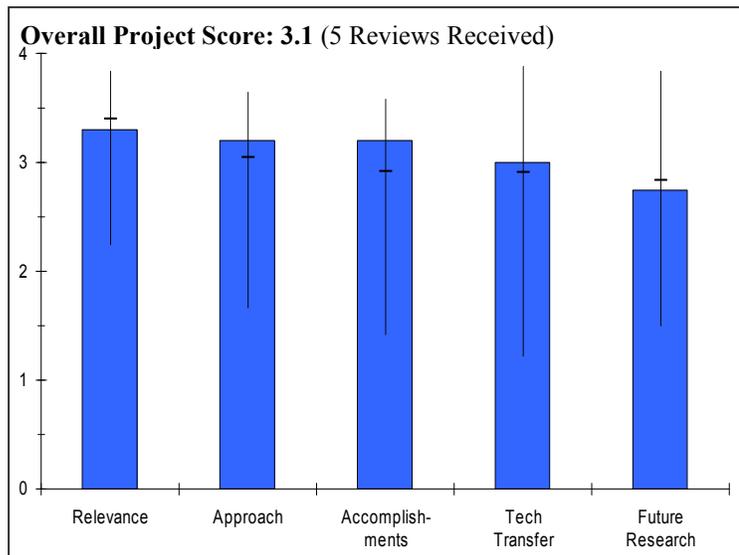
- PI needs to publish work (journal articles), using a "reference material" (i.e., not restricted by IP or other confidential constraints) so that techniques and results can be well documented for future reference. Alternatively, co-publish with PIs that were assisted with the diagnostic and analytical services.
- Most presentations were "invited presentations" with limited availability to researchers not present at the meetings.
- Lack of significant parametric analysis to correlate the microstructures and the corresponding performance of the MEA components, namely, catalyst, catalyst supports, polymer electrolyte, etc.
- PI should stick to discussing the characterization of the materials, since degradation mechanisms and/or impact on performance in the cell are not the PI's expertise.
- Other than alternative Pt alloys (e.g. Pt-W and Pt-Co), the project has not yet evaluated more exotic MEA component candidates. The simple strategy should be preserved, but with a wider expanse of materials. It is understood that this weakness is a function of collaborators, not ORNL.
- Techniques are being developed, but no mention was made of standardized methods.

Specific recommendations and additions or deletions to the work scope

- Suggest that the PI develop a plan to further make the described techniques available to the industry and national labs. Examples might be workshops, journal articles, contributions to "analytical technique" publications.
- Find a way to keep this funded on a permanent basis.
- Add the possible correlations that relate the microstructure of the various MEA components such as catalyst, electrolyte, supports, etc. to their functionality. This will enhance the quality of this project scope.
- Need to characterize changes in carbon (characterize the complete catalyst system). Continuing to ignore this component will lead to the postulation of incorrect degradation mechanisms.
- On used samples, are different cell locations examined? If not, it should be included. For example, one should look for differences between the reactant inlet and outlet locations; recommend comparing the fuel inlet and fuel exit of the 100% RH cycled sample.
- Sub-surface characterization needs to be addressed.
- The full range of the characterization utility has not yet been fully realized. Other MEA component studies (beyond catalysts) should be attempted.
- A more aggressive pursuit of durability vs. component microstructural order is missing and should be added.
- Is ORNL planning to standardize and publish test methods?
- Is ORNL going to evaluate commercial catalysts?
- Is the data to be made public by website?
- Does ORNL also plan to work with industry members on proprietary formulations?

Project # FC-04: Novel Approach to Non-Precious Metal Catalysts*Radoslav Atanasoski; 3M***Brief Summary of Project**

The goal of this project is to develop a new, lower-cost, non-precious metal (NPM) cathode catalyst for replacement of platinum (Pt) in a proton exchange membrane (PEM) fuel cell. The objectives of this project are to 1) reduce dependence on precious metals (Pt); 2) have NPM catalysts perform as well as conventional precious metal catalysts currently in use in membrane electrode assemblies (MEAs); 3) have NPM catalysts cost 50% less than compared to a target of 0.2 g Pt/peak kW; and 4) demonstrate durability of >2000 hours with <10% power degradation. The specific objective for FY 2007 is to produce new, better-performing more durable catalysts and identify the catalytic sites.

**Question 1: Relevance to overall DOE objectives**

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

- Cost is one of the 2 or 3 major hurdles towards fuel cell commercialization, and the stack precious metal loading is the key cost contributor. Thus low cost non-PM catalysts are a key objective, though a high risk, high gain program.
- This is a novel approach to meeting DOE's goals of reducing platinum loading/cost in fuel cells.
- Working well towards DOE's goals for non-precious metal catalyst performance.
- Is cost reduction of 50% valuable – probably not if the fuel cell will have lower power density (requiring more cells, larger air pumps, etc).
- Project addresses DOE goal of development of low cost non-precious metal catalysts; it is relevant to Hydrogen Initiative.
- Project is not critical to Hydrogen Initiative because non-precious metal catalysts have a long way to go before they find commercial application.
- Finding alternatives to platinum for cathode electrocatalysis may prove crucial to the future of polymer electrolyte fuel cells for transportation applications. This project is relevant to overall DOE objectives in spite of unimpressive performance of the catalysts.

Question 2: Approach to performing the research and development

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

- In the future, prioritize performance. Durability is important, but at this stage is secondary to performance.
- This is a very systematic and appropriate approach to development of non-noble-metal catalysts.
- Should investigate further support/catalyst interactions.
- Good physicochemical characterization.
- Modeling with something like density functional theory might be useful in the future to help understand/design better catalysts.
- Approach is well designed – scalable synthetic approaches, modeling and physicochemical characterization complement each other.

- Although far from generating performance of any practical value for transportation applications, this study of HNC catalysts offers a path forward for future development of non-precious catalysts for oxygen reduction.

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

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

- This is hard to rate. Progress is significant. Performance appears to be the equal of the best non-precious metal catalysts (about the same as for two other Program-funded projects). However, there is still a long, long way to go in catalyst activity before it would be viable for automotive fuel cell stacks.
- Durability results are promising. But performance needs to be an order-of-magnitude better before this durability matters.
- Significant improvement on performance with catalysts/substrates.
- Very good progress towards program goals.
- Work on support is interesting and could be useful for other catalysts.
- Excellent progress toward durability.
- Significant progress in catalytic activity.
- Amount of peroxide for the best catalyst is still high which makes this catalyst an undesirable candidate for potential application.
- Irrespective of the performance level, which remains marginal, the demonstrated durability of the best catalyst is definitely promising.
- Achieving higher surface area with thermally stable substrates is a nice accomplishment.

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

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

- The program performance targets are dauntingly high. For the best chance at achieving them, program participants need to leverage as much expertise as possible. I think they'd benefit from more collaboration between the various projects as well as disclosure of the materials.
- If not already done, I'd recommend independent outside testing of the candidate catalysts.
- Good collaborations with Dalhousie and Brookhaven; other interactions were not as clear.
- Lots of work with universities – helps bring them up to 3M's high quality standard for fuel cell research.
- Catalysts cannot be transitioned because catalyst performance is so poor.
- Close collaboration with universities and national labs.
- It is much too early to evaluate this and other alternative-catalyst projects by how successful they have been at the transfer of (yet non-existing) technology.
- Given rather fundamental nature of research, collaboration with several universities is the right approach.

Question 5: Approach to and relevance of proposed future research

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

- While durability is required, I think it is a little premature to prioritize when performance is still at least an order-of-magnitude away from being relevant to program goals.
- If not yet done, make materials available to DOE labs and OEMs for independent testing.
- Appropriate to explore stability and identification of active sites.
- Program is over, so proposed future research irrelevant.
- Making determination of the active ORR site the focus of research in the remaining months of the project is the right choice.

Strengths and weaknesses

Strengths

- Very good results.
- Interesting approach and smart separation between catalyst/support effects.
- Would like more fundamental understanding.
- Thorough work to develop novel catalysts.
- Innovative work on supports.
- Successful combination of good management and strong research plan allowed to make significant progress toward durability and catalytic activity of NPM catalysts.
- Novelty of approach, out-of-the-box thinking.

Weaknesses

- Due to poor performance and far separation from targets, would suggest that these non-noble catalysts belong in BES instead of this program in future solicitations.
- Catalysts unlikely to have any practical application.
- The nature of active centers is not determined.
- Unclear how modeling helped in making progress toward discovery of the best catalyst.
- Little insight into the mechanism of oxygen reduction and the nature of active catalytic site.

Specific recommendations and additions or deletions to the work scope

- The stated DOE goals are scientifically challenging but technically irrelevant (e.g. performance @ 0.8 V).
- Performance at high voltages is critical for high fuel efficiency
- Not only relevant to this 3M project, which is scheduled to end in a couple of months: efforts in alternative electrocatalysis, including non-precious compositions such as those demonstrated in this project, represent a potential high pay-off option in oxygen electrocatalysis and should be supported in the future.

Project # FC-05: Novel Non-Precious Metals for PEMFC: Catalyst Selection through Molecular Modeling and Durability Studies

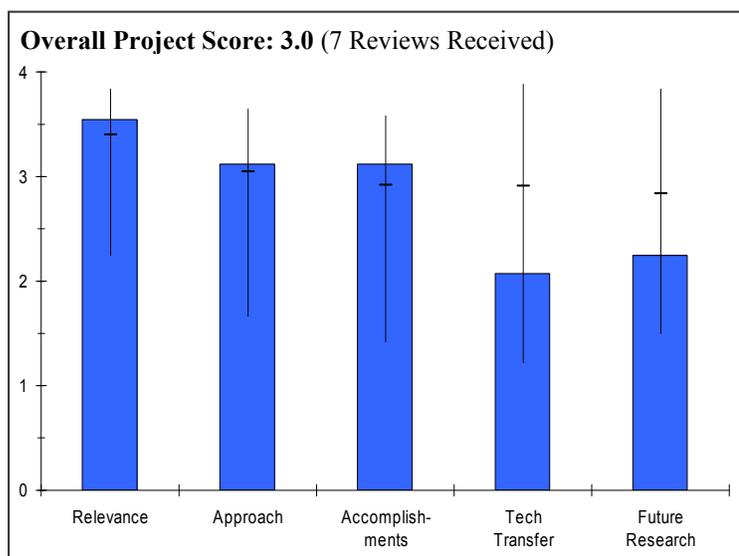
Branko N. Popov; U of South Carolina

Brief Summary of Project

The overall objective of this project is to develop non-precious catalysts for a proton exchange membrane fuel cell (PEMFC) with high catalytic activity, selectivity and durability with a cost at least 50% less than a target of 0.2 g (Pt loading)/peak kW. The specific objectives of this project for FY 2007 are to 1) use metal-free catalysts as a catalyst support; 2) use “metal-catalyzed pyrolysis” to increase the number of active sites; and 3) use chemical post-treatment.

Question 1: Relevance to overall DOE objectives

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



- Directly addresses low Pt loading targets.
- Cost is one of the 2 or 3 major hurdles towards fuel cell commercialization, and the stack precious metal loading is the key cost contributor. Thus low cost non-PM catalysts are a key objective, though a high risk, high gain program.
- Carbon-based and noble-metal-free catalysts offer potential for substantial cost savings compared to Pt catalysts if activity can be improved. Addresses a major barrier for fuel cells.
- Working well toward DOE's goals for non-precious metal catalyst performance.
- Increasing ORR activity of carbon very interesting and excellent research, but PI should be careful to not imply that this is a useful fuel cell catalyst because activity so low.
- The "holy grail" for reducing catalyst cost.
- A high risk, but potentially high return project.
- Development of a metal-free carbon catalyst provides potential for low cost to meet DOE goals.
- Even if the project is not fully successful, good basic research will provide significant insight for metal catalyst supports and potentially provide cost reduction through more efficient metal catalyst utilization.
- Project supports the DOE goal for development of low cost non-precious metal catalysts for the oxygen reduction reaction.
- Project is not critical to Hydrogen Fuel Initiative due to low activity of NPM catalysts compared to platinum.

Question 2: Approach to performing the research and development

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

- Approach is unique and fundamentally sound.
- Stability tests not done at relevant conditions.
- Systematic approach which allowed for the identification of the active site as pyridinic carbon.
- Technical barriers (cost, performance) addressed.
- Approach is largely empirical – impressive that they have made progress this way. Contribution of modeling not clear.
- Something is seriously wrong with the electrochemical evaluation – for instance, on part 6, all catalysts have different limiting currents. Pt/VC catalysts should have a mass activity of 0.16 A/mg Pt at 0.9 V at 25°C at a loading of 14 $\mu\text{g Pt}/\text{cm}^2$ – their performance is negligible at 0.9 V.

- Interesting approach that builds on previous work.
- Work may also result in improved catalyst supports, since it provides insight into the role of carbon.
- Approach modified during course of project based on insight gained from initial approach/research.
- Good fundamental materials research.
- Not clear how well approach addresses cost target.
- Approach is well thought and focused on identification of active sites, improvement of electrocatalytic activity of NPM catalysts and reduction of peroxide formation.

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

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

- Continued progress from last year.
- Still very far from meeting DOE activity targets.
- This is hard to rate. Progress is significant. Performance appears to be the equal of the best non-precious metal catalysts (about the same as for two other Program-funded projects). However, there is still a long, long way to go in catalyst activity before it would be viable for automotive fuel cell stacks.
- Most active non-precious metal catalyst developed in DOE programs.
- Decreased peroxide formation to <2% in carbon composites.
- Demonstrated increased durability.
- Identified problems with water management.
- Impressive amount of work on small budget.
- It's hard to evaluate their actual catalyst performance because their RDE measurements are inconsistent.
- PI should list electrochemical conditions (temperature electrolyte rotation rate, reference electrode, current density and disk size).
- USC has done an impressive job improving the ORR of carbon.
- No results presented of molecular modeling at CWRU. Why??
- Good results that also improve understanding of how to achieve good activity without Pt.
- Not clear how much of this was accomplished in the past calendar year.
- Insight into reduction of peroxide formation for carbon catalysts and supports significant contribution.
- Inclusion of baseline (standard) catalyst data on voltage-current plots would be beneficial to ensure consistent measurements done.
- Initial degradation results promising.
- Identification of active sites is a significant accomplishment.
- Tremendous progress toward improvement of catalytic activity and reduction of peroxide formation.
- Modest progress toward durability targets.

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

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

- Little evidence of any collaborative effort.
- The program performance targets are dauntingly high. For the best chance at achieving them, program participants need to leverage as much expertise as possible. I think they'd benefit from more collaboration between the various projects as well as disclosure of the materials.
- Independent outside testing of the candidate catalyst is strongly recommended.
- Collaborations with other universities – could use collaboration with industrial partner or OEM.
- Performance of catalysts is so low that they are unlikely to get picked up by industry.
- Not clear what was done by collaborators.
- Group should be careful to note in publications that these are not practical fuel cell catalysts (yet) and thus not direct more research to low voltage catalysts.
- Appears to be fairly minimal.
- Impact of collaborations not clear without independent knowledge of listed collaborator expertise areas.

- Modeling doesn't appear to play a role in FY05-07 effort – should indicate duration of collaboration if not over full performance period.
- Where does this go from here? No indication of providing materials to cell/stack experts for further validation.
- Close collaboration with universities.

Question 5: Approach to and relevance of proposed future research

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

- Only recommendation was to find way to add more nitrogen into catalyst.
- Follow through on plan to make materials available to national labs and OEMs for independent testing.
- Project is ending.
- Slightly empirical – not clear why they are focusing on hydrophobicity.
- Issue worth resistance of catalyst layer not explained in talk.
- Only a small amount of funding left – future research somewhat irrelevant.
- Little to no basis provided for how the future efforts in H₂O management, catalyst site optimization, and catalyst layer resistance reduction will be accomplished.
- Based on presented results, appears time to provide materials to group that can address the MEA engineering optimization, since this appears to be beyond the scope of expertise for this performer.

Strengths and weaknesses

Strengths

- Strong structural characterization work.
- In the future, prioritize performance. Durability is important, but at this stage is secondary to performance.
- Have developed an understanding of non-PM catalysts and identified active sites.
- Best activity of non-PM catalysts.
- Innovative basic research – studies of C=N ORR activity might be generally useful.
- Work is structured to attempt to elucidate mechanisms, instead of just trying different materials.
- Work may also result in improved catalyst supports; good opportunity for useful "spin off".
- Concerned about how much peroxide results from alternative ORR catalysts.
- Good understanding of history of this "holy grail" objective.
- Strong fundamental materials research that is providing good insight for future catalyst and support developments.
- Focus on identification of active sites allowed to change directions from transition-metal catalysts to metal-free catalysts.
- Fast progress in implementation of new synthetic routes.

Weaknesses

- Lack of data at relevant conditions.
- No benchmark against Pt catalysts.
- Very thick catalysts layers in MEAs.
- Collaborations with industrial partners who might be able to take advantage of this technology is absent.
- It's nice work/research but unlikely to have any practical value.
- Has not (yet) demonstrated the stability of the catalyst to potential cycling (like in automotive application).
- Explanation for flooding of catalyst layers is speculation with no evidence to support (Pt expels water?).
- Difficult to tell what was accomplished in prior year since FY05-07 lumped together.
- Lack of interaction/collaboration beyond limited materials characterization and theory.
- RDE data on different catalysts are not consistent. For example, it is not clear why limiting current on Pt/C is almost twice lower than limiting current on RuFeN_x/C.

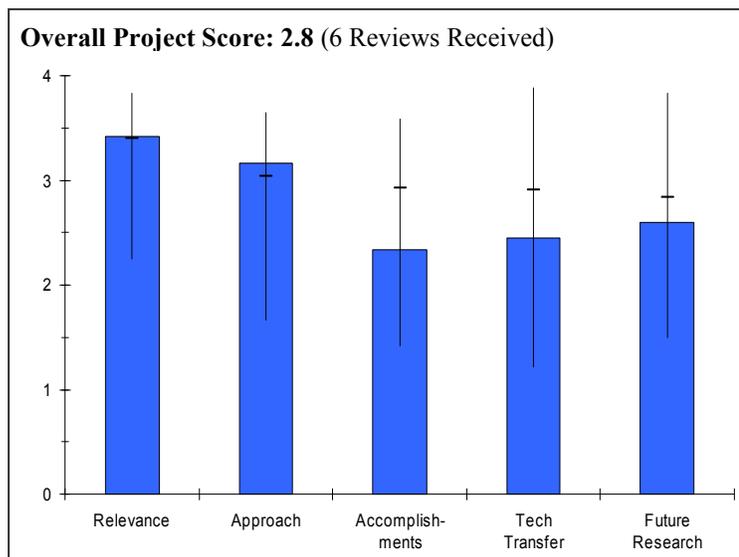
Specific recommendations and additions or deletions to the work scope

- PI should present progress toward DOE targets.
- Catalyst layers are too thick for reasonable conductivity.
- PI should run DOE-specified durability tests (as opposed to steady state low potential tests).
- Catalysts are not ready for MEA level testing.
- Demonstrate stability to potential cycles (80 hours at steady state is not a durability test).
- Project seems to have reached a natural conclusion barring independent validation of the metal-free carbon and composite carbon material performance and identification of the remaining fundamental issues that need to be addressed.

Project # FC-06: Development of Transition Metal/Chalcogen Based Cathode Catalysts for PEM Fuel Cells
Stephen Campbell; Ballard

Brief Summary of Project

The objective of this project is to develop a non-precious metal cathode catalyst for proton exchange membrane (PEM) fuel cells which is as active and as durable as current platinum group metal (PGM) based catalysts at a significantly reduced cost. The focus of FY 2007 was development of: 1) optimization of the composition and structure; 2) manufacturing process; and 3) evaluation, optimization and demonstration in fuel cell stacks. Materials based on transition metals such as Cr, Fe, Co and two chalcogens (Se and S) were screened for stability and activity for oxygen reduction in dilute acid. Down-selected materials were synthesized as supported catalysts for *ex situ* evaluation as nano-dispersed materials.



Question 1: Relevance to overall DOE objectives

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

- The development of a low-cost, durable cathode electrocatalyst for PEFCs would be a technology-enabling advance.
- Relevant to DOE goals of platinum loading reduction/cost reduction.
- The purpose of this project was to investigate a class of materials as potential replacement for platinum in the cathode catalyst. This is relevant to DOE objectives by reducing the cost of fuel cell systems.
- Project is relevant to Hydrogen Fuel Initiative; it addresses DOE goal of development of low-cost non-precious metal catalysts.
- Non-precious metal catalysts are very important to the future cost goals in fuel cells.
- Reduction of Pt usage through substitution/replacement is fully aligned with DOE objectives. Non-precious metal catalyst work is very important, even though the probability of success for any one approach is small.

Question 2: Approach to performing the research and development

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

- The chalcogen-based catalyst approach is promising and its promise has been demonstrated by several research groups.
- In this project, the promise of a particular chalcogen system was evaluated using sputtered thin film electrodes. A system with promising activity was found, but the PIs were unable to make this particular system in a high surface area fuel cell relevant form. Concurrent development of the sputtered systems and the high surface area catalysts would have allowed the PIs to reach this conclusion earlier in the project.
- Comprehensive approach with thorough characterization of materials.
- The PI adopted the staged approach of evaluating the electrochemical behavior of compounds in a well-controlled geometry before progressing to powder systems with geometries that would be difficult to measure.
- Project approach is well-thought and focused on the achievement of high electrocatalytic activity of the catalysts.
- Unclear why W and Ni were chosen as additives to CoS₂ thin films.

- Went for a challenging approach since they knew going in that the catalyst performance would be difficult to measure but I applaud the willingness to take risks and to take a chance on hitting a dead end (or a new opportunity).
- Ballard has done a thorough job of exploring the potential of transition metal/chalcogen based catalysts.

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

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

- Significant progress was made during the past year, unfortunately this progress did not translate into a realistic fuel cell cathode electrocatalyst.
- Good characterization of materials, but very poor performance.
- Although well intentioned and well conducted, this project failed to meet its objectives and was voluntarily terminated by the company at a preplanned go/no-go decision point.
- Significant progress has been made toward physicochemical characterization of synthesized catalysts.
- Moderate progress toward overcoming DOE targets on catalytic activity and durability.
- Some progress in the realization the tungsten was not a viable approach and some decent results using the nickel.
- Not totally clear why these materials were chosen over others and if the risks associated with the research would have been materially different with another approach. In other words, if you had it to do over again, would you take the same approach.
- Project added substantially to our understanding of this class of catalysts.
- Unfortunately, due to intrinsic properties of the materials, targets A (durability), B (cost) and C (performance) have not been achieved.
- Showed a lot of different materials and dopants both for thin films and powders. I was, however, left wondering whether all ideas for using these materials as catalysts have been exhausted. Really need to start thinking in terms of where a particular non-Pt group catalyst needs to get to in terms of performance, then look back and see whether any realistic pathways to get there seem possible. One way is to quantify the theoretical number of active sites.

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

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

- The University of British Columbia and Case Western Reserve University were listed as partners, but it was unclear what their contributions were.
- Good interactions with UBC and Case Western.
- Although these catalysts ultimately proved unsuitable for fuel-cell application, the project generated data on transition metal/chalcogen catalysts that might prove valuable in the future. The PI is encouraged to publish the data generated by this research in the open literature.
- No mention of specific activity from Case Western or UBC but backup slides do indicate that some level of resources were used.
- It is typically a good idea to specifically point out university and national lab collaborations during the presentations since other companies may benefit from being able to build on the research with them.
- Need more, though. I would like to see a Gordon Conference type workshop on non-precious metal catalysts for fuel cell applications, with participants including Prof. Jean-Pol Dodelet (INRS-Canada), Dr. Popov (Univ. South Carolina), Dr. Campbell (Ballard), Dr. Alan Hay (McGill), Zelenay (LANL) and Dr. Atanasoski (3M) at a minimum.

Question 5: Approach to and relevance of proposed future research

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

- Many people will attempt to keep a project going at all costs even if not in the best interest of the program overall.

Strengths and weaknesses**Strengths**

- Excellent capabilities and knowledgeable PI.
- A promising class of catalysts was explored.
- Excellent spectroscopic characterization strategy.
- Systematic approach with good eye on go/no-go decision.
- The project generated interesting material-science data on metal/chalcogen catalysts.
- Strong combination of electrochemical and physicochemical characterization.
- Good detailed investigations of the materials chosen for evaluation with complete testing even in the face of likely negative results.
- Test results were clearly shown with corresponding good data and there were no attempts at enhancing the data to make them appear better than they were.
- Very honest review and willingness to say that the research did not work out.
- Good team, with contributors from both the materials fundamentals aspects (university) and developer/implementer (Ballard). Need both to fully exhaust the possibilities of a given class of potential catalysts.

Weaknesses

- The synthesis of high surface area catalysts should have been performed in parallel with the sputtered electrodes to speed up the development of catalysts.
- Disappointing progress, but researchers acknowledged this and appropriately chose not to continue.
- The project did not meet its objectives and was voluntarily terminated.
- RRDE measurements were not performed which does not allow making any conclusions about peroxide formation during oxygen reduction reaction.
- There is no clear interpretation the difference in electrochemical behavior of sputtered films and powders.
- There is no interpretation of changing OCP after cycling potential to 1.4V.
- Nature of active sites is unclear.
- It seems like some of the issues encountered like the ability to react the metals with H₂S could have been known a little sooner and perhaps there would have been a chance to alter the scope of the project and achieve different results.

Specific recommendations and additions or deletions to the work scope

- Not applicable, project is ending.
- None.
- DOE should consider a follow-on solicitation for non-Pt catalysts. Would also need a workshop to define the focus areas.
- I would encourage on all these non-Pt catalyst projects to show results in terms of activity per site and site density (sites/cm³). Product of these two is A/cm³ and the target should be 130 A/cm³. See Gasteiger et al. for details [Appl. Cat. B 2004]. Without a standard basis for comparison across materials families, I cannot tell easily which ones show the greatest promise.

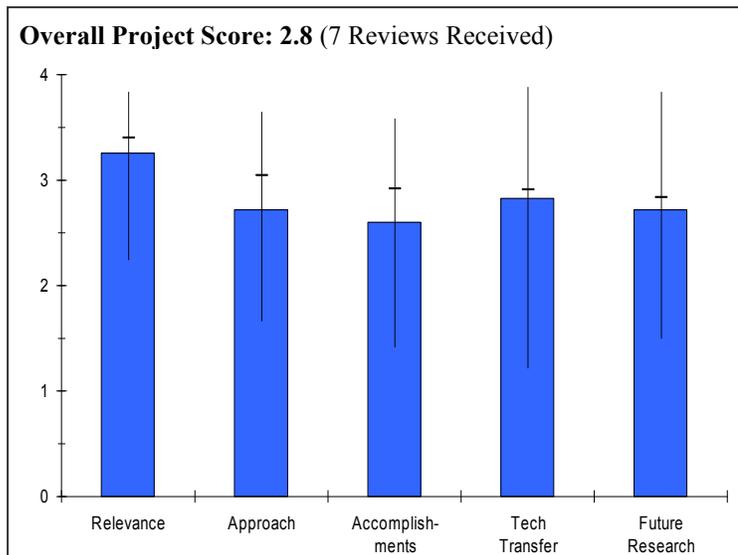
Project # FC-07: Applied Science for Electrode Performance, Cost, and Durability

Bryan Pivovar; LANL

Brief Summary of Project

The objective of this project is to assist the DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program in meeting cost, durability and performance targets by addressing issues directly associated with electrodes. The objectives for FY 2007 for this project are to 1) model oxygen reduction reaction (ORR) using reactive adsorption mechanism; 2) use micro-electrodes and interdigitated microarrays to study ORR and peroxide generation; and 3) to elucidate catalyst utilization and durability of electrodes.

Question 1: Relevance to overall DOE objectives



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

- Maximizing electrode performance, especially the efficiency of the ORR reaction, is crucial for future commercialization of PEMFCs to achieve the necessary power densities.
- Understanding degradation mechanisms and developing countermeasures is also crucial for future commercialization of PEMFCs to achieve the necessary lifetimes.
- This effort is well aligned with the goals and objectives of the overall DOE program.
- The title suggests the work is directed at the top three barriers. The project's focus on understanding better the utilization of dispersed, carbon supported catalysts, however, will only partially support the Hydrogen Vision and DOE R&D objectives, even if successful in finding a way to improve this quantity in a particular way.
- There is much disagreement in the literature as to whether catalyst utilization is as low as suggested by the findings of this work. Major organizations would believe it is at least 80%.
- Carbon-based supports are increasingly being proven not to have adequate corrosion resistance for the durability and tolerance of off-nominal operating events that are characteristic of real life automotive environments.
- The work on understanding ionomer/catalyst interface effects could be of more value.
- Good project that takes a systematic view and is generating some interesting results which may lead to relatively easy improvements (i.e., increasing catalyst utilization is probably easier than developing new ORR catalysts).
- Not clear how this is distinct from other efforts to understand MEA and electrode issues.
- Improvement of Pt catalyst utilization in the electrode is imperative to achieve the fuel cell cost target.
- As for durability, the technical problem is not well defined. Why was hydrogen peroxide formation prioritized?
- Understanding the kinetics of ORR and understanding whether Pt is utilized is crucial to lowering Pt loading and meeting the DOE cost targets.
- Proper measurement techniques for identifying degradation – including measurement techniques – are necessary for meeting component durability targets.
- Peroxide generation is immediately germane to all efforts devoted to extending membrane lifetime.

Question 2: Approach to performing the research and development

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

- The PI does not define the specific research topics in a clear and concise manner.

- The PI should clearly state the research topic with target values/results, define the research program to investigate the research topic and provide the current status vs. the target values.
- Lacking direction and focus on key topics – random research attempts on many topics.
- Approach is OK but it would be good to couple this with additional microscopy.
- Such materials changes with time are critical to understand – but, there is more to it than just knowing whether a catalyst particle is in ionic contact. Must also know what the activation energy is for moving a proton from the membrane to the ionomer in the electrode.
- Should focus on ionic transport within the electrode layer to the point where it is understood as a function of water, gas flow rates, current density, etc.
- Optimization of inks and electrode structure is very dependent on the materials and processes used for manufacture, and as such, it is unlikely that this project's use of a 20 wt% ETEK catalyst and their own LANL recipe for making inks will translate to the materials and processes used in MEAs manufactured at volume.
- The use of carbon blacks as catalyst supports should be recognized by this group as fatally flawed and will not be part of the solution in the future and therefore any findings has low probability of translating to help overcome the durability barrier.
- Their very important slide showing how the measured catalyst surface area progressively decreased as the process for forming the electrodes advanced is a clear sign that there are too many variables and process parameters for this project to really discover something fundamentally useful for ink formation.
- Their micro-electrode studies of potential ionomer reorganization at the interface with the Pt catalyst are exciting, (sounds like a potentially fundamentally important phenomenon that has not been appreciated before.)
- The examination of surface area with process treatments is interesting and may lead to novel MEA processes that improve catalyst utilization.
- Lots of little individual but related projects.
- Never connect the dots to address overall electrode issues that are the stated objective.
- More systematic approach is necessary to identify sensitive factors (e.g., operating conditions) with respect to hydrogen peroxide formation.
- Need to identify fuel cell failure mode mechanism led by hydrogen peroxide formation and discuss design and material criticalities to prevent failure modes.
- Need more discussion whether ECSA data can be compared among different measurements. And it is imperative to conclude potential of catalyst utilization (room for improvement).
- The probe into defining the true active surface area of an electrode is the most compelling aspect of this work and it deserves a resolution with some degree of finality and industry-wide acceptance.
- The use of hydrogen sulfide for surface area measurements is creative and enlightening, although a possible nightmare to the more timid safety administrators.
- The use of materials that were more prevalent five years ago (e.g. 20% Pt/C) is a drawback.
- The possibility of hydrogen evolution during hydrogen adsorption measurements should be confirmed to be non-existent.
- Interdigitated arrays helpful for describing the electrochemical peroxide formation.

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

This project was rated **2.6** based on accomplishments.

- Due to the poorly defined research topics, it is hard to gauge the status of the program.
- From what can be understood, the results thus far are good with a potential of high value and content.
- Accomplishments have been moderate in the last year.
- Follows the ORNL concept – need to understand if and how the proton moves within this layer.
- New understandings of the interactions amongst the critical parameters must be focused on and all as a function of the typical environments found within the electrode.
- Differences between the anode and cathode?
- The investigation of ionomer reorganization at the Pt interface is potentially very important, and should be pursued for different catalysts/ionomer structures and conditions.
- Appears to be not particularly impressive for the budget, although this may be more a limitation of the short presentation time at the review.

- All studies cited to indicate Nafion reorganization involve indirect assessment of this phenomenon. Not convincing that this is the mechanism.
- Lots of individual tidbits of knowledge, but not clear how it all comes together to improve electrode performance.
- Well-established measurements.
- At present, the project asks more questions than it answers. Although most researchers have had doubts regarding their electrochemically active surface area measurement techniques, they now have more. If CO stripping or other electrochemical methods are no good, what is? The hydrogen sulfide technique is not meant for *in situ* tests, but yet, surface area measurements are a common metric in accelerated stress tests. If surface area measurements are inaccurate, then why? How might we distinguish area lost by lack of electronic contact from that lost by lack of protonic contact?
- Trends shown with surface area loss throughout the ink and MEA fabrication processes have merit.
- Trends shown with peroxide formation against increasing RH and temperature have merit.

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

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

- High level of collaboration with various universities and national laboratories that are providing very useful insight.
- Lack of a clearly defined program indicates interaction with industry is lacking – while the PI mentions interaction with an OEM, it should be formalized to provide structure to the program.
- Collaborative efforts are good.
- Data is well disseminated to the community as a whole.
- Further interaction with industry would help to select materials better and identify more basic research topics.
- Appears to be minimal (to date), with the exception of the modeling work.
- Any MEA suppliers being consulted?
- Three collaborators listed, but only contribution of ORNL apparent.
- Only seem to be aware of/influenced by what has been previously done at LANL.
- Good interactions for HRTEM and other analysis.
- The ORNL collaboration appeared in the presentation to be more useful for supporting arguments, rather than as part of a proactive development effort.
- The collaboration with Brookhaven to find that PtOH is a dominant surface species is excellent.
- The CWRU collaboration did not have much impact.
- There is still no clear evidence of industry collaboration.

Question 5: Approach to and relevance of proposed future research

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

- The proposed research to improve the structure of the cathode electrode is poorly defined and difficult to gauge.
- Unclear if the optimization of the electrode structure has already been maximized through empirical research – the PI does not prove it is not.
- Stay the course and continue trying to resolve and answer the questions regarding ionomer-catalyst particles and the impact of electrode architecture.
- I expect greater depth of science from the National Labs.
- Further work on trying to optimize catalyst utilization of the electrode inks should be discontinued because it is not fundamental enough, i.e., it is too process and material dependent and best left to the large scale MEA manufacturers.
- Accelerated studies of the catalyst/ionomer interface should be considered, and include new catalyst structures, not just carbon supported Pt, but alloys and thin film forms of catalysts, to understand how it might influence charge transfer and catalyst surface structure.
- Good plan.
- Proposed kinetic studies are nothing new – what's unique here?

- Lacks scientific/technical basis for how they will correlate performance and structure.
- Lacks systematic approach to identifying characterization methods to develop for future insight – just keep trying things and see what works.
- Not so clear for approach of kinetics study, recommend incorporate modeling approach (e.g., molecular dynamics) to empirical approach.
- Focus on interface of coupling performance is good and useful outcomes are expected.
- The future work indicated is going exactly the direction it should. Catalyst accessibility must be increased.
- Decoupling of electronic and protonic conductivity losses must be approached in the future.

Strengths and weaknesses

Strengths

- Scientific ability of the PI and various collaborators is quite high.
- Understanding and maximizing the electrode structure could provide great improvements in power density values.
- Talented team.
- Resources are well utilized and are excellent.
- Taking a systematic approach to understanding what limits performance (and durability, presumably eventually).
- Empirical approach and measurement tool availability.
- Database development.
- Understanding of technical problems.
- The project demonstrates understanding of crucial electrode issues.
- Creative techniques are used to probe electrode issues (iterative deepening depth-first search algorithm, hydrogen sulfide surface area measurements).
- Reporting of trends involving hydrogen peroxide formation and surface area loss with processing.
- Mathematical modeling with Brookhaven NL.

Weaknesses

- Significant lack of high level project management – research is random and unorganized.
- PI did not sufficiently demonstrate that the work has not already been completed.
- Team seems to be limited in thinking to conventional electrode dynamics.
- Need to concentrate on the evaluation and the science of the interface and electrode layer as to how it impacts the electrocatalytic activity and proton conductivity within this later.
- Appear not to be working with state-of-the-art catalysts (20% Pt on C)?
- Random collection of experiments with no rationale for why they are the critical experiments or best technique.
- Survey of surface area measurements, but appears that they did "what worked for them." No justification for why their surface area number is good – where's the corroborating evidence?
- Systematic approach to identify factors to affect on technical problems.
- Unanswered questions still remaining regarding electrode surface area measurements.
- The project is now in a position where some *in situ* experimental technique must be endorsed for electrode surface area measurements (even if its weaknesses must be acknowledged).
- Lack of industry collaboration.

Specific recommendations and additions or deletions to the work scope

- Focus on key topics with a clear definition of targets and research pathway.
- None specifically except for the comments above about the evaluation of the electrode proton transport dynamics in greater detail.
- May want to consider consulting with MEA suppliers to ensure that their assumptions about state-of-the-art MEA processing are correct.
- Use higher wt % of Pt (or Pt alloy) on C.
- After gaining insight into the catalyst utilization and developing some improvements, look at effect on durability, including degradation of the carbon (as well as the catalyst surface area).

FUEL CELLS

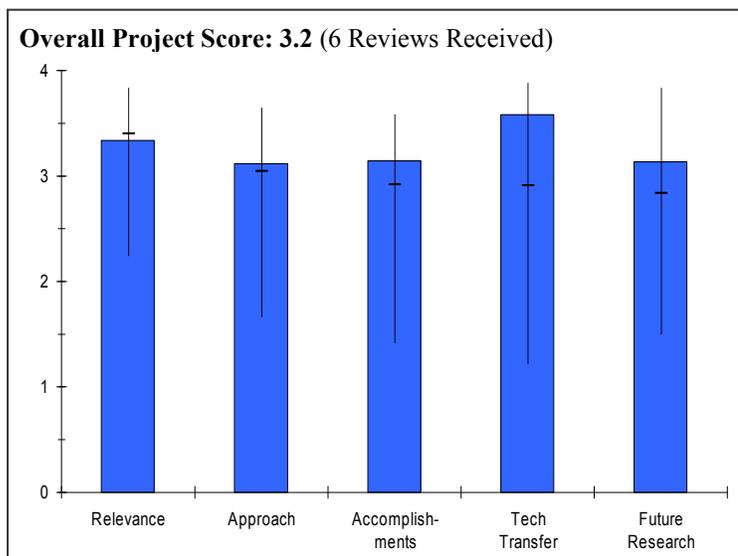
- Need to apply and correlate additional characterization techniques to determine whether Nafion reorganization is the appropriate mechanism and to determine how to influence the interactions at a molecular level to improve performance.
- For durability study, pursue the sensitivity measurement to identify factors that affect fuel cell failure before focusing on specific factors.
- Theoretical consideration is necessary to identify improvement room for catalyst utilization.
- The bonding of electrodes to the membrane should be considered for the project scope.
- General Motors has shown work indicating that the structural integrity of the catalyst layer has effects on membrane degradation. Los Alamos could pick up this effort and create a publicly accessible knowledge base on the issue.

Project # FC-08: Development of Polybenzimidazole-based High Temperature Membrane and Electrode Assemblies for Stationary Applications

John Vogel; Plug Power

Brief Summary of Project

The objective of this project is to identify and demonstrate a membrane electrode assembly (MEA) based on a high-temperature polybenzimidazole membrane that can achieve the performance, durability and cost targets required for stationary fuel cell applications. The membrane objectives for FY 2007 for this project are to 1) formulate and characterize polymers; 2) improve membrane mechanical stability; and 3) scale up process and fabricate full size MEAs. The MEA objectives for FY 2007 for this project are to 1) conduct 50 cm² screening tests at RPI; 2) conduct parametric tests to characterize fully MEA performance; and 3) assemble and test a full size short stack. The stack objectives for FY 2007 for this project are to 1) characterize acid-absorbing materials; 2) optimize flow fields and sealing; 3) develop novel electrodes using nanotechnology; and 4) perform cost assessment.



Question 1: Relevance to overall DOE objectives

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

- High temperature stationary stack operation is of high value for the consumer and the nation's energy security.
- The pursuit of stationary applications is in line with the Hydrogen Fuel Initiative, although not as critical for U.S. energy security as transportation.
- Development of a stack for high temperature and dry operation for stationary applications.
- This project is relevant because it is exploring the pitfalls and problems involved in taking the final and usually the most frustrating last steps to a commercial product. Such work, although often seen as work that industry should perform, is necessary to be done in the DOE program, as it provides useful lessons as to how single cell experiments translate into full stack deployment. A weakness of the presentation is that not much detail is provided on what these issues are. More detail on modeling of the stack would have been helpful to aid the DOE's goals.
- The project is clearly focused on a specific approach to meet the DOE stationary fuel cell durability goals.
- Project aligns well to goals of reducing manufacturing costs and improving durability.

Question 2: Approach to performing the research and development

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

- Not giving the initial specifications to BASF slowed down the program.
- Overall approach is high with well-defined and clear goals and targets.
- This is a development effort with little research. Tolerances, specifications and lifetime studies are necessary for commercial implementation.
- Graphitic carbon plates. Pt alloy catalyst. Eliminate low MW PBI. Oversized acid trap.
- Burner to eliminate condensation during start up/shut down.
- Approach to this project is good. The program description appears to cover all the necessary factors for successful completion of the program.

- This approach with high temperature PBI/PA is currently the only alternative to low temperature PEM systems and, as such, is good to explore for its effectiveness in this application.
- The approach to develop this technology in a manufacturing facility is good because it clearly shows the issues with integration of MEA and stacks.
- Technical approach is focused on overcoming barriers.

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

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

- Durability targets are increasing through membrane, GDL and system design.
- Current densities are still low – unclear how high they will eventually be and whether or not they will achieve a level for commercial success.
- Most of the effort has been focused on tolerance issues with GDLs and getting results to agree with BASF and RPI. Acid migration and trap work is also necessary as well as tradeoffs of temperature studies, but less was accomplished than I would have expected with too much effort just coordinating results.
- 2 MEA failure modes identified – BASF cannot meet specifications on MEA tolerance.
- 10,000 hrs before acid breakthrough.
- Projected 14,000 hrs stack life.
- Generally good progress in most areas. However, there is some concern about the durability and failure. The stacks are failing at fairly short lifetimes relative to the target 40,000 hours and no real cause or plan to discover the cause is outlined. This reviewer does not see how the durability goal will be achieved from this effort.
- Good rate of progress over past year, however, one wonders why the Nafion/PBI mind-set change took so long to be realized, since many of the same issues of compression control, catalyst degradation, etc. are practiced in their low temperature PEM systems.
- Project is nearing completion on accomplishing planned activities and through funding.

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

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

- Technical transfer is high – unclear what the relationship is between RPI and BASF.
- Higher interaction with BASF and Plug will be needed to prevent further slow downs of the program
- Strong collaboration involving people who will likely be responsible for commercialization of this technology, including BASF Fuel Cell, RPI, Albany Nano Tech, Entegris, and University of South Carolina.
- Good to excellent. The RPI work is excellent and the tech transfer issues have been instructive.
- It would seem the past year has been successful in resolving a number of unexpected issues.
- Appears to be good collaboration with BASF and RPI.

Question 5: Approach to and relevance of proposed future research

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

- Program is almost complete with good success.
- Further membrane/MEA/system optimization will be needed to achieve durability and performance targets – seems to approach with good concepts.
- Project is finishing. No plans for future are given, particularly how to meet the 40,000 hour goal.
- The plans are logical and necessary to fulfill the contract.
- Multiple tasks for 2007 will complete project.
- Need to get MEA cost estimates.

Strengths and weaknesses**Strengths**

- Unique technology to Plug, BASF and RPI with the technical leaders in this field.
- General program management appears to be strong.
- Real data and functioning systems.
- Very impressive reduction to practice of a new material.
- Funding should lead to commercialization of technology.
- Excellent demonstration of development problems and how the last few issues could cause a project to fail. The project shows good progress to deal with this.
- It would seem to be the only feasible approach currently known to make a high temperature PEM fuel cell (> 130°C).
- Good record of accomplishment of tasks as project nears completion.

Weaknesses

- Increase communications between Plug Power and BASF to prevent future slow downs of the program.
- Unclear if this technology can achieve the power densities needed for commercialization.
- Unclear if this technology can achieve the cost targets needed for commercialization (low power density will increase the stack cost due to a higher number of repeating units).
- Too much wheel spinning to baseline results between different organizations.
- BASF MEA needs improved manufacturing.
- Project is finishing and future planning not spelled out. Also some of the durability issues do not appear to be understood.
- The market requirements for cost, system volume and complexity may be difficult to meet.
- Still no MEA cost information.

Specific recommendations and additions or deletions to the work scope

- Cost predictions for MEA and system are vital – if predictions cannot achieve target values, the need of this program decreases significantly.
- Project concluding.
- Excellent work.

Project # FC-09: Development of a Low-Cost, Durable Membrane and MEA for Stationary and Mobile Fuel Cell Applications

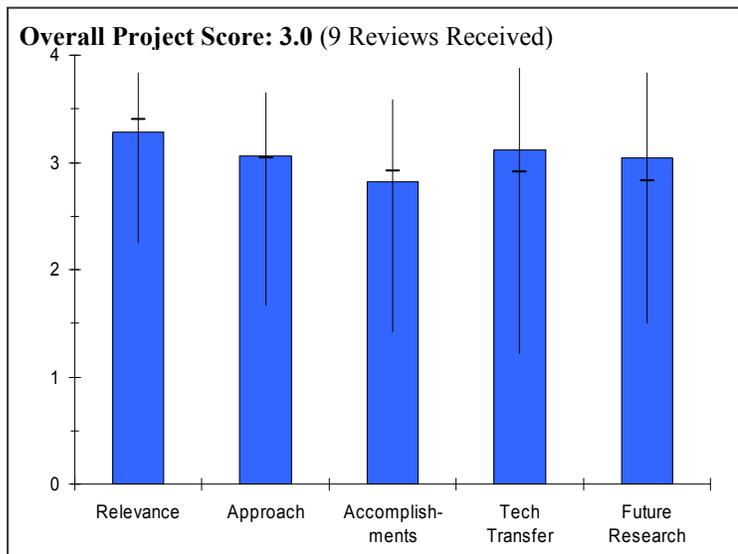
Jung Yi; Arkema Chemicals

Brief Summary of Project

The objective of this project is to develop low-cost and durable membrane and a membrane electrode assembly (MEA) that can meet DOE targets and help drive the commercial reality of fuel cells. The objectives for FY 2007 for this project are 1) the development and characterization of new-generation membranes; 2) MEA optimization; and 3) durability testing of the membrane in fuel cells.

Question 1: Relevance to overall DOE objectives

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



- The need for increased durability in membranes exists. Membrane cost is not a critical issue for fuel cell commercialization.
- Low cost, high performance membrane electrolytes are an enabling technology.
- This project is aligned with DOE objectives.
- Membranes for multiple applications within program.
- Contributes clearly and strongly to DOE energy independence goals.
- Very limited relevance to DOE Hydrogen goals since the demonstrated technology is coal-to-power.
- Unique approach to lower membrane cost in theory. Need to understand relative costs of full fluorination vs. modifications to make PVDF more chemically stable.
- This project addresses a critical need for fuel cell components.
- Important to go down in cost, but no data shown how to achieve the goal.
- Barriers are consistent with DOE goals.
- Relevant.

Question 2: Approach to performing the research and development

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

- Blended membranes have not been as widely pursued as other techniques. PVDF is a known stable, relatively low cost polymer.
- Blended membranes have notoriously poor durability because the driving force for phase separation is large. The lack of any long term morphology characterization or long term performance data is a serious shortcoming.
- More fuel cell data (not just initial performance and OCV tests) need to be presented.
- Decoupling the mechanical and conductivity properties of the membrane through blending of the structural polymer and the polyelectrolyte is an excellent approach which can potentially eliminate the inevitable trade-off between these properties in homogeneous materials.
- Hydrocarbon-based polyelectrolyte may be susceptible to degradation in the extremely oxidizing and acidic environment of the fuel cell.
- The proposed methodology to performing the research work is satisfactory.
- Good mix of materials selection testing and cell-level testing
- Data indicates good performance.
- High-temperature excursions should be at low-RH, not high-RH to mimic real fuel cell operating conditions.

- The approach of an ionomer/Kynar blend may be considered as a way to develop a "reinforced membrane", so the improvement in mechanical properties should probably be compared to a Gore membrane rather than Nafion.
- How much effort or opportunity is there to improve the properties of the polyelectrolyte? What are its fundamental advantages or disadvantages over a PFSA?
- The new generation M41 shows less sulfur loss (but no information how it was achieved).
- Good approach to use composite materials.
- Clear approach to get cost down by using hydrocarbon electrolyte and cheap reinforcement material.
- The PI should comment on compatibility between polyelectrolyte in membrane and electrode.
- H₂/air performance should be tested.
- The ex-situ and *in situ* resistances should be measured at the same conditions!
- The high-temperature excursion test has saturator dew point larger than cell temperature – condensation can occur.
- No low RH measurements → should be remedied → cycling needed.
- Swelling not reported → why? → dimensional stability is key.

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

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

- While there is some interesting data, the focus on only OCV and beginning of life tests is a significant weakness for a project focusing on cost and durability. OCV is only a measure of oxygen crossover and peroxide degradation and means nothing for other degradation mechanisms. The lack of lifetime fuel cell data is disappointing.
- High water uptake of these materials also leads to concerns with mechanical robustness.
- Excellent progress in improving the sulfur loss rate and the fuel cell performance from M31 to M41.
- Despite progress, sulfur loss is still high compared to Nafion.
- Substantial improvements since last year.
- Improvement on durability.
- New membranes have been developed/characterized and scaled up.
- MEAs have been optimized and fuel cell testing performed.
- Better mechanical properties and gas permeation than Nafion but lower conductivity.
- Nice adaptation to challenges around interconnect technology.
- Selection of anode catalyst seems to be successful.
- Need to provide information about cost projections (B. Cost Target is critical to program).
- Would like more information about implications of greater swelling in XY direction relative to MEA and seal design.
- Gas barrier properties are very interesting. Would like to compare H₂ to O₂ crossover for understanding of peroxide.
- Chemical stability data is compelling. Why are C-H bonds less susceptible than C-F bonds in Nafion?
- One might have expected the mechanical property improvements over Nafion 111 to have been greater.
- The durability test results look very promising.
- The electrode shorting issues alluded to in the slide on OCV durability testing is a concern since it could compromise the durability tests for both the Nafion controls as well as the project's membrane.
- The source of the electrode roughness should have been addressed in the MEA integration stage.
- What is known about their polyelectrolyte? How different is this from Nafion or standard PFSA?
- Good progress in decreased sulfur loss and achieving therefore a good longevity (even though it was not told how they achieved it).
- The PI should provide polarization data based on H₂/air and not H₂/O₂.
- The drop in performance over 8 hrs at high temperature (high RH) is a matter of concern.
- The PI should provide low RH data → cycling.

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

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

- The team has too little fuel cell experience, and perhaps this is why there have been so few meaningful fuel cell studies reported. No RH cycling, no lifetime performance.
- UTC inclusion on team is beneficial, however it appears that UTC has not been involved in the project up to this point and the project is ending in one month.
- The roles and contributions of the other team members were not clearly stated in the presentation.
- Good collaboration with other entities.
- Universities – Georgia Tech, University of Hawaii.
- Johnson Matthey Fuel Cells.
- No outside collaboration is apparent. Not clear that this impacts achievement of goals.
- Work with material suppliers could speed results.
- Good collaboration with developers at various stages of process (membrane, MEA, stack).
- Would like more information about MEA optimization for different membrane properties.
- Very good selection on industrial participants: Membrane and catalyst manufacturer as well as system integrator.
- Good collaboration.
- Role of Georgia Tech unclear.

Question 5: Approach to and relevance of proposed future research

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

- Project concluding.
- The project in its current form is ending and there are many tasks to complete in the very short length of time remaining in the project.
- The proposed plans are consistent.
- Complete durability testing.
- Larger scale fuel cell testing.
- New polyelectrolytes.
- Good cell testing will be critical information.
- Investigation to understand how PVDF can manage similar/better chemical stability in polymer backbone would be critical to understanding not only of this polymer but also other alternative membranes.
- Completing the stack testing at UTC, if it uses their water transport plate system, will prove performance and durability under fully humidified conditions, but not hotter, drier conditions.
- Wants to show lower RH measurements and different load cycling: important.
- RH cycling → step in right direction.
- No comments on dimensional stability → why?
- Lowering of OCV during accelerated testing not addressed → should be.

Strengths and weaknesses**Strengths**

- Cheap materials that if stable could find a use in fuel cells.
- Decoupling of the roles of various components of the membrane to optimize mechanical and conductivity properties independent of each other.
- Innovative approach to material development by decoupling mechanical and ionic conductivity properties.
- M31 and M41 have lower cost approach compared to Nafion.
- Kynar technology.
- Good collaborators.
- Good selection of material for anode and interconnect to address challenging operating conditions (carbon, sulfur).

- Nice use of testing to validate material selection.
- Good results (performance, durability).
- Thorough measurements of physical properties.
- Strong technology company with good conceptual approach.
- Variety of polyelectrolytes.
- Chemical stability of membrane seems to be good.
- This membrane leads to better water management.

Weaknesses

- No useful data for true evaluation of these materials given. I feel certain that lifetime data must have been taken with these materials and is not reported perhaps due to performance. I'd feel much more comfortable seeing this poor performance and having it correlated with morphology problems than having it completely deleted. Some concerns with temperature stability of these blends might be expected and nothing on this topic has been presented either.
- Degradation of electrode was observed with high temperature cycling. If this effect is due to degradation of the ionomer in the electrocatalyst layer, then developmental effort should focus on improving the stability of this ionomer.
- Swelling is slightly worse than Nafion, and since swelling is linked to degradation, it might have a negative effect on membrane durability.
- Really does not push the envelope in terms of proton conductivity for hotter/drier operation.
- At this point, little advantage over other reinforced membrane technology.
- Collaboration with suppliers and stack integrators could be useful for dissemination of results.
- High-temperature excursions are not realistic at high RH.
- Need to understand fundamentals better, e.g., why the PVDF backbone is stable.
- MEA integration appears to not be emphasized sufficiently.
- Project does not appear to have had a facet dealing with the optimization of the polyelectrolyte.
- No data with air.
- Accelerated tests not comparable to tests done in other projects.
- Unclear how using PVDF as a base will reduce costs considerably.
- Despite chemical stability, durability appears to be suspect as seen from OCV drop.

Specific recommendations and additions or deletions to the work scope

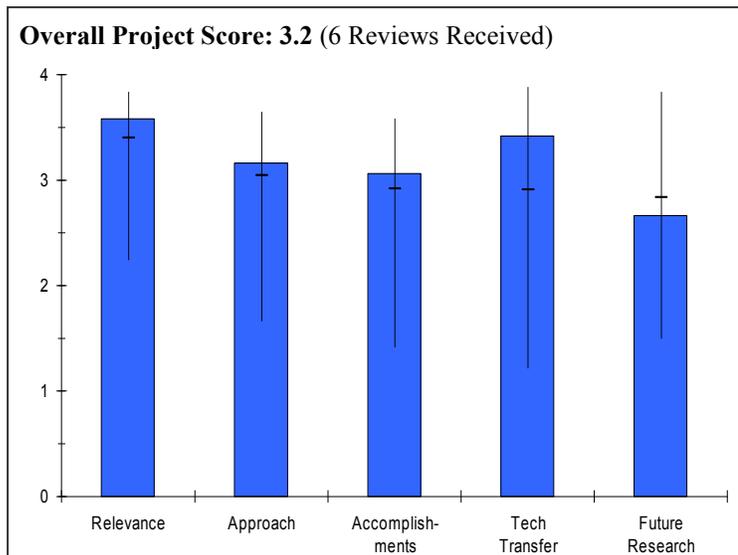
- Project is concluding, but follow-on projects should report more structural characterization, particularly as a function of time in these systems. Lifetime data needs to be presented from fuel cell tests.
- This project is ending in June 2007. Suggestions for the new project are to improve the high temperature stability of the electrode layers and to test the conductivity/performance under low relative humidity, low temperature, conditions and after low temperature cycling.
- Long-term testing higher than 400 hours should be performed.
- Hydrogen-air testing should also be performed.
- Performance tests at low temperatures should be carried out.
- Cost targets should be addressed.
- Arkema should be much more adventurous in their ionomer discovery program.
- The PVDF blend approach is demonstrated but is not useful unless they can improve the conductivity of their materials under hot and dry conditions.
- Need to keep ultimate goal of stack development in focus.
- More fundamental investigations/collaborations with academia to characterize.
- Testing under low-temperature/subfreezing conditions.
- Clarify the uniqueness or advantages of their Arkema polyelectrolyte over more standard ionomers, that is, are there properties that can be improved with this component?
- Include swelling measurements.
- Include H₂/air data reporting (this is a must).

Project # FC-10: MEA and Stack Durability for PEM Fuel Cells

Mike Yandrasits; 3M

Brief Summary of Project

The objective of this project is to develop a pathway/technology for stationary proton exchange membrane (PEM) fuel cell systems to meet the DOE’s 2011 objective of 40,000 hour system lifetime. The project goals consist of developing a membrane electrode assembly (MEA) and system with enhanced durability that is 1) manufacturable in a high volume process; 2) capable of meeting market required targets for lifetime and cost; 3) optimized for field ready systems; and 4) capable of a 2,000 hour system demonstration. The focus for fiscal year 2007 for this project are 1) MEA characterization and diagnostics; 2) MEA component development; 3) MEA degradation mechanisms; 4) MEA nonuniformity studies; 5) hydrogen peroxide model; 6) defining system operating window; 7) MEA and component accelerated tests; 8) MEA lifetime analysis; 9) stack testing with intermediate developments; and 10) final stack demonstration.



Question 1: Relevance to overall DOE objectives

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

- The program concept is quite relevant and will add to the overall understanding of the critical issues faced by stack developers and systems integrators today.
- The project focuses on durability (40,000 hours) and is in line with the DOE program objectives.
- Durability of fuel cells is a critical barrier, and thus this project is highly relevant.
- Important contribution to durability goals.
- Still no progress on evaluating cost impact, despite reviewer's comments from last year. No data presented to evaluate if this contributes or detracts from cost reduction goals.
- Project focuses on important durability issues. It demonstrates an excellent mix of fundamental science and empirical data collecting and handling in order to predict lifetime. This is critical for DOE to achieve its goals.
- Durability has evolved to be major deterrent to both successful vehicle and stationary fuel cell systems.
- It is very important to the program to have competent and well-equipped researchers like 3M and their partners putting serious efforts into improving durability.

Question 2: Approach to performing the research and development

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

- Approach is good yet it seems that too many tasks were signed up for and as the program ends this year, it would have been good to have seen selected tasks developed and the results "used" within this program.
- It is not clear what is driving the effort; is it the stack requirements, the system requirements from the end user, or is it the materials properties?
- Not clear what the stack design and capabilities are and which will impact the MEA – and as well, how the MEA dictates stack designs etc. and how all these are related in this program.
- The project has a good, balanced approach.
- The presented methodology addresses durability very thoroughly.

- Good use of the segmented cell as a diagnostic tool.
- Good use of fluoride ion mapping and membrane modeling to understand degradation modes and identify methods to improve lifetime.
- Good techniques for evaluating mechanism for peroxide degradation.
- Use of model compounds allows team to get a handle on degradation mechanisms and reactions.
- No evidence that capillarity modeling at Case was used in MEA design.
- Not clear from presentation how this work will impact pure H₂ vs. reformer systems.
- Approach is outstanding – chemical understanding, engineering and empirical lifetime predictions that take into account statistical variability. Would like more DOE projects to provide similar comprehensive coverage.
- The approaches for modeling membrane degradation, GDL characterization, and MEA non-uniformity studies appear well-thought out and effective.
- The approach for MEA lifetime modeling is very weak for many reasons, especially a) the combination of log-log plots is not likely to have any value outside the data range and b) with no transients included in the "lifetime" base data, the data (and resulting projections) would not be very robust..
- The testing approach of using only a series of steady-state load conditions is certainly questionable, at least for automotive applications. It is well known that start-ups, shutdowns, and transients dramatically affect durability.

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

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

- The accomplishments appear good but it was not easily discernable who was doing what or the significance of the findings. Also, did not see specific accomplishments from the various team members.
- Would like to have seen more data regarding the cell interactions from the segmented cell.
- Would like to have seen start-stops in the testing.
- Substantial progress on development of procedures to identifying membrane degradation mechanisms and operating strategies to minimize performance decay has been achieved.
- Progress on durability is good.
- The project has produced useful data on the various causes of membrane durability.
- Technical progress includes both improved components and improved operating conditions to extend lifetime.
- Segmented cell testing in a stack is coming late in the program. Reduces opportunity for learning and feedback to MEA design.
- Durability prediction equation software has not succeeded in making independent predictions. It only seems to work if "tweaked" by actual testing results. This will limit usefulness of equation.
- Final system goals remain to be completed. Some doubt about this. Otherwise everything is proceeding well.
- There has been important progress but possibly less than would be expected relative to the time (3.5 years) and funding.

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

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

- Good within the "team".
- Would like to see more information disseminated outside the group.
- Strong collaborative team.
- Excellent collaboration with industrial research partner and 3 universities.
- Good team including analytical, supplier and OEM/system test partners.
- Good evidence that university modeling and testing was translated into MEA design and into system testing.
- Excellent.
- There is a good distribution of strong partners indicated, but it wasn't clear from the presentation that all are fully involved.

Question 5: Approach to and relevance of proposed future research

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

- Program is ending.
- The proposed plan is adequate.
- The remaining portion of the project should focus on component improvements and completing the testing and post-test analysis, with lesser emphasis on modeling enhancement.
- Stack testing will proceed to failure.
- No clear plan for rectifying deficiencies in lifetime prediction modeling. If this only works when supported by test data, consideration should be given to stopping this effort now.
- No clear plan for integration of capillarity model into program goal of membrane durability.
- Incorporation of start/stop phenomena would make this more relevant to real world applicability. Constant power demonstration at system level is not realistic.
- Detailed future plans not given.
- There were no plans presented for efforts beyond the current contract (which is 90% done).

Strengths and weaknesses**Strengths**

- Excellent team.
- Tied to all elements of a "stack" (suppliers, developers, end-users).
- Life-time prediction modeling.
- Long-term testing up to 8000 hours is an interesting feature.
- Stack validation was performed in a system.
- Nicely integrated contributions from university, component and OEM participants.
- Good empirical results.
- Very strong project.
- A strong team of researchers covering a wide range of capabilities. They have completed some important activities.

Weaknesses

- Too many team members.
- Not sure what the contributions were from each team member (based on the funding of each).
- Too many tasks.
- Tests were performed at steady-state conditions (shut-downs were once per month). More realistic cycling profiles are necessary. Correlations should be established between current distribution and cell degradation.
- Predictive equations still do not contribute much value.
- Some university contributions appear not to be fully integrated – why are they continuing?
- No weaknesses.
- It isn't clear that all team members have been fully involved.
- As it is currently formulated, the final results will have only limited usefulness.
- No follow up, with appropriate direction changes, seems to be even proposed.

Specific recommendations and additions or deletions to the work scope

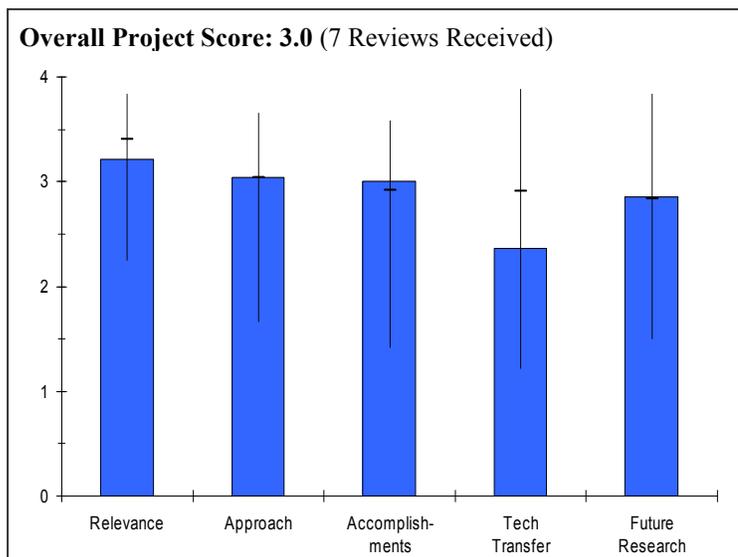
- Real life cycling tests are necessary (start/stop cycles).
- Need further project to develop in more detail the relationship of materials chemistry to failure modes and lifetime prediction.
- This project is near completion so it is too late for additions/deletions. However, a well-thought out (and redirected) follow-up program should be formulated and executed by a similar team.

Project # FC-11: Improved Membrane Materials for PEM Fuel Cell Applications

Robert Moore; U of So. Mississippi

Brief Summary of Project

The overall objective of this project is to ascertain and integrate critical structure-property information to develop methods that lead to significant improvements in the durability and performance of proton exchange membrane fuel cell (PEMFC) membrane materials. The specific objectives consist of 1) providing fundamental information regarding the origins of chemical and morphological degradation during accelerated chemical attack and PEMFC operation; 2) investigating the effect of modifications in membrane and membrane electrode assembly (MEA) processing parameters on performance and durability; 3) evaluating the role of controlled morphological features and reinforcing structures on membrane performance and durability; and 4) exploring the performance and durability of new hydrocarbon-based membrane materials as alternatives to the benchmark perfluorosulfonate ionomers. The objectives for FY 2007 for this project are investigations of membrane and MEA processing parameters on performance and chemical durability and the use of dielectric spectroscopy to probe molecular motions impacted by degradation.



Question 1: Relevance to overall DOE objectives

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

- Membrane durability and cost are key objectives of the Hydrogen Program.
- PI's project objectives are very well focused on providing an understanding of how morphological properties of membrane materials may be affected (improved/degraded) based on material processing and MEA fabrication conditions.
- It meets the DOE targets.
- In concept the project is relevant and can lead to a better understanding of the fundamental materials science of the key components of the MEA.
- Very relevant to commercialization of fuel cells with PFSA membranes for high temperature use.
- The work is generally relevant to the DOE effort to improve membrane durability and increase performance but the effort does not seem focused enough to result in a useful diagnostic by the end of the project.

Question 2: Approach to performing the research and development

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

- Need to demonstrate more clearly the relevance of the dielectric spectroscopy to the material properties and impact on Program and project objectives.
- Need to apply more diagnostics (e.g. conductivity measurement) to confirm and evaluate the changes that resulted from their annealing experiments.
- PI had clearly presented the connection between a material's morphological properties and fuel cell performance issues.

- Well organized approach, with initial emphasis on providing more (in-depth) insight for current membrane materials used today (and for the next 5-10 years), followed by a similar approach to examine new/alternative materials - relating physical properties to performance and durability.
- The presented methodology is satisfactory in meeting the objectives of the project.
- Approach is good as the techniques are useful in delineating elements of the fundamental polymer material science.
- The actual choice of materials, how they were processed and the tested could be re-evaluated to focus on membrane properties which relate to fuel cell conditions.
- Not sure the sol gel work should be part of this – focus on the polymer materials science!
- This has a very well thought out, systematic approach.
- The PI is a recognized expert in the field.
- Heat treatment studies on membrane are interesting and provide useful insight. Use of Si nanoparticles is poor idea. Si should never be added to any PEMFC membrane (hydration layer is small and it is highly soluble in acid environment).
- The approach is to develop methods to characterize the effects of degradation and to probe the origins of performance characteristics. There is some uncertainty regarding what actually is being studied by the dielectric spectroscopy (DS) method.
- The second approach is to modify Nafion membranes and MEAs by altering fabrication procedures, post-processing treatments, inorganic particle incorporation. The approach appears to be generally effective; however it is not clear how the knowledge gained in this study will be generally applicable to the community at large.

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

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

- The improvements in the polarization curve of the fuel cell with the annealed membrane are impressive, but also intriguing. The investigators should confirm with additional diagnostics.
- PI's accomplishments to date have included development of "screening tasks" needed for evaluating current and future membrane materials – and the relationship to fuel cell performance issues.
- The team appears to be meeting most of the current milestones.
- Accomplishments are just OK.
- There are many other questions and specific tests which should be performed and would be valuable in elucidating the polymer changes.
- The group must understand the membrane processing history as well, not just what they do to it.
- The assumption that melt-extruded film is the same as solution cast is not correct.
- Work describing changes in mechanical and chemical stability upon annealing is very good.
- This work provides a good, basic understanding of important properties of PFSA's.
- The results show that the acid form of the membrane degrades upon heating and becomes more susceptible to chemical attack. Fluoride release increases when the membrane is annealed above 200°C. This is not a favorable result.
- In the ionized form, the membrane appears not to degrade at elevated temperature.
- The DS technique can be used to characterize the relaxation of the polymer chains and determine the degree of shortening of the chains upon exposure to Fenton's reagent, potentially a valuable tool to determine the degree of degradation of a membrane.
- Hydrophilic silicate nanoparticles were incorporated into the polar domains of Nafion in the hope of creating hyperbranched structures with a large amount of open space and OH that will impart high-temperature water retention.

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

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

- There are no partners in the program. Membrane annealing results suggest they should have independent verification and further diagnostic application. Given they used NREL, why not DuPont?
- If the dielectric spectroscopy technique is indeed useful, there should be collaborations with other advanced membrane programs within the Program.
- PI and partner have consistently published their work, and routinely have made available their knowledge and expertise to others in the fuel cell program and industry.
- More links with other entities are needed.
- Acceptable.
- This project could benefit from collaboration with group with that can do more in-depth fuel cell evaluations.
- Collaborations need to be expanded especially in area of dielectric spectroscopy interpretation.
- The university is the only partner.

Question 5: Approach to and relevance of proposed future research

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

- There's a lot of "Future Work" listed for only 6 months remaining in the program. Needs focus?
- Recommend they measure the conductivity of the annealed NRE membrane and attempt to understand what change actually occurred that increased the polarization curve performance.
- Recommend applying FC Tech Team durability protocols including RH cycling accelerated durability test.
- Future work plan is very aggressive for the May to November 2007 time frame.
- Examine whether thermal annealing is sustainable during operational conditions.
- Conductivity values after annealing should be measured.
- Focus on the polymer as opposed to trying to develop additives which are not new and which have not been shown to yield results yet.
- Expand the approach and testing as a function of the new materials being developed by 3M, DuPont etc.
- Focus on what the membrane "sees" during actual fuel cell tests.
- It will be interesting to see this work expanded to hydrocarbon systems.
- Inorganic additives need to be rethought and approach modified.
- Synthesis of hydrocarbon-based PEM membranes is only partially completed but was not discussed.

Strengths and weaknesses

Strengths

- Comprehensive approach, from material properties to fabrication requirements and how these two parameters affect fuel cell performance.
- Introduced broadband dielectric spectroscopy techniques for assessing membrane materials.
- Thermal annealing.
- The development of characterization methods to evaluate the effects of degradation is promising.
- Good team and good resources. Good use of an under-utilized technique.
- This work provides a good, basic understanding of important properties of PFSA's and addresses important issues in fuel cell commercialization.
- Fundamental membrane studies are relevant and provide insight and when coupled with inorganic additives should lead to improved membranes.
- The DS technique appears to be able to determine the extent of degradation of fuel cell membranes.

Weaknesses

- Impact of thermal annealing should be further investigated.
- Don't try to score a home run with respect to the additive task. Focus on what you know best – elucidate the polymer dynamics first.
- There is no consensus on the relevance of dielectric spectroscopy or how to interpret what the spectra mean. Some thought needs to be given to determine the relevance or moving on to other analytical techniques. Si should never be added to any PEMFC membrane (hydration layer is small and it is highly soluble in acid environment). Idea of inorganic additives good, but execution needs to be rethought.

- It is not clear that heat treating membranes will lead to improved durability or performance. More work is required to sort this out.

Specific recommendations and additions or deletions to the work scope

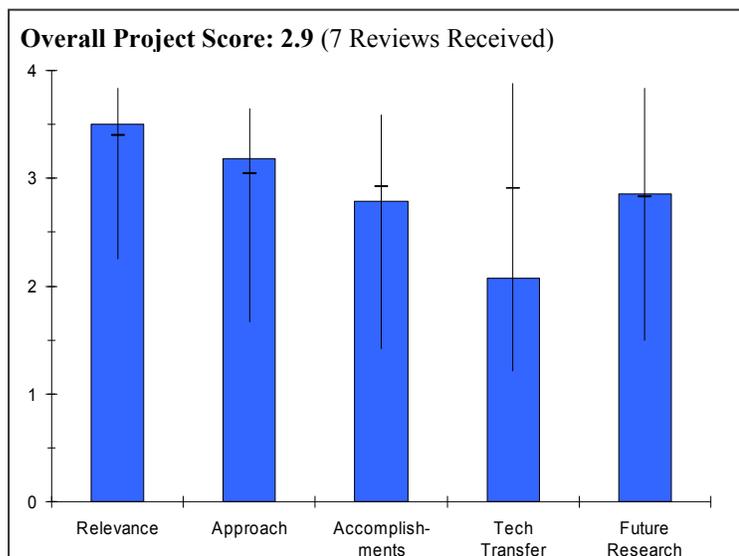
- The project scope may need to be re-assessed and reduced in scope, depending on the outcome of in progress investigations (i.e. "too successful").
- The project's duration (and funding) should be extended (increased) for the benefit of both industry and Hydrogen Program projects dependent on outputs from this project.
- Comparison of the current approach with existing results in literature should be performed.
- Ensure that the enhanced performance is not due to thickness reduction of the membrane.
- Add and enhance the tasks related to the techniques.
- It would be good to use gel permeation chromatography or another analytical technique to verify the theory that the MW is decreasing with degradation due to loss of small fragments.
- Add go/no go on dielectric spectroscopy.
- University of So. Mississippi should be encouraged to interact with membrane/MEA developers to explore the practical use and application of the DS technique.

Project # FC-12: Poly(p-phenylene Sulfonic Acid)s with Frozen-in Free Volume for Use in High Temperature Fuel Cells

Morton Litt; Case Western Reserve University

Brief Summary of Project

The issues addressed in this project are 1) molecular weight; 2) graft copolymer synthesis; 3) conductivity; 4) permeability; 5) acid loss; and 6) oxidative stability. Polymer synthesis work for fiscal year 2007 has reproduced earlier results but with low molecular weight. Li salts were found to be soluble in N-methylpyrrolidone and dimethylformamide. The polymer trimethyl benzyl ammonium salt is insoluble in NMP. Grafting work for FY 2007 produced a successful reaction but the mechanical properties were too poor to cast films. Comonomer synthesis for FY 2007 consisted of grafting biphenyl in high yield using mild conditions but have not yet grafted t-butyl or neopentyl substituted aromatic moieties without some scrambling.



Question 1: Relevance to overall DOE objectives

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

- The project is highly relevant to the DOE's objectives and to support the President's Hydrogen Fuel Initiative.
- Highly relevant to meeting DOE goals of enabling system simplification and cost reduction with low-RH membranes.
- Should be good means of introducing orthogonality to standard conductivity/solubility vs. EW trends.
- The target polymers intrinsically need water for conduction. This will require a large humidifier to maintain RH at 120°C. This does not address the long term problem. Is there any prospect of replacing water? The mechanism of water retention involves structures that limit the mechanical properties which will change with RH and temperature. This system is interesting scientifically but appears to lack robustness.
- Not entirely clear if these new types of membranes will meet cost targets (difficult synthesis with liquid crystalline polymers).
- Increasing operating temperature, especially for automotive application (cooling problems) and stationary application (CO poisoning), is addressed.
- Relevant.
- This work is highly relevant to the DOE technology goals. However, the goals were not clearly stated in the presentation and the presentation focused almost exclusively on the lower RH conductivity with dimensional stability, which is one key goal but other factors need to be considered and evaluated.

Question 2: Approach to performing the research and development

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

- The project is for 5 years. The project addresses polymer membrane electrolyte issue. The technical approach for the program is reasonable.
- Very interesting approach: creating structures that allow protonic transport even at lower relative humidities should allow for decoupling of equivalent weight and conductivity.
- Need to address solubility/decomposition in liquid water.

- The approach is sound. The investigator appears to have a good appreciation of the limitations inherent in the approach and is working around them.
- Other than the basic concept (e.g., copolymers with free volume), it is not clear what the approach is here.
- Good to start really at the basics for this new approach.
- Experienced, because of work done in 2002-2005.
- Through-plane conductivity should be reported especially if anisotropy is expected.
- Approach must be reevaluated if proper films cannot be formed.
- Nafion conductivity reported appears to be low . What temperature was it measured at?
- Agree with the general approach – novel polymers need to be developed. Believe this approach could be improved by defining progressive evaluation criteria beyond just *ex situ* RH/conductivity and dimensional stability. Recommend key project tasks should be stated and progress against such tasks highlighted (as in most other presentations)

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

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

- The project was started April 2006. It is too early to make a judgment for technical accomplishments at this time. So far, the project progress is good.
- Impressive results on conductivity.
- Need to see more exploration of robustness in liquid-water conditions.
- Progress is good for a first year project due to prior work. Expect more progress in next year as staff becomes more familiar with the materials.
- Progress in the last year is not particularly impressive.
- Progress is slow, but that might be due to delayed start of the project.
- Important to overcome brittleness problem to get stable membranes.
- Project is at initial stage, thus, progress to date is modest. Only a single conductivity measurement is shown.
- Much of data shown were not part of this project.
- Problems to be addressed were well described from a polymer perspective.
- The tracking of progress against technical targets is challenging due to the focus on novel polymer development. Recommend a progressive evaluation of these materials against a set of *ex situ* and *in situ* goals. Interaction with other researchers/industry could be used to validate approach *in situ*.
- Delays in project start were described during the oral presentation which influenced and limited the progress made to date.

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

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

- The project was started April 2006. It is too early to transfer technology to industry.
- For early stages, measurement and testing in laboratory is appropriate, but as progress is made, need to engage outside partners for testing, processing, etc.
- No good connection to industry or an MEA fabricator. Need to consider this as an opportunity.
- Appears to be none, outside of Case Western Reserve University.
- Would be useful to involve industry partner, especially to look after cost and manufacturability.
- Unclear why only interactions with colleagues were reported.
- This was not highlighted in the presentation. Interaction with Samsung was mentioned.

Question 5: Approach to and relevance of proposed future research

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

- Based on the presentation information, the future research work is clearly presented and technical approaches are reasonable.

- Needs a more concrete plan for next steps.
- Must address solubility issue.
- Further characterization of polymer in various states is needed.
- PI appears to be cognizant of pitfalls of approach, except for how to convert to completely water-free operation if water is not desired.
- The rationale for the next steps has not been well explained.
- Focus on just a couple of monomers/polymers should be done very early.
- This was not clearly addressed.
- No clear path forward observed.
- The proposed work is good; however it needs to include a wider set of goals with *in situ* criteria.

Strengths and weaknesses

Strengths

- The PI, co-Pi and coworker have excellent R&D experience for polymer membrane electrolyte and also for fuel cells.
- Very high conductivity at low RH.
- Unique approach.
- Good, experienced PI.
- Excellent fundamental understanding.
- The proposed work is good; however it needs to include a wider set of goals with *in situ* criteria. This project represents one of the most viable approaches of those reviewed.

Weaknesses

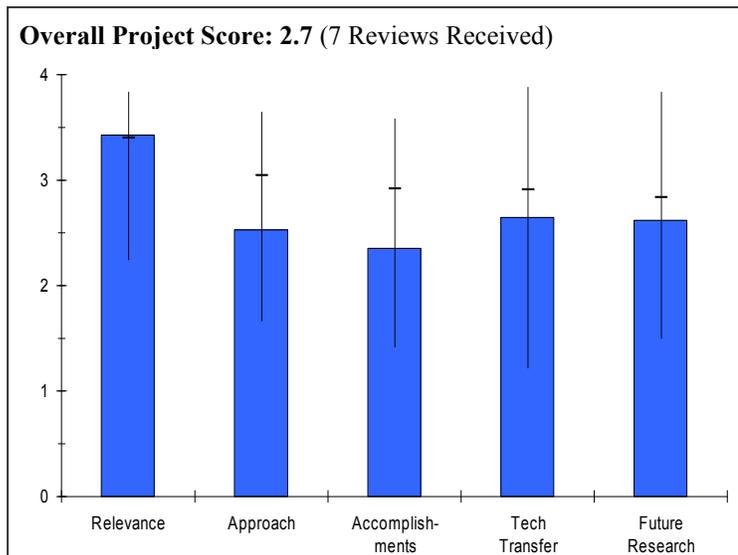
- Need to explain better how to address stability.
- Needs better tech transfer plan.
- Not clear where the engineering plays a role.
- How stable are these polymers? Does not appear to be much emphasis on determining stability under fuel cell conditions.
- No industry partner is involved.
- Materials studied appear to be ones with poor film forming ability measured Nafion[®] conductivity is very low.
- Very focused on novel material development without a fuller set of criteria for evaluation. No *in situ* evaluation in the plan.

Specific recommendations and additions or deletions to the work scope

- This project just started the second year, project progress is good. No action is need at this time.
- Measure conductivity in the transverse direction. No good excuse for not doing this measurement.
- Involve industry partner to comment on manufacturability and cost.
- Measure through plane conductivity.
- It may not be productive to focus on materials that do not yield films.
- At a minimum, some degradation studies need to be performed on candidate materials.
- Collaboration with researchers/industry to evaluate more fully the materials developed.

Project # FC-13: Poly(cyclohexadiene)-Based Polymer Electrolyte Membranes for Fuel Cell Applications*Jimmy Mays; U of Tennessee***Brief Summary of Project**

The objectives of this project are to synthesize and characterize novel neat and inorganically modified fuel cell membranes based on poly(1,3-cyclohexadiene). To achieve these objectives, a range of homopolymer and copolymer materials incorporating poly(cyclohexadiene) will be synthesized, derived and characterized. The successful completion of this project will result in the development of novel proton exchange membranes (PEMs) engineered to have high conductivity at elevated temperatures and low relative humidity.

Question 1: Relevance to overall DOE objectives

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

- The pursuit of improved membranes for high temperature and low RH conductivity is reasonable.
- Polycyclohexadiene has not been studied as a polymer electrolyte and the ability to control polymerization in a living polymerization allows a phase space to be pursued that has not yet in polymer electrolytes.
- The oxidative and hydrolytical stability of the polymer has not been studied. The cross-linking sites and unaromatized rings are unlikely to have good chemical stability.
- Satisfies the DOE's request for a "fresh and novel" approach to identifying new materials for PEM membranes.
- Project is aimed at the discovery of new materials for PEMs that will operate under hotter and drier conditions.
- Project addresses important cost and durability issues.
- This work represents a new method of synthesizing sulfonated, crosslinked polyphenylenes. Such polymers may be useful in membranes, if conductive enough and stable enough.
- The project objective is critical for realizing renewable energy economy.

Question 2: Approach to performing the research and development

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

- The use of cross-links and post-sulfonation are both shortcomings of this proposal. Post-sulfonation gives poor control over location and extent of sulfonation. Cross-linking leaves weak chemical spots and increases brittleness.
- The characterization of the polymers has only focused on thermal properties; conductivity has not been pursued.
- There was no discussion about what block structures would be pursued or why they should be expected to yield better performance- this is particularly important in the context of post-sulfonation and crosslinking which could eliminate any of the advantages of a synthesized block.
- The premise for inorganic particle incorporation improving performance was loose and no results suggesting significant improvements possible were presented.
- Systematic, focused approach, coupled with excellent "Plan B" next step based on prior outcomes.
- This approach to reaching the DOE targets for higher temperature, drier operation is apparently new with the starting advantage of potentially very low cost materials.
- It is too early to anticipate where the major weaknesses of this approach will be, but some effort should be expended at the beginning to seriously identify the one or two major fundamental failure points that could prevent durability or conductivity performance targets from being achieved.

- Approach is solid and is focused on overcoming barriers.
- The stability of the cross-links is a concern, both the disulfide linkage and the aliphatic ring to which it is attached. It is not clear why these polymers would be superior to other sulfonated polyphenylenes or why this is the best method to prepare this type of polymer.
- The point of the sol gel aspect of the project needs to be made clearer. A lot of people have tried very similar things in the past.
- Clear strategy of obtaining high conductivity at low relative humidity is not laid out.

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

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

- While the project is rather new, far less data on these polymers were shown compared to other projects funded at the same time.
- Only a few polymers and membranes were characterized and the properties characterized were not the properties of primary concern for novel high temperature membranes.
- Excellent progress and very effective planning of experiments and related property analysis.
- Factual assessment of developmental materials, and if they meet targets.
- Films with good mechanical properties have been achieved.
- No conductivity data yet.
- The PI admits to a slow start.
- Good efforts to characterize the materials chemistry and structure.
- While it appears progress is being made with respect to cost reduction and material properties, clear status to targets should be shown.
- The researchers should measure the proton conductivity of these materials at this point to assess the viability of the approach. The durability should also be addressed soon, both *ex situ* (Fenton's tests) and in an MEA.
- The mechanical property testing is quite thorough.
- Successful synthesis of first trial of membrane has been accomplished.
- No activity has been shown on characterizing key properties, conductivity and chemical and electrochemical stability.

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

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

- The combination of a characterization person and synthesis person makes good sense, however the type of characterizations performed are not those most relevant to the project, a person more familiar with electrochemical characterization may be a better choice. The techniques of Mauritz for evaluating polymer degradation are valuable, but not of primary importance for this project.
- Too early in program for technical transfer opportunities.
- Excellent use of University of S. Mississippi and ORNL to provide material property analysis, etc., and as a planning tool for determining the next steps in PI's program.
- Should consult with industry partner.
- Poor right now as it is a new idea just beginning in an academic laboratory.
- Consider expanding collaboration with membrane supplier.
- This program would benefit from collaborating with a "Fuel Cell" group (e.g., Los Alamos).
- Collaboration with institutes have capability of electrochemical property characterization is in need.

Question 5: Approach to and relevance of proposed future research

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

- Future work on sol-gel chemistry leaves many questions about improvements possible.

- Brittleness as a primary problem suggests crosslinking is an issue, optimization of chemistry might be best served by looking at non-crosslinked samples as well.
- Cross-linking is a key issue, and the PI has assigned appropriate emphasis on this topic.
- Some comments on material manufacturing issues (barriers, etc.) would be a useful addition, once a candidate material has been identified.
- Improve mechanical properties.
- Incorporate sol-gel chemistry.
- Proton conductivity measurements.
- The project plans are very sensible for demonstrating progress toward the goals of improved conductivity.
- The PI should try to identify the most likely failure point of this technology and address it early – for example the susceptibility of hydrocarbon membranes to attack from peroxy radicals.
- The use of Cl-containing crosslinking agents is a real concern, due to the potential for catalyst poisoning when the membrane is degraded by peroxy radicals – it will happen. They should find alternatives.
- Project has several years to go, however future work is not described clearly.
- It is not clear what Type B or Type C polymers are, or how these would behave differently than the materials this group is currently studying. The conductivity has not even been measured on the current polymers.

Strengths and weaknesses

Strengths

- Novel materials with the ability to be made using living polymerization.
- Program well-defined and organized by the PI.
- Successful use of "experts" in material characterization to accelerate evaluation of candidate materials.
- Novel polymer architectures.
- Intelligent use of sol-gel chemistry.
- A new approach which always holds promise for new gains in performance.
- Strong collaborative effort with University of Southern Mississippi.
- The PI is working on the chemistry different enough to address the key issues, conductivity and cost of fuel cell membrane.
- Both groups present adequate experiences of developing new chemistry membranes for fuel cells.

Weaknesses

- Resulting structures to this point have not been characterized for conductivity. Chemistry being explored has significant chemical stability concerns. Crosslinking reduces processing possibilities and increases brittleness.
- All "high temperature, low RH" projects have a very high hurdle to achieve (e.g., conductivity).
- Fuel cell durability needs to be verified for "new materials", in addition to the conductivity target.
- PI can only post-sulfonate material. It is not clear that there will be any control of sulfonation chemistry.
- Cross-link chemistry illustrated in talk is totally unsuitable for fuel cell electrodes.
- No conductivity data.
- Combining the new polymer chemistry with the whole area of sol-gel chemistry is an enormous task to address for a level of this effort. The parameter space becomes enormous.
- The stability of the crosslinks is a concern, both the disulfide linkage and the aliphatic ring to which it is attached. It is not clear why these polymers would be superior to other sulfonated polyphenylenes or why this is the best method to prepare this type of polymer.
- The point of the sol-gel aspect of the project needs to be made clearer.
- No evidence has shown for the capability of characterizing electrochemical properties.

Specific recommendations and additions or deletions to the work scope

- Explore block chemistry further. Figure out what blocks may be possible and determine reasons why to pursue them. Specific recommendations would include developing monomers with protected sulfonic acid groups to avoid post-sulfonation or copolymerize monomers that don't allow random sulfonation.
- Reduce sol-gel chemistry effort.
- Eliminate cross-linking for at least baselining purposes.

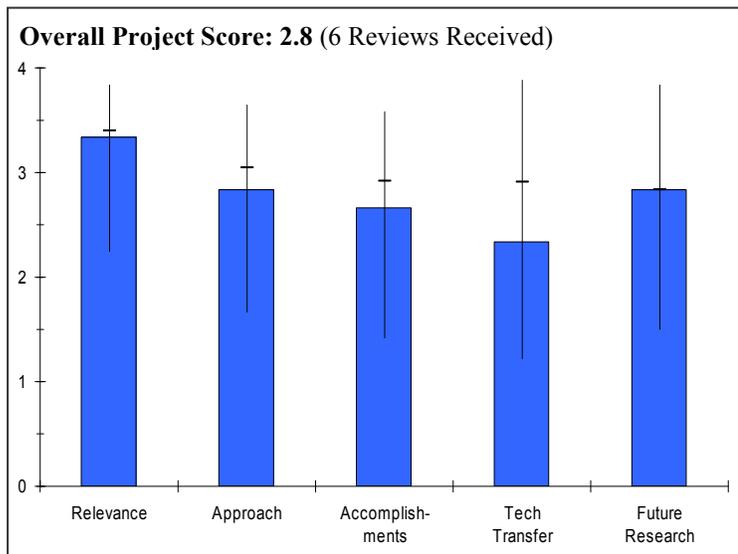
- The development of "new materials" may require additional technical resources (and funding).
- Find a fuel cell company or expert to consult with.
- Use proton conductivity for optimization; mechanicals can be improved after Go/No-Go decision is passed.
- Do some serious durability tests challenging the materials as soon as possible to get a feel for the baseline stability of the materials.
- Try to make full MEAs for fuel cell testing as soon as possible also, or better, work with experienced MEA testing group.
- When starting a new area, put some effort into trying to identify any fundamental failure mechanisms that will ultimately prevent success on that path, as well as developing all the good characteristics.
- Show status against DOE technical targets.
- The PI needs to put higher priority on characterizing electrochemical properties at the realistic operating conditions.

Project # FC-14: 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 (NCN) proton conducting membranes for hydrogen/air fuel cells that operate under high temperature, low humidity conditions. To achieve these objectives, the project will employ electrospun nm-sized fibers of a high ion-exchange capacity polymer that are vapor-welded and imbedded in an uncharged polymer matrix. There will be an addition of molecular silica to further enhance water retention. Additionally, the project will employ the concept of capillary condensation for membrane water retention.



Question 1: Relevance to overall DOE objectives

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

- High temperature membranes are critical to the realization of the Hydrogen Fuel Initiative, to increase system performance and efficiency and to reduce system cost and volume to meet automotive targets.
- Membrane material test conditions should mimic real world usage profile and temperature and humidity should be defined. For automotive applications, a wide range of temperature and humidity (hydration) should be tested. High temperature operation is very small fraction of entire life (less than 5%).
- Relevant.
- This project has highly relevant technical goals towards the DOE technical targets for this critical core component.
- The project objective is critical for realizing renewable energy economy.

Question 2: Approach to performing the research and development

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

- Good approach to membrane morphology (NCN structure).
- Novel approach to membrane fabrication.
- Silica has limitations.
- Unique approach, however, is this cost effective compared with conventional membrane process?
- Materials stability of additives, water retention, in the membrane under condition (hydration) changes.
- Fuel cell test will be necessary to validate membrane structure optimization.
- Approach is novel, but lacking focus.
- Chemical production not considered.
- The technical approach presented is logical and appropriate.
- Identifying the desired pore structure for water retention and conductivity can help to expedite the development.

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

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

- Membrane fabrication process demonstrated and optimization initiated.
- Treatments of material show promise to increase conductivity.
- Membrane conductivity at high temperature and low RH not investigated yet.
- Too early to discuss technical outcomes. Performance is still low.
- Lacking relevant fuel cell results.
- Good proof of concept.
- Unclear how low RH conductivity target can be met.
- Given the limited effort thus far, this project has made excellent progress.
- Demonstrated the feasibility of making capillary network membrane using electrospinning.

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

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

- Collaboration with Wright State University for polymer synthesis seems to have yielded polymers suitable for electrospinning.
- Polymers with higher conductivity have been prepared.
- Fuel cell testing will be necessary for membrane material/structure optimization and this could be a collaboration opportunity.
- Could use cross fertilization with other fuel cell experts at Case.
- Good team.
- As this project is in its initial stages, the amount of collaboration is appropriate.
- Contributions from the partners are not discussed.

Question 5: Approach to and relevance of proposed future research

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

- Logical plan focuses on opportunities to increase conductivity and improve the membrane properties.
- Plan for molecular silica is not clear.
- Materials stability should be evaluated, e.g., water retention of additives.
- Electrode interface characteristics should be investigated prior to fuel cell testing.
- Gas separation should be evaluated (hydrogen permeability).
- Need to add some basic fuel cell test to demonstrate viability of approach as well as water uptake and stability tests. More detailed approach is needed.
- Low RH studies must be done → not claimed. Otherwise very comprehensive.
- The proposed project work is appropriate, given the early stage of this exploratory work.

Strengths and weaknesses

Strengths

- Novel approach.
- Membrane material/membrane process.
- Membrane performance testing.
- Novel concept.
- Very experienced P.I.s.
- Proof-of-concept very convincing.
- This project investigates a potentially viable PEM membrane structure which may address one of the failure modes of dense PEM membranes.
- Significant progress has been made.

Weaknesses

- Membrane tortuosity and durability are of concern.

- Understanding of application and usage conditions.
- This project lacks cohesion and a proper set of detailed tests to determine uptake and stability. Approach needs validation. At present, approach would appear to increase proton path length which would decrease power. PI needs to prove this concept.
- Low RH conductivity will be an issue with material used.
- High temperature stability of thermoset is questionable.
- There is no theoretical investigation for the structure of the membrane to quantify the required properties of water retention.

Specific recommendations and additions or deletions to the work scope

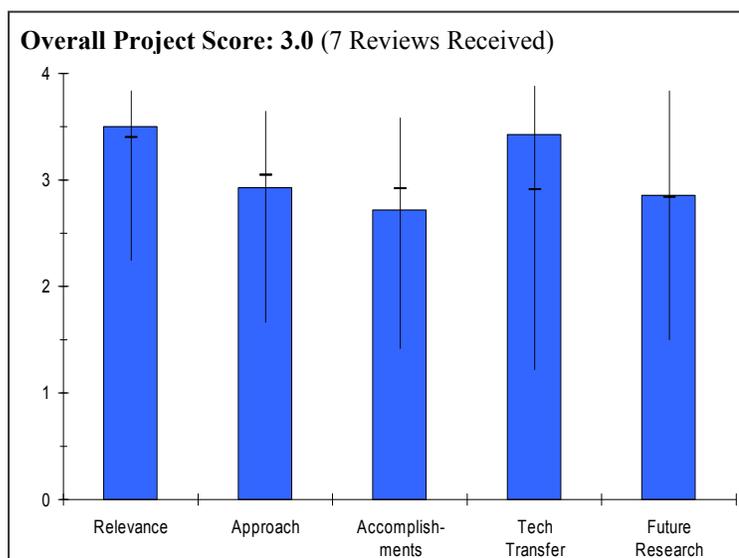
- Recommend confirmation of the basic requirement of PEMs for fuel cells, gas separation is one of the critical requirements. Need to clarify how this porous membrane achieves enough gas separation.
- Need to estimate ball park cost to identify cost benefit compared to conventional membrane process, e.g., casting.
- There should be a go/no go decision gate added in the program plan (if it isn't there already) to evaluate the feasibility of the electrospun, PEM fiber matrix approach to achieve the required membrane conductivity.
- Recommend a cost assessment of this approach be included in the project objectives to ensure these additional manufacturing steps do not add excessive cost.
- Recommend rework on project plan, including definition of basic requirement of PEMs for fuel cells and technical problem to be solved in this project.
- Set proper performance evaluation items with respect to defined basic requirement.
- Confirm the structure and materials are within reasonable cost to make a fuel cell. Ball park cost estimation is recommended.
- Detailed study of active fiber loading in an inert matrix to determine conductivity, power, uptake and stability.
- Durability studies to be added (chemicals).
- Low RH studies to be added.
- Addition of a go/no-go decision gate to assess the viability of the electrospun, matrix approach to achieve the DOE proton conductivity targets without losing the functional advantages of the impregnated matrix.
- Possibly include collaboration with others to examine alternative polymer electrolyte materials for the electrospun matrix approach.
- The PI needs to quantify the desired property/structure for water retention.

Project # FC-15: Lead Research and Development Activity for 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) employ new polymeric electrolyte/phosphotungstic acid membranes; 2) standardize characterization methodologies (conductivity, mechanical, mass transport, and surface properties, durability); 3) provide High Temperature Membrane Working Group (HTMWG) members with standardized tests and methodologies (short courses); and 4) organize HTMWG bi-annual meetings. Task 1 membranes use non-Nafion based poly(perfluorosulfonic acid) – phosphotungstic acid membranes and membrane electrode assemblies (MEAs). Task 2 membranes use sulfonated poly(ether ketone ketone) or sulfonated poly(ether ether ketone) – phosphotungstic acid composite membranes and MEAs.



Question 1: Relevance to overall DOE objectives

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

- The development of high temperature/low RH membrane materials is highly needed for the successful commercialization of PEMFCs.
- Standard of proton conductivity in-plane and through-plane testing is very important for the industry.
- The coordination of the HTMWG is a significant responsibility, although the separation of this as a research project and a coordination project make its review more difficult.
- The use of HPAs with Nafion or PEEK is not novel; using lower EW materials make sense for conductivity reasons, but leaves big questions regarding stability.
- Coordination of HTMWG is valuable work.
- The development of a high temperature, low relative humidity proton-conducting membrane electrolyte would reduce system complexity and cost and enable the application of this technology to automotive propulsion power.
- PI has identified reasonable alternative membrane materials and additives to meet the project's objectives.
- PI had made concerted effort to assist other project PIs in evaluating their choice of alternative materials, which will benefit all DOE projects in this area.
- The activities are clearly relevant. However, there are some holes that are worrying. There appears to be no provision for mechanical properties and gas permeation.
- This is a critical activity to identifying new membranes which will meet DOE targets.

Question 2: Approach to performing the research and development

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

- Immobilized PTA in PFSA materials could help with low RH performance but it is unclear how mechanical improvements can be achieved.
- sPEKK and sPEEK are notoriously brittle. While low RH performance with immobilized PTA could be beneficial, it is unclear how mechanical improvements can be achieved also with this material system.

- Proton conductivity work is very important and being pursued in an excellent manner.
- The significant effort being used to baseline conductivity measurements is reasonable as these are the primary properties of concern. Addressing water uptake would also be useful.
- In-plane conductivity seems reasonable for almost all samples tested; some question exists about how much effort should be expended on through-plane measurements.
- Addition of PTA not expected to enable achievement of membrane performance goals.
- Effort to standardize conductivity measurements for all HTMWG programs is good approach.
- The coordination and lead laboratory aspect of this project is excellent.
- The approach to standardizing testing and reconciling some of the differences in various testing protocols is outstanding and the results will be invaluable.
- The approach to developing new materials is not novel and it is unclear what new aspect these PIs bring to this approach.
- Well-organized and focused on two main objectives: development of new membrane material and reliable conductivity measurement instrumentation.
- Good approach (material and additive selection) for achieving conductivity at both high and low RH.
- Approach is good for the organization of the measurements. However, the lack of polymer mechanical characterization and how mechanicals help in making electrodes and MEAs is critical. This is missing and must be rectified.
- More focus should be put on working with other 11 group members. Each material will have different needs for adequate testing and evaluation. It is important that this not be just "screening".

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

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

- PTA/PFSA materials show promising proton conductivity results.
- PTA/HC materials show very low PC; not clear how the PI will level up the data.
- In-plane/through-plane conductivity is progressing very well.
- The project is rather new, and has thus far focused on baselining efforts; while these are reasonable they don't advance towards lower RH conducting membranes.
- Results shown for Nafion composites don't look that different from IONOMEM results, and no strong reason for expected improvements in conductivity using PEEK was presented.
- Significant work has been accomplished in automating data on conductivity as a function of RH.
- Showed progress in in-plane conductivity testing at Bekktech.
- PI successfully made numerous polyelectrolyte membranes with PTA, but data shows no significant performance benefit.
- This team has made excellent progress in baseline proton conductivity measurements of Nafion membranes.
- Initial material development efforts are on target and well documented.
- Development and qualification of conductivity instrumentation on target.
- So far so good, but add the dimension of polymer mechanical properties.
- It should be shown how "characterize mechanical, mass transport and surface properties of membranes" and "predict durability of membranes and MEAs fabricated from other eleven HT low RH membrane projects" will be carried out.
- A very good system of conductivity evaluation has been put together. These measurements can be quite difficult.

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

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

- Good collaboration with BekkTech.
- HTMWG may want to implement industry more to get a realistic perspective on membrane needs.
- The combination of people in this project makes sense for the oversight part of the project. The only question being the appropriate level of effort for through-plane conductivity.

- The development of novel materials seems to be an independent endeavor.
- Strong collaboration with BekkTech & Scribner for conductivity testing.
- PI organizes HTMWG meetings with all other PIs.
- By definition, the category two winner must have well-established collaborations and transfer of technology. It is apparent that this aspect of the project is working very well.
- Collaboration with commercial membrane and MEA manufacturers would ensure the timely transfer of newly-developed membrane technology to the application.
- PI has made excellent progress in coordinating the qualification of both in-plane and through-plane conductivity measurement instrumentation and protocols with external consultants and commercial suppliers.
- PI's "extra efforts" to hold workshops for university and national lab participants in the High Temp/Low RH program, and offer to test their "in-progress" material development efforts prior to the "go/no-go" deadline.
- Good.
- The High Temperature Membrane Working Group has an excellent group of researchers.

Question 5: Approach to and relevance of proposed future research

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

- Continuation of PTA/PFSA material is worthwhile – unclear how worthwhile the PTA/HC materials are considering how far they currently are from the DOE Go/No-Go targets.
- Proton conductivity continuation is important and being finalized.
- Future work is reasonable, but is unlikely by itself to contribute significantly to obtaining materials with the requisite properties.
- Developing standard through-plane conductivity test is a good idea.
- PI plans to evaluate lower EW membranes with HPAs.
- No durability test plans specified.
- Continued work on through-plane conductivity measurements is outstanding.
- Very little detail was given on the direction of the research in new membrane development.
- PI's plans for low EW ionomers and new formulations of sPEEK, sPEKK, etc. may need concurrent durability analysis in addition to the "conductivity" goal.
- Too little information was provided. There is no discussion of starting any fuel cell testing, mechanical property testing, or anything other than conductivity testing. These activities are critical.

Strengths and weaknesses

Strengths

- Excellent project management.
- Excellent partners of BekkTech and Scribner.
- It appears an automated and efficient process will result in meeting key deliverables.
- Leadership of HTMWG.
- Knowledge and coordination skills of the PI.
- Focus on standardization of testing procedures.
- Development of reliable conductivity instrumentation vital to all high temperature/low RH membrane participants.
- Novel approach to incorporate PTA for improved conductivity.
- Excellent start on conductivity testing.

Weaknesses

- Material novelty and potential seems to be rather weak – should step out of the box a little more.
- New materials development doesn't show particular insight and is unlikely to lead to further improvements necessary to reach DOE goals.
- Approach of adding PTA to existing sulfonic acid ionomers not likely to meet DOE high temperature performance targets.
- No focus on durability.

FUEL CELLS

- Lack of rationale for the use of phosphotungstic acids.
- Lack of high-temperature, low relative humidity conductivity data for newly-developed membranes here and for all high temperature/low RH membrane projects – it may be very difficult to achieve the conductivity target.
- Polymer mechanical properties are missing.
- It is not clear to what extent the project leading and coordinating the High Temperature Membrane Working Group as a fuel cell membrane testing expert, and to what extent it is to use the polymers developed by the group to develop a new phosphotungstic acid doped membrane. I'm not sure these goals are compatible within the same program.

Specific recommendations and additions or deletions to the work scope

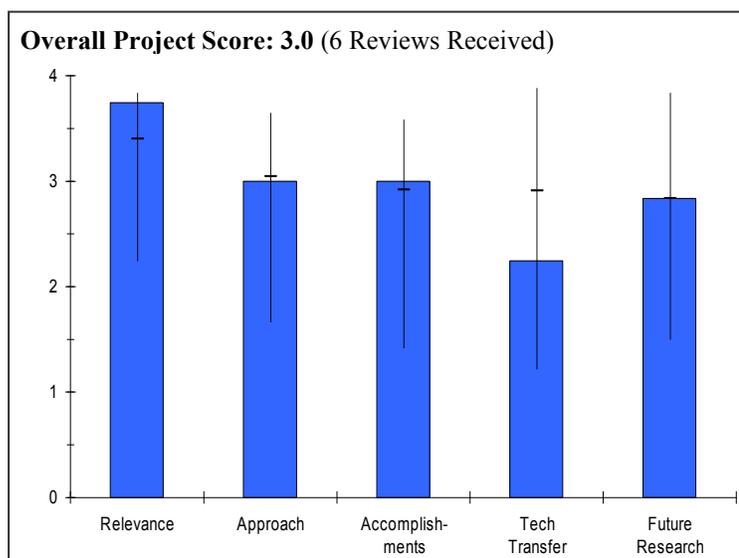
- Continue to work on project management and proton conductivity.
- Unclear what the PTA composite membranes are bringing to the fuel cell community – does the PI really think this material can be commercialized and implemented in a vehicle?
- Delineate the project better between a research project and an administration project.
- PI should run durability tests on membranes with and without PTA.
- HTMWG meetings should have more technical content & discussions.
- HTMWG should focus more on durability.
- May be appropriate to set up a "support lab" for conductivity measurements, since not every project PI will be able to install the instrumentation. In the future, this might be a suitable project for a national lab (ORNL, etc.), or turn over to industry (service work and/or instrument supplier).
- Add a polymer specialist to the team.

Project # FC-16: 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 (PEM) materials. These PEM materials should have 1) high proton conductance at high temperature (up to 120°C); 2) effectively no co-transport of molecular species with proton; 3) reduction of fuel cell overpotential; and 4) good mechanical strength and chemical stability. Protic ionic liquids (PILs) will be used to model membranes. Acid and base moieties and polymer properties will be varied to optimize properties of the protic salt membrane. The first goals are to make a stable liquid then membrane electrolytes with a conductivity >0.2 S/cm at 120°C and >0.0005 S/cm at -20°C.



Question 1: Relevance to overall DOE objectives

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

- Project focuses on the development of high-temperature, low-humidity membranes using protic ionic liquids.
- Clearly addresses DOE targets and goals.
- High performance membranes capable of operation at high (up to 120°C) temperature are a key objective of the program.
- Aligned with DOE goals for PEM membranes.
- This pursuit of a new electrolyte provides a possible alternative to existing technology and may lower costs and may improve performance.
- Alternative electrolytes may provide a pathway to increase commercialization.
- Solid electrolytes could bring benefits of durability, higher proton conductivity, and lower cost.
- The objectives of this project are fully aligned and highly relevant to the DOE technical goals.
- This project is a higher risk, fundamental materials study which addresses in novel ways the DOE technical goals.
- The project objective is critical for realizing renewable energy economy.

Question 2: Approach to performing the research and development

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

- Good task description; well thought out.
- Approach addresses identified technical barriers.
- Approach (protic salts) appears novel and at least has some promise (high temperature, non-aqueous, high performance shown at very low current density) of achieving 120°C target.
- Addresses technical barriers for conductivity at very low-RH and high temperatures.
- Conduction mechanism is not dependent on the presence of water.
- While work with ionic liquids in porous matrices and sorbed in polymers will help develop this class of fuel cells, for an automotive membrane, need to focus more on immobilized PIL concepts.

- This approach is starting from a position that is less advanced or developed than others, but has a higher potential payoff.
- The program plan effectively addresses the issues in a methodical manner.
- The methods used – moving from liquids to solids – was chosen to improve the likelihood of success.
- The transition from liquid to solid is one difficult hurdle – this may make the chosen method more difficult.
- The approach described is logical and addresses the appropriate technical barriers in an appropriate order.
- The PI needs to identify the strategy of obtaining both stability and conductivity.
- Morphology studies of stable protic salt membranes are needed.
- The project unitizes a new water-free conduction approach.

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

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

- Given the project is only 20% complete, progress to date has been good. Several membranes incorporating protic ionic liquids (PILs) have been synthesized and initial testing complete.
- Initial results are encouraging.
- While a long way to go from liquid salts to a membrane, progress appears more than commensurate with the elapsed duration of the program.
- Some promising conductivities. But need to combine with stability and performance at higher current density.
- Demonstrated fuel cells with liquid protic ionic liquids with some advantages.
- Conductivities need to be improved, especially for non-leachable systems (need orders of magnitude improvement).
- The progress, compared to the total project timeline, appears to be tracking well.
- The accomplishments so far appear to be tracking towards resolution.
- It seems to be too early to make a final judgment, but progress so far is good.
- Investigations into mechanisms of proton transport are very good and appropriate.
- Understanding of stability mechanisms is an important factor that requires characterization.
- Demonstrated the feasibility of making protic salt membrane electrolytes.
- The limiting step of the proton conduction needs to be identified to address the conductivity issues with stable membranes.

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

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

- Reference made to Boeing collaboration but actual interaction was not documented.
- Collaborations are unclear.
- Collaborations with other universities.
- Not clear what Boeing's role is.
- The project includes collaborators, but little collaboration was mentioned outside the project participants.
- Some additional technology transfer, perhaps to the SECA program, might be beneficial.
- Given the initial phase of research, collaboration with researchers in other specialties has been appropriate and results are encouraging.
- Contributions from the partners are not discussed.
- Collaborations for morphology characterization of the membranes are needed.

Question 5: Approach to and relevance of proposed future research

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

- Future plans are adequate and directed toward achieving DOE targets.
- Concentrate on developing and characterizing conductive, durable (non-leaching, non-dissolving) PIMs before rushing to the next level (i.e., fuel cell testing).

- Work with ionic liquid filled PEMs will help understanding of these materials and fuel cells based on them but immobilized PILs are what is applicable to the high temperature membrane project goals.
- NMR experiments should be helpful in determining proton transport properties and mechanisms.
- The project is early in its timeline. Future work is the majority of the work.
- Proposed future work seems consistent with the overall project plan.
- Project is progressing well and future research is appropriate and well considered.
- Consideration of potential issues with developing electrode needs to be planned.

Strengths and weaknesses

Strengths

- PI seems knowledgeable and well-qualified to perform the proposed research.
- Novel approach that, in theory, has promise.
- Concept with the potential for a truly non-aqueous conduction mechanism.
- Solid PEM electrolytes are a unique field, providing much opportunity for innovation.
- Project plan appears to be logical – moving from liquid to solids.
- Project has achieved much in a short period of time.
- Good exploratory work into novel materials.
- The project utilizes a new water-free proton conduction mechanism for novel membrane development.

Weaknesses

- Membrane stability and catalyst poisoning may be issues in the future affecting fuel cell performance and durability.
- It may not be possible to find a viable solid electrolyte to meet the goals. Many barriers remain.
- Some lessons learned from other technologies (e.g., SOFC) might be helpful, but have not been discussed.
- The project has insufficient planning and collaborations lacking morphology and electrochemical aspects.

Specific recommendations and additions or deletions to the work scope

- Work with experienced MEA developer to allow program focus on electrolyte.
- It is too early to recommend changes at this time. The project is progressing well.
- Addition – evaluation of these PIL materials as catalyst ionomers (this was implied in the presentation but could be added to the project objectives). If this could reduce the cathode overpotential loss, this might be advantageous for all fuel cell applications.
- Morphology studies are in needs for the stable protic salt membranes.

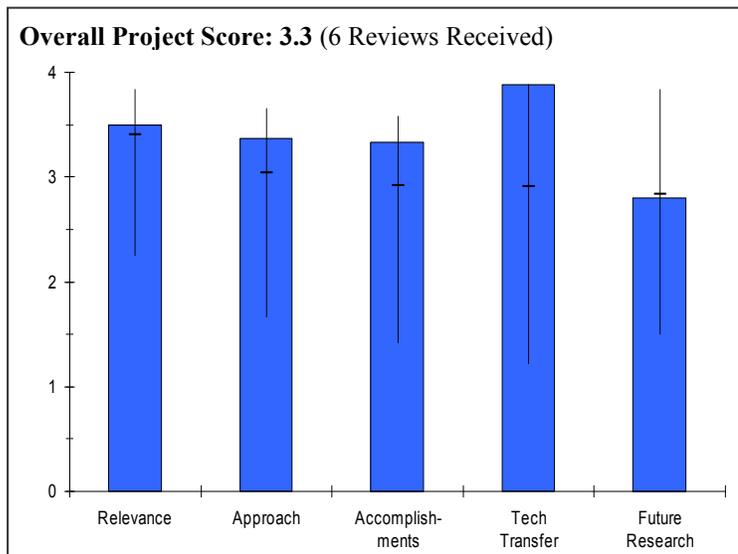
Project # FC-17: Novel Approaches to Immobilized Heteropoly Acid (HPA) Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes

Andrew Herring; Colorado School of Mines

Brief Summary of Project

The overall objective of this project is to fabricate a hybrid HPA polymer (polyPOM) from HPA functionalized monomers with $\sigma > 0.1 \text{ S cm}^{-1}$ at 120°C and $< 1.5 \text{ kPa H}_2\text{O}$. The objective for fiscal year 2007 was the synthesis and optimization of hybrid HPA polymers for conductivity from room temperature to 120°C . Phenyl HPA derivatives will be subjected to low pH/high temperatures to determine optimum chemistry for fuel cell stability. A determination will be made of the most facile conversion of HPA polymers to proton conducting systems.

Question 1: Relevance to overall DOE objectives



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

- The development of high temperature/low RH membrane materials is highly needed for the successful commercialization of PEMFCs.
- The need for increased membrane performance at low RH exists, but it is not the primary barrier to commercialization.
- Objectives are addressed by program elements.
- Concern with proprietary efforts around material supply and "smart formulation" for film formation.
- Development of membranes for low humidity and high temperatures is one of the key issues for DOE.

Question 2: Approach to performing the research and development

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

- Immobilization of "polyPOM" in polymer materials is very important for the success of this program and is being pursued by the PI.
- Use of caustic pre-screening of cross-linker is an excellent way to speed up development time and prevent dead-ends.
- Inorganic heteropolyacids have shown promise for high temperature fuel cell use; few others are modifying chemistry and directly incorporating into polymers the same way as this group.
- Novel approach (HPA moieties), and "new territory".
- Consideration of hybrid organic-inorganic monomer HPAs.
- Unique approach that appears to hold promise.
- Good approach to start at the basic monomer work and going then step-by-step up to membrane stability at 120°C .
- The approach recognizes previous work done with heteropoly acids and builds on previous work.
- CSM recognizes risks related to oxidative stability and taking a success-oriented approach. Oxidative stability may have to be addressed later.

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

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

- "polyPOM" relies on water for proton conductivity – unclear how proton conductivity at low RH is possible when "polyPOM" is blended with polymer "X". No data was shared to prove this concept.
- Focusing on linkages that survived caustic tests is a very good idea.
- 100 plus films to date is significant and must be leveraging other work.
- Reported performance for compounds besides the pure powders is still very low.
- The proprietary nature of some of the data makes it difficult to technically review.
- Reported progress is satisfactory.
- Program may require additional personnel, since initial results indicate the program may require additional effort to assess and resolve "new issues", similar to those reported (stability of initial candidates).
- Appears to be good results for this point in the program.
- Fundamental understanding of phosphate linkage and model phenyl derivatives.
- On-schedule achievement of the first project milestone appears likely.
- The project is fairly new but important progress has already been made.

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

This project was rated **3.9** for technology transfer and collaboration.

- Collaboration with 3M provides the needed guidance to the PI on this novel concept.
- Collaboration with 3M is extremely valuable as they can potentially help commercialize.
- PI's project will benefit from identified industrial partner (3M), who can provide the necessary materials, processing and fabrication support for this program.
- Good collaboration between institute and their "friends" from 3M.
- Collaboration with 3M Company is advantageous and has facilitated progress.

Question 5: Approach to and relevance of proposed future research

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

- Incorporation of "polyPOM" in polymer "X" with significant testing of membrane properties is very important and scheduled.
- Methacrylate-based systems may not be the best choice for durability.
- Project should place more emphasis on oxidative stability of polyPOMs.
- Good plan to elucidate understanding, as well as drive towards a viable material.
- Focusing also on MEA preparation and test. The best membrane is nothing when it does not work together with the electrodes.
- No obvious show-stoppers have been identified although a few significant technical hurdles are listed.
- Critical involvement of 3M for the next steps is recognized by CSM.

Strengths and weaknessesStrengths

- Novel concept with high potential.
- 3M's ability to keep the PI focused on the application.
- Good team, novel area of pursuit.
- Alignment with 3M for polymer synthesis and polymer conversion to membrane.
- PI appears to be well aware of what the targets are for membranes (e.g., good conductivity at 120 and -20°C with little water).
- Partnered with 3M early to help ensure that membrane is commercially viable.
- Good understanding due to having and testing model systems.

Weaknesses

- Unclear how polymer "X" will provide the ability to conduct protons at low RH. No proof of concept was shown due to IP issues.
- Based on the data presented (and no other clear rationale for significantly improved performance), it seems unlikely that these materials can be improved enough to meet DOE targets.
- Conversion of HPA to free-acid may be a challenge.
- Polymer durability in fuel cell environment needs to be actively addressed.
- PI not able to discuss actual formulations.
- CSM is deliberately delaying addressing some technical hurdles that may turn out to be show-stoppers (3rd bullet slide 23).

Specific recommendations and additions or deletions to the work scope

- The program thus far is on track.
- Upon blending with polymer "X", significant testing will be necessary to prove this particular concept for the "Go/No-Go" decision.
- Need to create a compelling story for what level of conductivity these types of materials can obtain.
- Continued/additional emphasis on low RH conductivity (< 70% RH).
- Add work on MEA.

Project # FC-18: High Temperature Membrane with Humidification-Independent Cluster Structure

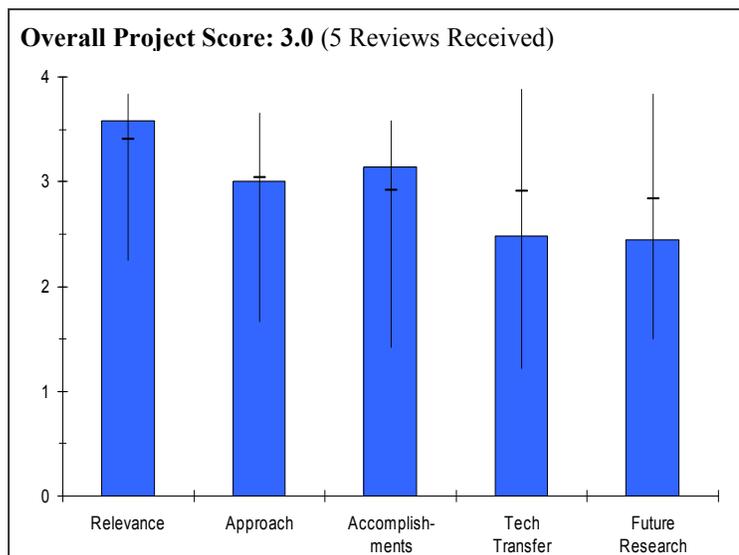
Ludwig Lipp; FuelCell Energy, Inc.

Brief Summary of Project

The technical accomplishments of this project were: 1) a multi-component composite (mC2) membrane concept was defined; 2) an improved baseline polymer was selected and characterized (6 month milestone met); 3) additives for water retention and protonic conductivity enhancement have been identified and fabricated; 4) measurements were verified by BekkTech; and 5) conductivity is used as a “figure of merit” and mechanical properties were used as a check point.

Question 1: Relevance to overall DOE objectives

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



- The development of a proton-conducting membrane that can operate under low relative humidity conditions and high temperatures will enable the widespread implementation of this technology to solving the country's energy needs.
- The project supports the overall DOE objectives, and if successful, could simplify fuel cell system requirements and thereby reduce overall fuel cell system costs.
- A new electrolyte provides a possible alternative to existing technology, may lower costs and improve performance.
- Alternative electrolytes may provide a pathway to commercialization.
- The focus on the target of high temperature membranes is appropriate.
- The materials are clearly being fabricated to meet the automotive DOE conductivity/area resistance targets for room temperature and 120°C.
- There is no indication as of yet that any of the DOE targets for membranes are being ignored.

Question 2: Approach to performing the research and development

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

- Approach is good as it combines aspects of many other successful approaches, however, it is difficult to fully evaluate the approach without the identity of the materials.
- The baseline polymer shows conductivities far from the DOE 2010 target – what is limiting this conductivity?
- The project approach, based on a multi-component composite membrane concept, is technically sound.
- Project plan is methodical and planned to move from material to material – this is a strength.
- Project builds upon success, using additives to increase performance – this is a strength.
- The approach is rather "standard", that is a new membrane with additives. There was not enough information about the materials presented to evaluate the novelty or merit of the approach adequately.
- Approach to addressing conductivity, water retention, and mechanical support is clear.
- "Stabilized nano-additives" are described as the approach to maintaining conductivity at freeze conditions. These nano-additives are either not mentioned in the drawing showing the membrane concept, or they are confounded with some of the other additives.

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

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

- Good progress in establishing a baseline polymer with improved conductivity compared to Nafion.
- Without the identity of the baseline polymer or the mechanism by which it achieves its improved performance compared to Nafion, it is difficult to evaluate if this baseline polymer is a viable candidate for long-term operation in the fuel cell.
- Good technical progress achieved so far in very little time (9 months) with low level of effort (<\$250K).
- Shown conductivity of 2.5 x Nafion – good result.
- Conductivity tracks Nafion over the range of RH – good result.
- Additive studies show opportunity for improvement.
- Worked hard to obtain good repeatable data – shows rigorous scientific application.
- Checked data against an independent testing lab – good approach.
- The additives described seem to be quite effective. Also the extruded, baseline membrane seemed to have very good conductivity.
- The speaker said that the additives had the same relative effect on the newer extruded membrane as they had on the cast membrane (data in slide 11). Additive B seemed to provide an increase in conductivity at 30 % RH of about 5 to 6 x. If that is the case, the additive would raise the conductivity of the baseline membrane to 100 mS/cm at 120°C, 30% RH. Is this the case?? These conductivity values should be reexamined.
- The extruded baseline polymer is far from the DOE target at 120°C, although progress has been made from the original cast material (6 to 30 mS/cm at 40% RH).
- Verbally, it was stated that the water retention and conductivity enhancement additives will provide the same benefits for the extruded material that they did for the cast material. These data need to be shown.
- Mechanical stability should be shown with an *in situ* test such as an extended mechanical cycling test (quick cycles of 100% RH and dry gas).
- Low thickness shown (25 μ).

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

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

- No partners in this project. Only apparent outside interaction is with BekkTech for conductivity tests.
- Good participation with other researcher on developing testing protocols, and independent measurement of membrane conductivity.
- Collaboration with testing laboratory is laudable.
- The team includes diverse collaborators, including potential customers – this is a strength.
- The close work with UCF and Bekktech is an important aspect of this program to allow good evaluation of these new materials.
- Collaborators listed are expected within the context of DOE high temperature projects (DOE, BekkTech, UCF).
- Although it is difficult to suggest collaboration at present, it is expected that project hurdles will necessitate collaboration. For example, the mechanical support may be addressed, but what if an additive is unstable or leaches? Are there large membrane producers that have experience with additives that could be of assistance? How much experience does FuelCell Energy have with adding additives to membranes?

Question 5: Approach to and relevance of proposed future research

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

- No details were given as to what would be done in the future research beyond "improve materials and processes".
- Work plan for future development is clearly defined and well structured.
- Project is early in its schedule. Future work is consistent with project plans.

- More information should be provided. The proposed future research seems to be to "optimize the membrane and meet the targets".
- Achieving only the room temperature conductivity target by next year is not aggressive enough.
- It is not understood what is meant by "improve functionality of individual components." Does something have to be improved regarding the individual additives before they can be fabricated into the membrane?

Strengths and weaknesses

Strengths

- Multi-pronged approach to achieving DOE membrane targets.
- Alternative electrolytes are a field with many opportunities.
- The project plan appears to be well thought-out and methodical.
- Verification of project data by a third-party laboratory helped to validate the data protocols – good practice.
- Excellent results so far.
- Some good conductivity values were obtained.
- An overall material strategy has existed from the beginning to achieve most of the membrane targets.
- Some progress has been made towards achieving room temperature conductivity targets.
- Some experiments show that there is reason to believe mechanical strength will be adequate, and that additives will make a difference on performance.

Weaknesses

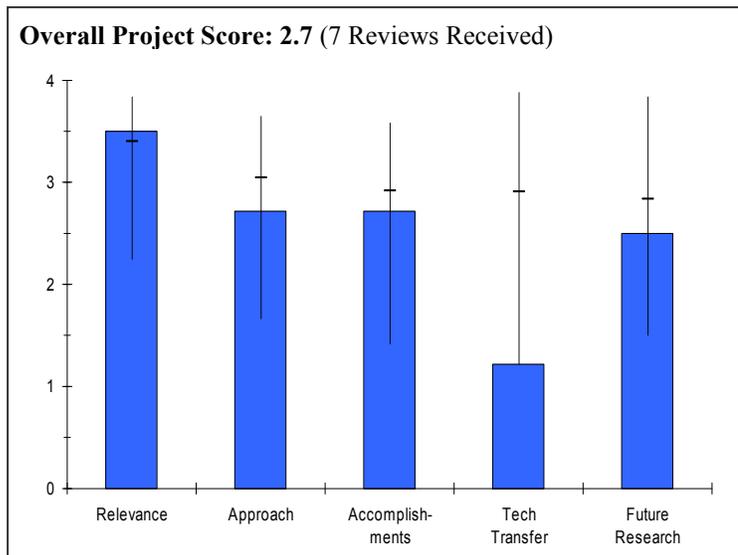
- Lack of partners.
- Macroscopic heterogeneity of membranes may lead to non-uniform current distributions in the cell.
- Alternative electrolytes may be difficult to perfect. Many barriers exist.
- More information on the materials or more thorough material evaluations needs to be provided to assess this work properly.
- There is no clarity regarding how certain targets will be met (e.g., freeze, additive stability).
- Samples described in the presentation must be more clearly marked. A sample code would help greatly.
- Mechanical testing limited to tensile strength and elongation measurements; mechanical testing needed for thinner membranes.

Specific recommendations and additions or deletions to the work scope

- Suggest inclusion of at least a broad description of the materials or materials properties to allow evaluation of project by reviewers.
- Project is early in its schedule. No recommendations at this time.
- Testing that assures stability of the additives in the membrane should be done in the next year.
- Obtain *in situ* mechanical cycling protocol from FreedomCAR Fuel Cell Tech Team.

Project # FC-19: Design and Development of High-Performance Polymer Fuel Cell Membranes*Ryo Tamaki; GE Global Research***Brief Summary of Project**

The overall objective of this project is to design and develop novel polymer electrolyte membrane materials for fuel cell operation at high temperature (up to 120°C) and low relative humidity (RH) (25-50% RH). The objectives for fiscal year 2007 are to 1) design and synthesize a cross-linked system; 2) prepare a high acid density proton exchange membrane (PEM) in porous supports; 3) integrate hygroscopic inorganic additives; 4) evaluate membrane performance at different relative humidity; and 5) improve chemical and thermal stability.

Question 1: Relevance to overall DOE objectives

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

- The development of high temperature/low RH membrane materials is highly needed for the successful commercialization of PEMFCs.
- The project addresses issues with fuel cell membranes and emphasizes hot and dry operating conditions.
- Project is aligned with DOE objectives and addresses DOE goals for PEM membranes.
- The project addresses most of the needs of DOE.
- Extended testing conditions are relevant to usage profile.
- Cost analysis is necessary for material modifications and additives addressed in the project and ensure those will be implemented with reasonable cost.

Question 2: Approach to performing the research and development

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

- The approach of random/block/grafted/cross-linked/reinforced HC materials is in-line with the industry's attempt to improve performance and durability of membrane materials based on these various membrane technologies.
- IP issues limit the ability for the reviewer to grasp the content at a high level.
- Barriers are addressed but approach is scattered. The PIs appear to have five or six different approaches – random copolymers, block copolymers, graft polymers, cross-linked systems, systems with porous supports, systems with additives, and want to try everything – not very focused.
- The approach is puzzling. The presenter says that there is an organic additive but the presentation describes an inorganic additive. The need for the porous support is also not explained. With the architecture of the polymers, there should be no need for this. It is puzzling.
- Unique and good approach of material modification to be sticking with target achievement.
- Weak at porous material downselection. Quantitative evaluation is necessary.
- Interactions among material modifications and additives should be tested.
- With the degree of swelling demonstrated, how can the support remain intact? Approach needs clarification.
- The approach taken in this project appears simplistic and has not benefited from advances made in other DOE sponsored research.
- Metrics for technical evaluation should be reviewed and aligned with DOE component technical targets.

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

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

- Progression of various generations show steady improvement in the material development in regards to proton-conductivity.
- No material durability has been investigated at this point.
- Have achieved acceptable conductivity compared to Nafion but no high temperature data yet.
- Claim year 2 milestone.
- Attempts with copolymer architectures have been unsuccessful.
- Cross-linking attempts have shown conductivity higher than or comparable to Nafion at high RH, but no real improvement at low RH – have not demonstrated conductivity at high temperatures.
- Significant progress appears to have been made. The presentation is a little unspecific and hence the lessons are hard to share.
- Promising performance data has been developed.
- Technical approach is not well thought out. More detailed characterization needs to be integrated into this program to determine viability of membrane.
- The project in early stages has demonstrated limited technical progress to date.
- Slide 17 – do not understand the advantage of reduced 'z' thickness change with significant x-y dimensional changes with cross-linking of the 4B polymer. This is the inverse of the technical objectives of other researchers so this appears to be disadvantageous.
- Recommend a technical go/no-go decision gate be added in the next phase/year to evaluate technical progress against DOE performance metrics.

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

This project was rated **1.2** for technology transfer and collaboration.

- No collaborators outside of GE.
- Will eventually need a MEA manufacturer. Will eventually need a stack developer.
- Should interact with an established MEA manufacturer, automotive company or a university or national lab with extensive experience.
- Very poor. There is no sharing or collaboration. The results are cloaked as well. This project is close to the line of misusing public funds.
- Fuel cell testing and collaborations should be planned.
- Cost should be analyzed to evaluate materials and processes, third party evaluation is recommended.

Question 5: Approach to and relevance of proposed future research

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

- Future work is in-line with the material development.
- Due to IP issues, it is difficult for the reviewer to fully understand and review this program at the level which is needed for the DOE.
- Continue more of the same.
- Cross-linked chemistry must have higher conductivity if placed in a porous support to make up for lack of conductivity of support. Also have stress issues between support and cross-linked ionomer, since these still appeared to swell quite a bit.
- Materials stability should be evaluated, e.g. retention of additives.
- Electrode interface characteristics should be investigated and recommend to pursue fuel cell testing.
- Needs to be expanded to and details provided about characterization to be performed.
- The proposed research is very general in nature and not directed at solving specific problems/issues.
- The project would benefit from staged metrics by which progress could be measured and activities directed at solving specific problems.

Strengths and weaknesses

Strengths

- Systematic approach to material development with the conventional technologies in membrane development.
- Brings a lot of different elements together which if performed correctly could result in a superior composite membrane.
- Systematic materials modifications.
- Material handling and testing capability.
- Understanding of fuel cell membrane requirement.
- Cross-linking polymers is a solid approach to adding sulfonic acid groups to polymeric chains to increase conductivity and strength.

Weaknesses

- Unclear how GE polymer will improve and with what technology as very little information was shared.
- There is too little disclosed to make a judgment on the approach, but many people have used inorganic additives previously with little success.
- Lack of collaboration.
- Have not shown improved conductivity at low RH yet.
- Approach lacks focus.
- NO collaborations.
- Interface characteristics between membrane and electrode.
- Project lacking fundamental mechanical integrity tests, Fenton's tests, and stability tests. The correlation between swelling (water uptake) does not correlate with the degree of cross-linking or sulfonic acid concentration and needs to be addressed. Measurement of swelling is primitive. Results to date are no any better than Nafion. Si should never be added to any PEMFC membrane (hydration layer is small and it is highly soluble in acid environment).
- This project update reflects a generic 'kitchen sink' approach, in which multiple approaches are being combined.
- Metrics by which technical progress can be evaluated could be improved.

Specific recommendations and additions or deletions to the work scope

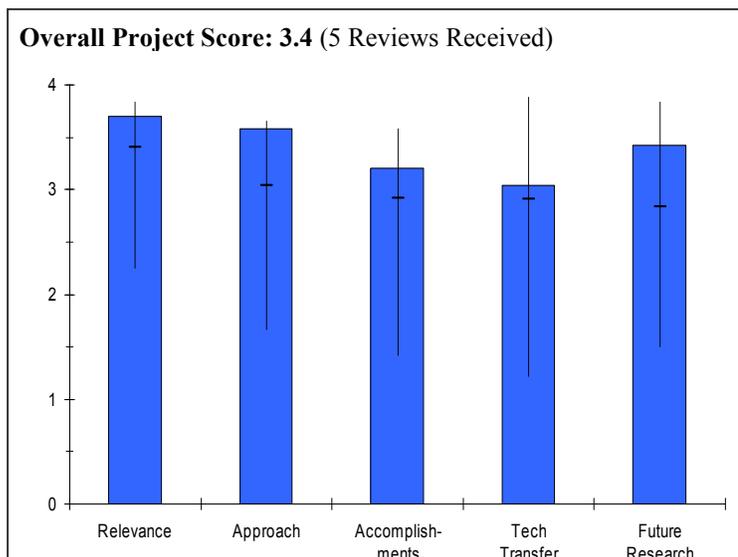
- Disclose IP after getting the IP protection – very difficult to gauge this project in the manner which is necessary.
- Eventually line up with MEA and stack developers.
- Establish collaborations with established expertise in the field.
- Develop proper collaborator to identify membrane/electrode interface characteristics and fuel cell testing.
- Pursue cost analysis on each materials modification addressed and ensure those are with reasonable cost.
- Technical metrics for each stage of development should be added into the project plan.
- Add metrics to evaluate cost potential of developed membrane technology.

Project # FC-20: Fluoroalkylphosphonic-acid-based Proton Conductors

Stephen Creager; Clemson University

Brief Summary of Project

The overall objective of this project is to provide new electrolyte materials for use in next-generation hydrogen fuel cell power systems, especially for transportation applications. The specific project objectives are to 1) synthesize and characterize new proton-conducting electrolytes based on the fluoroalkylphosphonic acid functional group and 2) create and apply new computer models to study proton conduction in fluoroalkylphosphonic acid-based electrolytes. The objectives for FY 2007 are to 1) synthesize and/or purify at least of 10 g each of one or more small-molecule fluoroalkylphosphonic acid electrolytes; 2) fabricate and validate an apparatus for measuring ionic conductivity of electrolytes at temperatures between ambient and 120°C and relative humidities between 25 and 100%; 3) develop classical force fields for and perform molecular dynamics (MD) simulations of low molecular weight fluoroalkylphosphonic acid electrolytes using the developed force fields; and 4) develop first generation of the multi-state empirical valence bond model (MS-EVB) for proton transport in fluorophosphonic acid.



Question 1: Relevance to overall DOE objectives

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

- The development of high temperature/low RH membrane materials is highly needed for the successful commercialization of PEMFCs.
- Project appears to focus on development of new, somewhat innovative electrolytes but stops short of actually synthesizing membranes for testing and evaluation.
- Project addresses the important task of identifying and qualifying a polymer candidate having acceptable conductivity over a broad range of RH levels and temperatures.
- The prospect of creating a phosphonic acid analogue of Nafion is particularly exciting. The utility of phosphonic acid groups at higher temperatures is almost as well-known as the leaching of phosphoric acid from membranes where phosphoric acid is bound only by hydrogen bonds.
- Mathematical modeling of the proton transport in the membrane is relevant to the progress towards developing membranes that conduct protons at lower humidity.
- The project is very relevant to the DOE program objectives in high-temperature, low humidity membranes.

Question 2: Approach to performing the research and development

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

- Fluoroalkyl-phosphonic acid based materials could provide a useful material to learn about proton-conduction mechanisms in a fuel cell.
- Synthetic approach is excellent.
- Modeling work has the potential to save time and money in membrane fabrication.
- Approach is directed toward the DOE targets of high-temperature, low-humidity PEMFC operation, but only emphasizes novel electrolytes rather than membranes – the ultimate measure of success would be incorporating

the new electrolytes into a membrane configuration. The project seems to stop short of the ultimate DOE objective of high-temperature, low-humidity membranes.

- The project includes a strong modeling effort.
- Good "scouting approach", with reality checks along the way.
- Screening test method for evaluating conductivities of liquid electrolyte candidates – good approach.
- Will the "work details" supporting the defined tasks be sufficient to resolve any deficiencies due to "benefit" assumptions for fluoroalkyl-phosphonic acids (weaker adsorption, higher oxygen solubility, chemically/thermally stable)?
- The sequential approach to transition from small molecules to monomers to the polymers themselves is reasonable.
- The one failing of the approach is that it neglects to include mathematical modeling of Nafion. How would the proton transport change from a perfluorosulfonic acid to a fluoroalkylphosphonic acid?
- The approach is very good. The concept represents a potential solution to high-temperature, low-humidity membrane.
- Understanding small molecule synthesis and simulating proton transport for low RH conditions is critical for success.
- The approach is a novel attempt to maintain adequate proton conductivity at low humidity conditions.
- Molecular modeling is being used to guide the synthesis of the fluoroalkylphosphonic acid electrolytes. Theory-guided synthesis provides a rational basis for certain pathways.

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

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

- Synthetic approach and modeling approach have thus far has shown success.
- Project is only 20% complete.
- To date, and given the limitations of project objectives, project appears to be off to a reasonable start with modeling refinement underway and several candidate electrolytes synthesized and initially tested.
- Good progress to date on several fronts (modeling, polymer synthesis, etc).
- Validation of conductivity apparatus for phosphonic acid has been completed.
- A different monomer has been synthesized than expected due to surfactant issues. Is there a way to use a different solvent in order to create the intended monomer? Is it possible to use the unintended monomer to enhance cross-linking for a new and unintended polymer (which would still be very interesting)? These issues should be explored.
- Equivalent weight is high.
- Good progress has been made on thermal stability.
- Progress has been made on reducing computation time for modeling.
- Good progress shown in difficult synthesis of small-molecule model compounds and trifluorovinyl ether monomers.
- Conductivity measurements are underway for several fluoroalkyl-phosphonic acids. The first results approach the 0.07 S/cm target.
- Molecular dynamics simulations are underway for two electrolytes. The simulations will be validated against NMR and conductivity measurements.

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

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

- Excellent team and collaboration of university professors.
- Will need industry support at some point to confirm the commercialization of this project.
- Several potential collaborators identified, but to date little actual collaboration accomplished. Perhaps this will come later.
- Project appears to have good selection of participant skills to achieve project goals, in particular computer modeling.

- Project is missing an industrial partner, who may be needed for resolving current and future polymerization issues.
- Collaboration with Kreuer bodes very well for this project.
- Industrial monomer synthesis experience could assist in removing hurdles concerning the monomer synthesis.
- Close collaboration between Clemson (synthesis) and University of Utah (theory) is evident.
- Two other collaborators on NMR studies are mentioned.

Question 5: Approach to and relevance of proposed future research

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

- Future work is in-line with this membrane material.
- The target is difficult and needs to be followed very closely to see if this material can achieve the DOE targets.
- Future plans appear to be appropriate and well-thoughtout.
- Project tasks are clearly focused on targets and milestones.
- During the next phase of this project, the PI should identify qualified resources who might assist in resolving potential setbacks in preparing useful polymer samples – should that become necessary.
- The future work follows closely with the established approach, which is the strength of this project.
- Items that would improve the future work have already been mentioned (enhanced industrial collaboration, modeling of Nafion to compare against the fluoroalkylphosphonic acid).
- Future activity involves continuing synthesis and characterization of small-molecule model compounds and optimizing ionomer preparations.
- Molecular dynamics simulations will prevent the synthesis of compounds that do not exhibit adequate proton conductivity at low humidity. The work is highly relevant to the objectives of the DOE program.

Strengths and weaknesses

Strengths

- Good researchers with clear scientific approach.
- PI has a strong background in the required technical areas and is well prepared to address the project goals and objectives.
- Computer modeling efforts and analysis regarding expected properties and performance.
- Disciplined, meticulous approach.
- The most compelling chemistry amongst the DOE membrane projects.
- Depth of planning regarding the mathematical modeling approach.
- Progress made on synthesizing small molecules.
- Progress made on thermal stability.
- The project is an excellent example of the use of theory to guide synthesis of materials that show promise for good proton conductivity at low humidity and high temperature.

Weaknesses

- Assumptions are made which could end up being invalid – phosphonic acid vs. sulfonic acid strength and ability to operate at low RH and high temperature.
- Lack of industry support to validate the commercialization of this project.
- Project seems to stop short of actual membrane fabrication and testing.
- Current monomer end group "fixes" may not be suitable for successful aqueous emulsion co-polymerization.
- Too many assumptions, e.g., "fluoroalkyl-phosphonic acids should be chemically and thermally stable", etc.
- Hurdles have arisen in monomer and polymer synthesis.
- The synthesis of the various phosphonic acid-based electrolytes is likely to be difficult.
- Conductivity drops off significantly at low temperatures.
- While a rationale for the choice of a phosphonic acid membrane was presented, it was not supported by theory/calculations that showed that the phosphonic acid-based membranes are indeed better than sulfonic acid-based membranes.

Specific recommendations and additions or deletions to the work scope

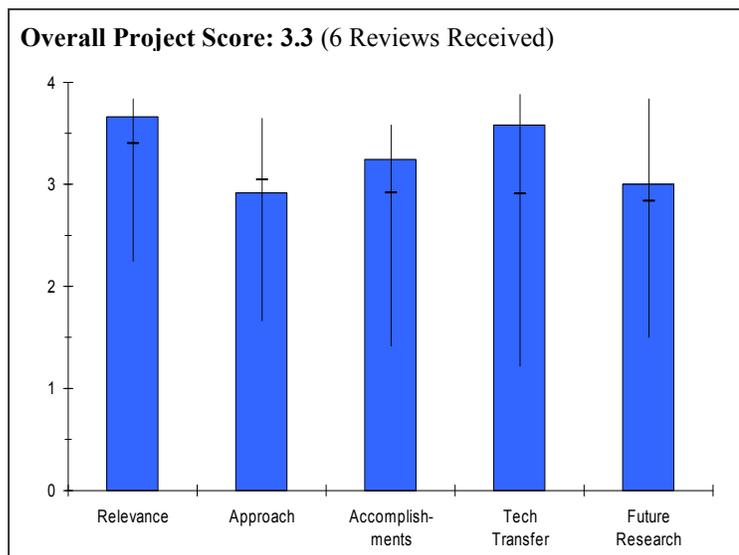
- Involve industry at some point to keep the project realistic in regards to scale-up and commercialization.
- Prepare membranes using the "best" electrolytes for test and evaluation.
- Select alternative monomer with end-group compatible with aqueous polymerization (e.g., one that does not need separate surfactant).
- Industrial collaboration on monomer synthesis.
- Mathematical modeling of Nafion as a baseline versus the fluoroalkylphosphonic acid polymer.
- The project should be continued long enough to allow for an adequate amount of research to determine the true potential of this approach even if the initial results do not meet the interim milestone of 0.07 S/cm at 25°C and 80% RH.
- Some thought should be given to the cost of producing these membranes.

Project # FC-21: Dimensionally Stable High Temperature Membranes*Cortney Mittelsteadt; Giner***Brief Summary of Project**

The fiscal year 2007 objective of this project is to demonstrate, by the 3rd Quarter, membrane conductivity of 0.07 S/cm at 80% relative humidity at room temperature using non-Nafion materials. Samples will be prepared and delivered to the Topic 2 awardee. Samples will be prepared and delivered to the Topic 2 awardee.

Question 1: Relevance to overall DOE objectives

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



- The goal of this project, to develop a proton-conducting membrane that can operate under low relative humidity conditions and high temperatures, is critical to the Hydrogen Fuel Initiative as it will decrease the cost and complexity of polymer electrolyte fuel cell power systems.
- Development of membrane for operation under hot and dry conditions.
- The project is relevant to DOE goals. If it turns out that water is necessary to achieve the goals then a higher EW is necessary. The swelling issue will then be critical. This approach is therefore good for dealing with this problem.
- The project addresses development of membranes for high temperature and low humidity. This is one of the key enabling technologies for automotive PEM.
- This project is very well aligned with the DOE H₂ Fuel Initiative.
- The Giner project aligns very well with the DOE objectives for high-temperature, low-humidity membranes.

Question 2: Approach to performing the research and development

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

- A reasonable rationale for the low equivalent weight, PFSA approach was given.
- The stability of membranes utilizing extremely water soluble, low equivalent weight ionomers is questionable.
- Using very low EW material in a stable 2D or 3D support.
- The premise is ok but it assumes water is always necessary. The humidifier problem will be horrendous. The use of the particular supports described is not immediately compelling. Will there be an adhesion problem?
- It is not clear why PFSA would provide the desired properties at high temperature and low humidity simply because it is held in a dimensionally stable matrix.
- It is not clear how separation of the monomer from the walls of the matrix would be prevented during cycling, especially humidity swelling and shrinking cycles.
- Approach is both appropriate and logical.
- The project focuses on understanding how support matrices can be used as a design option and technical feasibility of this option is well assessed.
- Excellent use of metrics to monitor and track technical progress.
- The approach is very good, innovative, and relatively low-risk. It is one of several different approaches taken by DOE to achieve membranes for high-temperature, low-humidity operation.
- It is focused on the technical targets required for automotive applications.

- The polymer support provides needed strength and stability for the incorporation of a low equivalent weight ionomer to increase conductivity at low RH.
- There is a need for adequate conductivity at very low ambient temperatures so that a fuel cell vehicle can achieve an unassisted start. Conductivity at low temperatures should be measured.

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

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

- The progress toward achieving the objectives of this project has been excellent and the Year 1 milestones have been achieved.
- Have investigated polyimide and polysulfone 30 μ hole/50% void space supports.
- Have demonstrated 700 EW PFSA in a fuel cell, but best at 100% RH.
- Polymerized Nafion monomer with co-monomers and impressively made the Nafion homopolymer.
- Good progress made.
- The project is fairly new so major progress is not expected.
- A significant portion of the progress seems to concern the matrix mechanical properties.
- The system shows no advantage over Nafion at low (25%) humidity (Slide 16).
- This project has elucidated the challenge and has made good progress in understanding methods of achieving the technical goals.
- Giner has demonstrated that their supported, dimensionally stable membrane achieved a conductivity of 0.1 S/cm at 30°C and 80% RH. This accomplishment meets the interim DOE target.
- Performance of the low equivalent weight-supported membrane in a fuel cell operating at 95°C and 25% RH was much worse than had been predicted.
- The supported membrane did not swell on the x-y plane and the ionomer did not separate from the support when dried.
- Giner appears to be making steady progress towards the objective.

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

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

- Excellent partnerships with GM and SUNY-ESF. Partnership with GM will facilitate the rapid incorporation of new membranes into fuel cell systems.
- Collaborations are a bit weak since GM owns the company.
- This project incorporates good coordination and guidance from GM.
- Close collaborations are evident with SUNY (new ionomers) and with GM (automotive targets for membranes).

Question 5: Approach to and relevance of proposed future research

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

- Continue to synthesize new ionomers.
- Expand work to 3D supports.
- Future work logically follows progress to date.
- More emphasis should be put on monomers than on the matrix.
- The planned work is appropriate. An evaluation of solubility of impregnated polymers in the DSM might be included if it is viewed as a risk item by the project team.
- Future plans are focused on developing even lower equivalent weight ionomers to achieve 0.1 S/cm at the low humidity condition.

Strengths and weaknesses**Strengths**

- Support architectures.
- Access to novel PFSA polymers.
- Well-focused and directed effort.
- The effort is well focused and driven by a clear understanding of automotive requirements.

Weaknesses

- It is not clear how this really differs from work at Gore and other MEA manufacturers using reinforced/supported membranes.
- Need more polymer characterization in the program. Adhesion will be a problem.
- A clear path to synthesizing an ionomer with low enough equivalent weight to meet the conductivity requirement yet remaining stable is not evident.

Specific recommendations and additions or deletions to the work scope

- Fuel cell work should be postponed until after the Go/No-Go decision has been passed.
- The laser-drilled 2D support is impractical and should be used to direct research using the 3D support.
- Giner needs to balance the need to understand the poor fuel cell performance against the need to develop new ionomers with low equivalent weight. Significant resources should not be diverted from ionomer development to understand the fuel cell performance issue at this time.

Project # FC-22: New Proton Conductive Composite Materials with Co-continuous Phases Using Functionalized and Crosslinkable TFE/VDF Fluoropolymers

Serguei Lvov; Penn State

Brief Summary of Project

The overall objectives of this project are to 1) contribute to DOE efforts in developing a high temperature proton exchange membrane (PEM) for transportation applications and 2) develop a new composite membrane material with hydrophilic inorganic particles and TFE/VDF polymer matrix to be used in PEM fuel cells at -20 - 120°C and 25-50% relative humidity (RH). The Year 1 objectives are to: 1) synthesize inorganic proton-conductive materials; 2) develop chemistry for functionalized TFE/VDF polymers; and 3) develop membrane fabrication methods.

Question 1: Relevance to overall DOE objectives

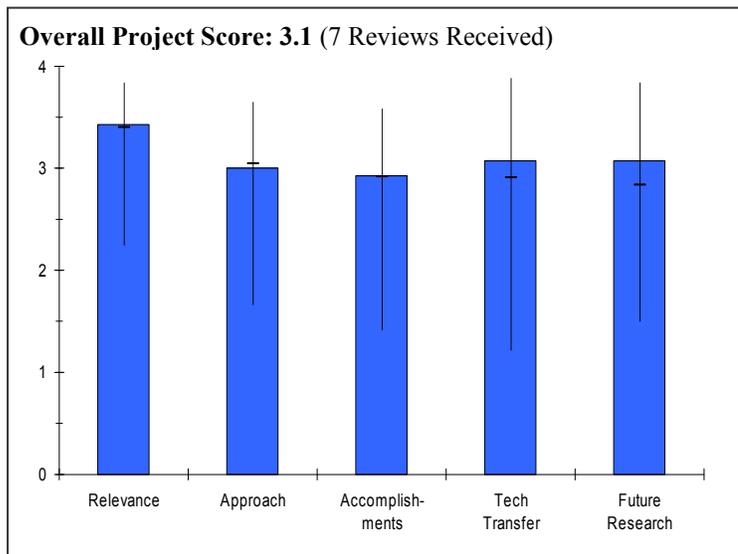
This project earned a score of **3.4** for its relevance to DOE objectives.

- Addresses the DOE goal of developing a high temperature, low relative humidity membrane for PEM fuel cells.
- The project is highly relevant to the DOE's objectives and to support the President's Hydrogen Fuel Initiative.
- Project aligns to multiple challenges of the hydrogen vision.
- New material development is important.
- This project addresses the need for high temperature membranes.
- Relevant.
- The development of composite membranes with hydrophilic inorganic particles in a functionalized fluoropolymer matrix is one of a number of diverse approaches being taken by DOE to meet the advanced membrane targets. The project is very relevant to the DOE objectives related to high-temperature, low RH membranes.

Question 2: Approach to performing the research and development

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

- The technical approach focuses on the development of a composite membrane - a unique and innovative approach.
- The project is for 5 years. The project addresses the polymer membrane electrolyte issue. The technical approach for the program is excellent. The tasks are clearly presented.
- The project is well organized and divided into manageable tasks.
- To provide a membrane that meets DOE targets, it is likely that more will be required than hydrophilic additives. It is not clear that the polymers being used here will provide the required conductivity or durability to do this. Nafion does not.
- Achieving percolation will be difficult if matrix is not conductive.
- Blending with Nafion—unlikely to help, especially if the same equivalent weight is used.
- The proposed technique will make it difficult to get small particle sizes.
- The approach has multiple pathways to achieve the desired conductivity including different avenues without Nafion. This increases the chances of success.



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

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

- Given that the project is only 20% complete, progress has been good.
- Several initial composite membrane samples have been synthesized.
- Testing/characterization instrumentation in place with initial conductivity measurements done.
- The project was started in May 2006. It is too early to make a judgement for technical accomplishments at this time. However, the project progress is excellent.
- Project has accomplished year 1 tasks, but more clear alignment to DOE technical targets should be shown.
- There is nothing to suggest that the polymers used have adequate chemical stability. The path to high conductivity under hot, dry conditions needs to be explained more fully. The current conductivity is quite low.
- None of the approaches appear to come close to Nafion.
- No mention of durability.
- The accomplishments by the PSU team have been pretty significant. Several inorganic additives have been synthesized, the most promising of which is zirconium phosphate.
- The team prepared several membranes with these additives in a fluoropolymer matrix and measured the conductivities of the composite membranes. Initial results showed conductivities at 120°C and 70% RH to be about 0.01 S/cm. This conductivity was achieved with poly VDF-CTFE/Nafion blends.
- Conductivities of the non-Nafion-containing polymer composites were about three orders of magnitude less than the those containing Nafion.

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

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

- Conductivity instrumentation provided by BekkTech—it wasn't clear whether this was a collaboration or just a procurement.
- ORNL was mentioned as a collaborator in characterization, but there was no indication of interactions with ORNL to date - perhaps this is to come later in the project.
- The project was started in May 2006. It is too early to transfer technology to industry at this time.
- Collaboration appears to be primarily within Penn State.
- Consider collaboration with membrane supplier.
- A good team has been assembled for this project.
- A good team in place.
- Collaboration with ORNL and with BekkTech is in evidence.
- Many stakeholders provided input in formulating the baseline assumptions and defining market requirements and criteria for acceptance.

Question 5: Approach to and relevance of proposed future research

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

- Project appears to be off to a good start - future plans appear to appropriate and reasonable.
- Based on the presentation information, the future research work is clearly presented and technical approaches are reasonable.
- Future work continues overall solid plan.
- Important to reach go/no-go decisions.
- Eliminating Nafion has been proposed, but given the low conductivity of the alternates, unclear how realistic this is.
- Future plans call for continuing to modify materials and process conditions in an iterative fashion until the conductivity requirements are met. A rationale for specific modifications should be developed.

Strengths and weaknesses

Strengths

- A high risk approach, but with a potential high reward.
- PI is knowledgeable, understands the challenge, and has structured a meaningful research project and clear, well-defined objectives.
- The PI, co-PI, and coworker have excellent R&D experience for polymer membrane electrolyte chemistry.
- Well organized.
- Approach is novel.
- The PSU project team has succeeded in casting composite membranes. With some Nafion in the blend, conductivities approached that of Nafion.
- New mechanisms for conduction through the interfaces in composite materials.
- The work was well received by the community.

Weaknesses

- Stability of the composite membrane may be an issue.
- SiOH attack may adversely affect stability and membrane lifetime.
- Water may hydrolyze the silane functional group.
- The polymers used may not have adequate chemical stability. The path to high conductivity under hot, dry conditions needs to be explained more fully.
- Focus appears to be on testing a number of additives, none of which seem to come close to milestones. An alternative approach (Plan 8) would be useful.
- Durability not addressed.
- Without Nafion the conductivities of the composite membranes were quite poor.

Specific recommendations and additions or deletions to the work scope

- This project just started the second year, project progress is excellent. No action is needed at this time.
- Reduce the number of additive options.
- The project could benefit from theory/simulation of the conduction mechanism to see how it matches with experiment.

Project # FC-23: Advanced Materials for Proton Exchange Membranes

James McGrath; Virginia Tech

Brief Summary of Project

The overall objective of this project is to design, identify, and develop the knowledge base to enable proton exchange membrane films and related materials to be utilized in fuel cell applications, particularly for H₂/air systems at 120°C/low relative humidity (RH). Thermally, hydrolytically, and oxidatively stable aromatic ionomers with high T_g, ductility, and controlled hydrophilicity are required. The PI will synthesize linear multiblock hydrophobic/hydrophilic copolymers.

Question 1: Relevance to overall DOE objectives

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

- This work aims to improve the performance and durability of low cost membranes.
- New polymeric systems should be a component of the longer term approach to address the key objectives of the DOE program with respect to stack life.
- The program addresses an important aspect for development and introduction of automotive PEM fuel cells.
- Relevant.
- This project is directly relevant to key component technology goals of the President's Hydrogen Fuel Initiative.
- The project objective is critical for realizing a renewable energy economy.

Question 2: Approach to performing the research and development

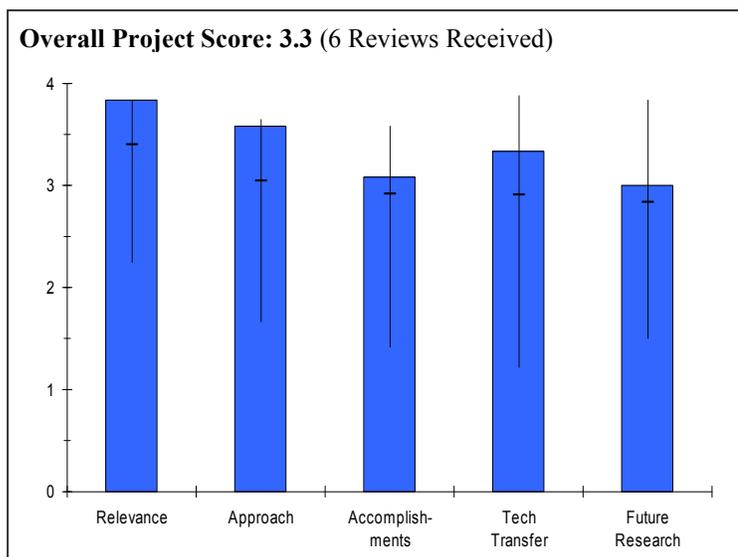
This project was rated **3.6** on its approach.

- All approaches make sense (block copolymers, lower x-y swelling, Flory-Huggins modeling).
- PI is conducting all the right *ex situ* tests (conductivity vs. RH, dimensional stability, mechanical tests, structural analysis).
- Approach is sound – block co-polymers have a chance of evolving into a viable membrane with tailored properties.
- Synthesis route and supporting activities approach are appropriate for this level of funding and commitment.
- Understanding of mechanical properties and water transport and conductivity mechanisms is a key part of this effort.
- The approach builds on previous work at VA Tech.
- Very elegant – a good mix of fundamental and applied science.
- This project has a logical approach to understand and develop novel polymer materials.
- Good understanding of key material attributes has been demonstrated by the project team.
- The PI provided a noble approach for low relative humidity operation understanding property/structure relationship.

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

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

- Significant progress in conductivity and swelling reduction.
- Still need to demonstrate fuel cell performance and durability.



- Too early to really assess the results but the materials under study and the approach will provide greater insight with time.
- Conductivities of new materials are comparable to Nafion.
- Mechanical behavior of some of the new materials has been evaluated and compared to Nafion.
- Water retention of the new materials is higher than Nafion.
- Low RH results are very impressive – certainly a step in the right direction. Same with water retention.
- This project is focused on developing novel materials and leverages from previous DOE-sponsored R&D by the same team. It has demonstrated good to outstanding technical progress as well as deeper understanding of the polymer design factors.

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

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

- PI has taken advice of OEMs.
- PI could benefit from some external testing of the membranes.
- None.
- Team includes LANL, Giner, and Hydrosize.
- Good team.
- This project has good collaborations, however these were not well highlighted in this review presentation.
- Contributions from the partners were not discussed.

Question 5: Approach to and relevance of proposed future research

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

- PI should include fuel cell performance and durability testing in future work.
- Prof. McGrath is a solid contributor and what is proposed is exactly what needs to be done.
- Future research builds on progress and addresses issues relevant to attainment of project and DOE goals.
- Should include chemical degradation! Otherwise sound.
- The proposed work is focused on polymers but not on creating fuel cells with films made from these polymers.
- Proper plan has been laid out for the next step.

Strengths and weaknesses

Strengths

- PI shows excellent combination of synthesis, characterization, and modeling skills.
- Solid team and lots of history and experience with such polymeric materials.
- Innovative approach – examines most angles.
- Excellent PI and team.
- Strong level of innovation in this project.
- New approach to formulate fuel cell membranes.

Weaknesses

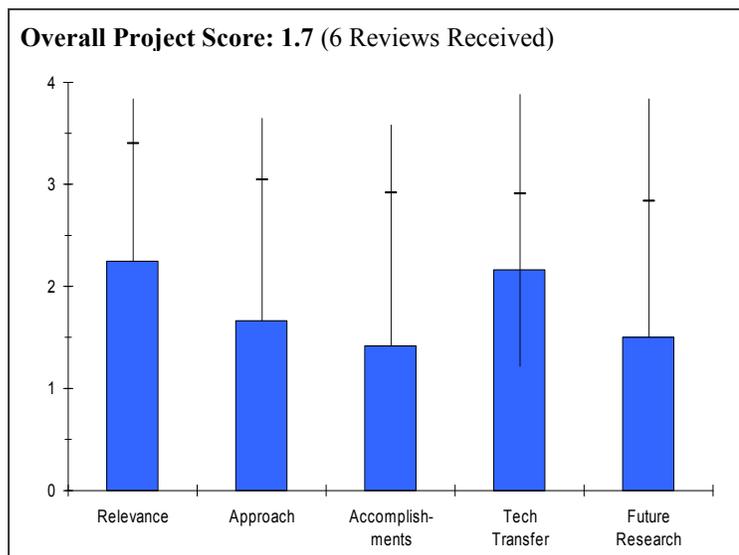
- Materials unlikely to meet 2015 DOE performance targets.
- Use of tensile tests as sole measure for mechanical strength.
- Durability not yet addressed.

Specific recommendations and additions or deletions to the work scope

- PI should include fuel cell performance and durability testing in project scope.
- PI should consider doing cost of production study of most promising membranes.
- Durability tests should be introduced.
- Addition - an assessment of these novel polymers against key performance and failure modes (such as wet/dry hydration cycles) to be used as a metric to measure progress.

Project # FC-25: Center for Intelligent Fuel Cell Materials Design Phase 1*Denise Katona; Chemsultants International***Brief Summary of Project**

The objective of this project is to develop novel polymer architectures capable of 1) improved mechanical stability vs. Nafion (117) 212; 2) improved conductivity vs. Nafion (117) 212; and 3) $\geq 120^{\circ}\text{C}/\leq 50\%$ relative humidity (RH) operational capability (4,000 hours). Additionally, the project aims to identify new solution casting methodologies for thin, roll-to-roll membrane formation. This could consist of thin single layer membranes, discrete multi-layer membranes and reduction in stack component cost (membrane).

Question 1: Relevance to overall DOE objectives

This project earned a score of **2.3** for its relevance to DOE objectives.

- The pursuit of improved membranes for high temperature and low RH conductivity is reasonable. However, the project is following routes thoroughly explored as much as 10 to 15 years ago by the research community. The work presented is essentially "reinventing the wheel" and not using the most current and evolved technology in the area. The exception to this is the novel additives that are being pursued, however this is a fairly minor addition to the state of art in this area.
- Addresses new membrane materials.
- Addresses manufacturing needs of the hydrogen economy.
- This project involves sulfonation of a commercial polymer. Little new knowledge is generated for the DOE objectives. It may demonstrate the company's capabilities but does not contribute to new knowledge.
- This project is relevant to the objectives of the HFCIT program as addressing the important issue of high temperature membrane.
- Insufficient targets for either automotive or stationary application.
- For automotive, performance and materials stability at lower temperatures are required.
- Unclear project objectives, long-term research project or short-term optimization based on available materials?
- The technical objectives related to development of new materials are highly relevant to DOE goals. The objectives to identify new solution casting film manufacturing processes are not relevant as these are well established and mature.

Question 2: Approach to performing the research and development

This project was rated **1.7** on its approach.

- Post-sulfonation of poly ether sulfones has been done in the past. The community generally favors polymerization of sulfonated monomers at this time as the resulting materials tend to have lower water uptake and higher conductivity. Combining additives to polymer electrolytes is a viable approach to improving high temperature membranes, however little understanding of the system or of prior work in this area has been demonstrated in the presentation.
- Polymer modification.
- Addition of nanoparticles.
- Optimization of loadings/layers.
- Manufacturing.

- This project appears to be a demonstration of capability. It provides little new insight. What is the purpose of the nanoparticles?
- The approach used in this project is not innovative; this applies to both "modification" of polymers and the use of "additives".
- The advantages of the approach taken remain unclear.
- Benefits from the use of SEM, TEM and other microscopic techniques are not obvious at the moment.
- Further investigation is necessary to identify proper metrics for performance target. Water uptake is not sufficient to characterize to achieve proton conductivity target.
- Not meaningful to investigate the manufacturing process prior to characterization of materials.
- For fuel cell testings, materials and MEA design (other than membrane materials) should be defined and identify correlation between membrane material and fuel cell performance should be identified.
- Unclear criteria to use additives A and B.
- This project has insufficient focus on the key performance metrics and premature focus upon manufacturing methods. The polymer platform chosen does not appear to be adequate in terms of its basic properties and the separation of the effects of the nanoparticle additives from those of the base polymer platform was not highlighted (beyond the *ex situ* properties table which is insufficient).

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

This project was rated 1.4 based on accomplishments.

- Conductivity and fuel cell performance reported are regressing from current state-of-the-art already demonstrated for similar materials. Roll-to-roll processing may be of some value, however the materials being investigated are of too inferior a quality to make much difference at this time.
- Very little data was presented on conductivity, and none was presented as a function of relative humidity.
- There appears to be little evidence that any significant improvements in conductivity have been achieved at hot or dry conditions.
- Fuel cell testing using bad MEAs and no evidence of reproducibility or error analysis.
- Manufacturing of polymers with minor improvements will not be useful.
- The project has made polymer films. Unfortunately, they do not work. The results show little chance of reaching the goals. The presenter displayed ignorance of how a fuel cell works by not knowing if the polymer was used in the electrode.
- Subpar performance data obtained with the reference Nafion membrane make all performance comparisons difficult.
- Difficulties with performance comparisons notwithstanding, polarization plots indicate significant performance drop relative to Nafion, especially at low current densities.
- Tensile strength drop at high sulfonation levels is somewhat disappointing, especially in the context of the stated intent to obtain polymers with improved mechanical stability vs. Nafion.
- Fuel cell performances are insufficient (low performance to proceed).
- Effects of additives should be evaluated.
- Even though the project is 65% complete, there is little demonstrated progress against the key technical performance goal!
- This project is looking to develop a suitable polymer system for higher temperature, lower RH operation but there is only relatively poor *in situ* performance demonstrated at relatively "gentle" operating conditions (80°C and 50% RH).

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

This project was rated 2.2 for technology transfer and collaboration.

- Michigan Molecular Institute and Case Western Reserve University are collaborators. Coordination seems reasonable, however the experience of this team appears insufficient and the addition of more experienced researchers in this area could greatly improve the project.
- Collaboration with Michigan Molecular Institute, GrafTech, and Case Western.

- On paper this looks good. However, if the investigator really had interactions with CASA, she would have been able to answer some critical questions.
- The flow of information between Chemsultants and Case Western pertaining to the materials testing should be improved, including such important issues as electrode compositions, possible reasons for poor fuel cell performance, etc.
- Disconnection between materials test and fuel cell testings.
- It appears that better overall leadership and prioritization of activities between partners would help this project focus on the key risk areas.

Question 5: Approach to and relevance of proposed future research

This project was rated **1.5** for proposed future work.

- Future work is more of the same, focusing on approaches demonstrated by others that have not led to materials that were sufficient to meet DOE technical targets.
- New polymers.
- New additives.
- Fuel cell testing – premature.
- Manufacturing – premature.
- Do not know where this is going.
- Poor performance to date makes the need for scale-up questionable at this time.
- Future work should focus on major improvements to membrane/MEA performance.
- Materials characterization to achieve the target is insufficient to larger scale testings and manufacturing process study.
- Given the future work stated, this project has low probability of reaching its technical goals with the remaining budget and time. Focus on achieving technical performance goals (higher temperature, low RH conductivity) should be prioritized in favor of efforts on low technology risk activities such as film manufacturing.

Strengths and weaknesses

Strengths

- Few.
- Nice use of novel nano-inorganic functionalized additives.
- Manufacturing.
- Demonstrated manufacturing by two different techniques.
- Materials optimization for hydrocarbon-based polymer electrolysis.
- Consideration of synthesis and film fabrication provides valuable direction to the core material development.

Weaknesses

- Too much emphasis on fuel cell testing and manufacturing of materials with few advantages over existing materials.
- Investigator does not appear to know how a fuel cell works.
- Very little achieved in spite of very significant funding.
- Response to questions was not the strongest part of the presentation, among others, indicating certain disconnect between Chemsultants International and partners at Case Western.
- Understanding of fuel cell membrane requirements and metrics.
- Insufficient focus on core material properties.

Specific recommendations and additions or deletions to the work scope

- This project provides almost no value to the community and the funding for the project would be much better spent elsewhere.
- Emphasize investigations of composite membranes and conductivity testing.

FUEL CELLS

- Do not perform fuel cell testing or manufacturing on these materials. The project is too short and the emphasis should be on materials discovery.
- This project should be terminated.
- Much better performance should be demonstrated before any effort is invested in scale-up and manufacturing; without a major improvement in MEA performance, this project should be terminated.
- An addition of a sound cost analysis would help better understand benefits of the approach.
- Basic evaluation of membrane stability is needed.
- Focus on membrane materials characterization for the rest of the project time.
- Further investigation to identify proper metrics for material characterization, other than water uptake, e.g., dimensional stability, etc.
- Incorporation of feedback from fuel cell performance testings.
- Add metrics and project technical gates for core material performance metrics, consistent with DOE technical goals.
- Reduce or delay activities focused on low technical risk activities such as film manufacturing.

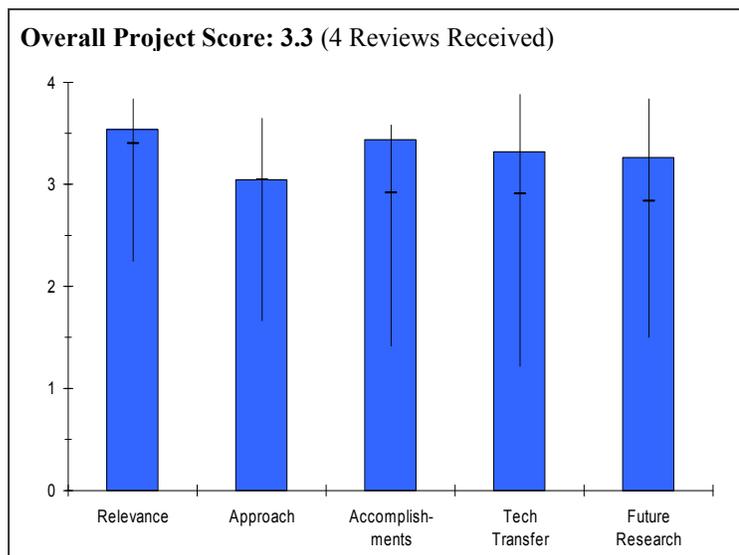
Project # FC-26: Economic Analysis of Polymer Electrolyte Membrane Fuel Cell Systems

Kathya Mahadevan; Battelle

Brief Summary of Project

The objective of this project is to assist DOE in developing fuel cell systems by analyzing the technical, economic, and market drivers of direct hydrogen proton exchange membrane fuel cell (H-PEMFC) adoption. Support in 2006 included 1) market segmentation of 1-250 kW H-PEMFC into near-term (2008) and mid-term (2012) market opportunities; 2) lifecycle cost analysis of H-PEMFC and competing alternatives in near-term markets; and 3) market opportunity assessment of H-PEMFC in near-term markets.

Question 1: Relevance to overall DOE objectives



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

- The project objectives are very closely related to DOE objectives.
- The market analysis data that will be collected in this project are very critical to understand the market.
- The cost comparison data resulting from this project will be very crucial for fuel cell manufacturers for developing their technology.
- The market opportunity data from this project will give the clear understanding on the market readiness for fuel cell technology.
- The cost modeling will be valuable to determine the possibility of success in different market segments, such as forklift, portable, federal markets, etc.
- DOE is coming to an increased realization that early adopters in "premium power" markets will provide private-sector market pull (demand) for advancement in fuel cell technology (i.e., through private sector investment). These technical advancements could then "spill over" into the more demanding automotive application.
- This project is a thorough and comprehensive study to determine market niches for which fuel cell technology could be competitive today, thus providing seeds for technology development within the private sector.
- Near-term market understanding is a critical stepping stone to the transportation sector and a clear independent analysis is in full support of the DOE objectives.
- All fuel cell manufacturers are likely doing similar studies without government help.
- Much PEM system technology is not the same for automotive and non-automotive applications.
- Not much can be gained from this study to help project goals.

Question 2: Approach to performing the research and development

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

- Company sampling and information collection process was adequate.
- The approach to the market and cost data collection and analysis techniques was adequate.
- The approach to the development of market penetration modeling was good.
- Near- and long-term market selection process through information collection was adequate.
- The data on the reliability expectation of the customer companies can be included as a part of this model.
- The "Approach" slide (#4) is eye-candy for management. In reality, the "approach" of this project must be judged on the strength of its research.

- The PI demonstrated a thorough and comprehensive research program that provides a solid foundation for conclusions ultimately reached.
- The topic is really broad so it is reasonable and understandable that the scope had to be limited in the quantitative analysis to only PEM fuel cells and to the fuel cell specific markets.
- Suggest that consideration be given to speaking to financial stakeholders such as venture capitalists in this sector or to investment banks that cover some of the public fuel cell companies to see how they view the market.
- In the report, some qualitative analysis may be appropriate on the applicability of other fuel cell technologies like solid oxide or DMFC.
- Even much larger numbers of survey responses than involved in this study are known to be unreliable. Survey answers also are known to depend on the questions and how they are phrased.
- There did not seem to be any innovation or significant original thought in the approach.

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

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

- Seventeen completed surveys and three meetings for USFCC.
- The outcome of the H2A model for comparison between fuel cell and alternate power seems to be realistic.
- Capital cost barrier for H-PEMFC implementation was addressed.
- Forklift market analysis (cost, life, battery comparison) will be very useful to fuel cell community.
- Reliability and capital cost for forklift implementation was determined.
- Market penetration analysis for forklift products will be very useful for fuel cell developers.
- The PI demonstrated detailed results for the forklift and material handling equipment, and indicated that similar analyses (for other markets) were part of the final report, available to DOE.
- A note on slide #19, "Reduce[d] vehicle repairs due to fewer moving parts." True – the repairs may not be due to moving parts, but what available data justifies a claim that one technology would require fewer repairs, regardless of cause?
- Very thorough analysis was done. One comment for improvement is to clearly articulate what of the results was different or improved upon from last year. It feels like I heard most of this before.
- Neither the limited modeling nor the few resulting projections represent significant accomplishments.

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

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

- The data and model out of this project will be available to public.
- Considerable collaboration between the fuel cell developers and customers from different market segments are being developed through this project.
- The data will be shared with future fuel cell developers to give them the realistic view on the market.
- The nature of this work was to have extensive interaction with potential customers and suppliers during the research phase.
- The accumulated data and conclusions of this project would be best reviewed by opening them to validation by all stakeholders (i.e., as part of the formal process, both prospectively (before new market adoption) and retrospectively (after field experience in new markets is obtained).
- Strong outreach to industry and other technical stakeholders.
- There is little evidence of collaboration except perhaps with NREL.
- The individuals contacted and/or surveyed and/or participated in discussion groups hardly represent technology transfer or collaboration.

Question 5: Approach to and relevance of proposed future research

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

- The same approach will be taken to collect VOC data and develop models for federal and portable markets.
- The study will be restricted to H-PEMFC for portable markets, unless DOE advises otherwise.
- DMFCs for portable markets won't be considered for future work.
- The forklift market penetration and viability analysis will be a good tool to develop future models.
- The PI is wise to address EPACT requirements in future work.
- Clearly articulates what will be done for the balance of 2007 and within the current scope of funding.
- Would have liked to see some specific recommendations for how they could take this research to the next level of detail in out years if more funding were to be made available.
- This is something that needs to continued to be funded either through Battelle or another contractor.
- No future work proposed beyond continuing current activities.

Strengths and weaknesses

Strengths

- Significant amount of VOC data had been collected.
- The data collection and analysis methods were very thorough and systematic.
- Through the forklift market study, a good tool has been developed for future implementation into different market segments.
- Comprehensive research.
- Thorough analysis.
- Inclusion of sensitivity analysis (slide #16).
- Structured analysis that clearly states the assumptions and characteristics of the work performed.

Weaknesses

- Only six months (March 2007 to September 2007) is left for the completion of 36% of the project.
- Lack of stakeholder feedback, both immediate and based on operational experience.
- Could add additional stakeholders like investment community to the data collection to solicit other points of view.
- Work is likely a duplication of efforts ongoing or already completed in the fuel cell industry.
- Low power systems with completely different duty cycles would not likely provide significant aid to vehicle fuel cell system development.

Specific recommendations and additions or deletions to the work scope

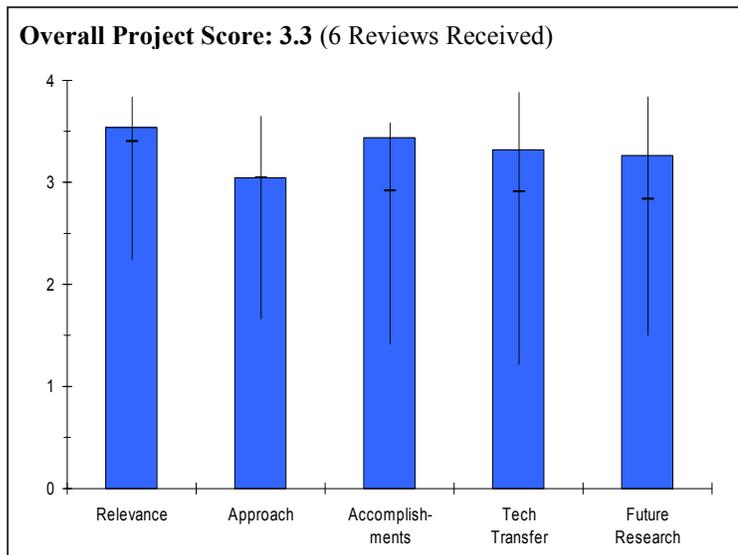
- Important data, such as customer views on reliability and maintainence expectations of fuel cells can be incorporated in the study.
- Although DMFCs are not a part of hydrogen economy, they are PEMFC technology. Therefore, DOE should consider using DMFC applications for portable market as a subject for this study.
- There is an inconsistency between slide #3, in which they say that DOD applications are out of scope, and slide #7, which says that the scope includes DOD markets.
- I would recommend a more detailed but much broader project in the future that focuses on 2-3 very specific market segments like fork lift trucks and perhaps telecom backup power. In these scenarios, competing technologies and other market barriers to entry could be further enhanced in a more narrow scope of work.
- Do not continue this type of project beyond the current contract.

Project # FC-27: Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications

Stephen Lasher; TIAX

Brief Summary of Project

The overall objective of this project is to perform a manufacturing cost assessment of an 80 kW direct H₂ proton exchange membrane fuel cell (PEMFC) system for automotive applications. The objectives for fiscal year 2007 are to perform 1) a high-volume cost projection for a PEMFC system using current performance/ cost assumptions; 2) a bottom-up manufacturing cost analysis for balance-of-plant (BOP) components; and 3) evaluation of economies-of-scale impacts on the stack and BOP and of technology/cost breakthroughs needed for systems to meet 2010 and 2015 targets.



Question 1: Relevance to overall DOE objectives

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

- Fuel cell cost is the number one barrier. Understanding cost drivers is critically important to achieving the DOE objectives.
- Addresses one of the top three barriers, cost.
- That's very important for the automotive OEMs as well as for the suppliers to see, if they really can make the fuel cell car an economic reality.
- Addressed stack as well as system cost targets from the DOE based on 500,000 units a year.
- Very important to track progress towards the fuel cell cost goals using an independent body to do so.
- We need to know where we are relative to fuel cell cost goals!
- In general, the effort of estimating fuel cell system costs is highly relevant.
- The concept of using 3M NSTF technology at high volume in 2007 is not at all realistic. However, there is benefit in using this technology for a cost estimate since it is the only technology that moves away from the "business as usual" of using high surface area carbon supports.
- Some system assumptions are unrealistic, although the difficulty in obtaining proprietary system information is recognized.

Question 2: Approach to performing the research and development

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

- Very rigorous approach, based on well-established corporate expertise for conducting cost analyses, coupled with a good understanding of the technology. Approach includes bottoms-up costing and developer feedback.
- The TIAX proprietary model for costing the stack components, if independently vetted, is critical for accuracy.
- Close collaboration with ANL modelers is excellent.
- Good to look also at hydrocarbon membranes.
- I have some reservations about basing this cost estimate on 3M's alloy catalyst exclusively. I think it should be captured as a footnote whenever the cost estimate is referenced. On the other hand, I don't have a better idea.
- System assumptions are scheduled to be updated this year, but should be challenged this year. It is doubtful that the 3M MEA technology requires external humidification devices on both gas lines.

- Given the specificity of the assumptions, a sensitivity analysis is in order and should be shown in the presentation.
- Balance-of-stack components are greatly neglected, although the difficulty in obtaining information is recognized.
- The merits of performing a cost analysis using 3M technology are real and are commendable.

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

This project was rated **3.4** based on accomplishments.

- Excellent progress in updating the cost projections as the technology improves and material costs, especially platinum cost, change. Design basis is up-to-date, assumptions are clearly presented, and the results are completely defensible.
- This project builds on the previous year's progress. This year's analysis, based on new feedback from ANL systems modeling, has been accomplished relatively quickly.
- Key result is that by lowering the MEA costs, the overall system costs are reduced and now the balance of plant costs become an increasing portion of the cost.
- Progress from stack to BOP is in progress.
- Includes different grades of humidification.
- Good articulation of specific changes from previous work and what the drivers for those changes are.
- Slide 7: I think TIAX is talking about the price TO the OEM, not the price an OEM will charge.
- Current cost estimate relies heavily on the 3M alloy catalyst, the cost, performance, and durability of which remains to be proven. Not that I have a better suggestion; just a caveat on the cost estimate that should be kept in mind.
- Leaving aside any perceived issues with the approach, the technical delivery is excellent. It is understood that copious MEA processing details are proprietary to 3M and they are not expected to be shown here.
- DTI showed an active investigation into graphite versus metal plates. The same should have been done here.
- A number of assumptions are not well understood, such as the motivation for woven GDLs, the motivation for two stacks per system and other details.

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

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

- Excellent interaction with system developers and component manufacturers to ensure reasonable inputs. Good dissemination of results at review meetings and with the Fuel Cell Tech Team.
- Good to collaborate with Argonne.
- MEA supplier data taken into account, important.
- Excellent collaboration with industry to help pull the information together.
- TIAX has made a good effort to get industry input. Unfortunately, industry is reluctant to provide cost data, so this is a very difficult area in which to work.
- The project is entirely dependent upon collaboration, so the collaboration level is already high.
- Answers to questions revealed that there is too much dependence upon National Laboratories. Greater industry collaboration (if possible) should be expected.
- As system update is performed in 2007, collaboration should be expanded to investigate a variety of vendors for system components.

Question 5: Approach to and relevance of proposed future research

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

- Plans for future work will focus on balance-of-plant costing. Plan for getting feedback from developers and stakeholders is good.

- Very good to continue to reevaluate, from the bottom up, and get more stake-holder feedback, on all the assumptions.
- More feedback on the validity of the bottom-up models is recommended.
- Important to also factor in durability advantages/disadvantages of the system subcomponents, using real data from similar types of systems.
- Feedback will be incorporated, important.
- Should publish the results in the peer-reviewed literature.
- Updating the BOP cost assumptions is critical to this project and this need is clearly identified.
- The need for sensitivity analyses is also critical and the investigators acknowledge that.
- Some of the questions identified additional areas of study, such as MEA component recycling and supply chain analysis. The presenters stated that they had studied supply chains, but the criticalities within individual component supply chains were not shown.
- Some evaluation of stack assembly time and conditioning time should be included.

Strengths and weaknesses

Strengths

- Experience with this kind of analyses.
- Great database on material and manufacturing cost in BOP components.
- Sensitivity is included.
- Good job of taking a very varied group of design parameters and distilling them down to something that is easy to track from a baseline and update approach.
- Excellent, thoughtful analysis of cost drivers.
- Cost analysis on a specific technology with advanced catalyst supports.
- Stack assumptions have been modified to reflect advances in components.
- Collaborations with some system component manufacturers to understand costs.

Weaknesses

- No OEM included to deliver updates on system design.
- Relies on cost estimation from suppliers on key components; e.g., membrane or bipolar plates.
- I do not think that the cost estimates coming out of these studies (TIAX and DTI) include all the same elements as those coming out of the H₂ infrastructure side (e.g., H₂A). For example, H₂A has permitting costs, stranded asset costs, and assumed return-on-investments, none of which are in this study. DOE should put some effort into identifying some of these differences.
- Some stack assumptions require explanation.
- Greater depth needed for understanding the possibility of supply chain sensitivity and choice of bipolar plate.

Specific recommendations and additions or deletions to the work scope

- Revisit expediency of factoring in costs and benefits of Pt recycling, taking into account new approaches for Pt recovery that might make it more effective to start recycling at lower volumes.
- Include cost of battery, if you see this as a BOP component.
- Include grade of hybridization and therefore calculate optimized grade of hybridization.
- Do own analysis on cost of manufacturing membranes and bipolar plates.
- A question was asked about other volumes which is very important to the overall analysis and understanding of the potential market rollout. When doing these other volume analyses, it is also important to consider higher margins for the supply chain as they need to recover all of the investment dollars they have put in to these efforts. While that will slow the ramp of the pricing curve, it is more reasonable than just assuming the automakers will drive everyone to a 15% markup on cost.
- Harmonize the DTI and TIAX study assumptions because 1. the cost of Pt is different in the two studies. 2. the Pt loading is different in the two studies: 0.19 vs. 0.2 mg/cm². While this looks small, it makes a significant difference in the results because of the price (!) of Pt.
- Publish these results in a peer-reviewed journal. It would add a lot of credibility.

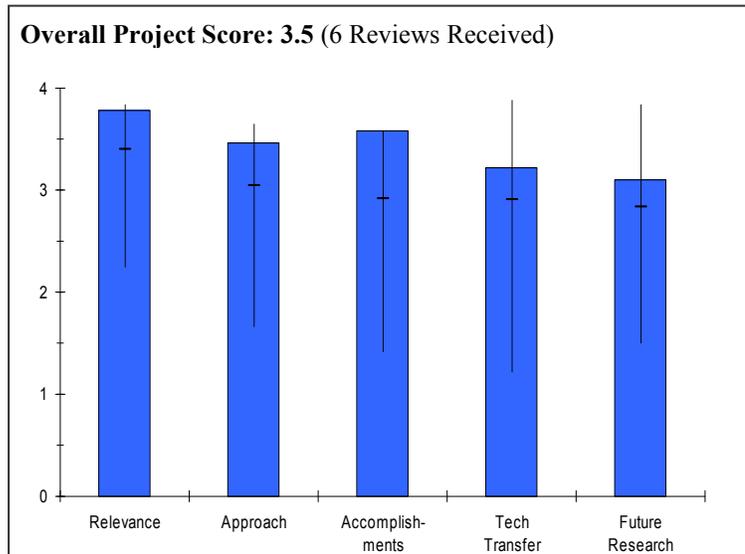
- Exploring greater variation of system components and plates (the non-MEA components) is recommended. If such exploration is already done, explanation should be given.
- Stack conditioning should be covered in the stack assembly section.
- The balance-of-stack components should be identified; the time required for assembly should be evaluated.

Project # FC-28: Mass Production Cost Estimation for Direct H₂ PEM Fuel Cell System for Automotive Applications

Brian James; DTI

Brief Summary of Project

The objectives of this project are to 1) identify the lowest cost system design and manufacturing methods for an 80 kW_e direct-H₂ automotive proton exchange membrane fuel cell (PEMFC) system based on three technology levels (current, 2010 and 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 impact of system performance on cost. The cost results will be used to guide future component development.



Question 1: Relevance to overall DOE objectives

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

- Very relevant to the DOE Hydrogen Fuel Initiative and objectives.
- The results from this work will be very useful for fuel cell manufacturers targeting the automobile market.
- All the stack and systems components considered for this study are very relevant to the present state of technology.
- This project provides cost estimates for what PEM fuel cell production costs might be, and compares them to DOE cost targets.
- In some sense, this project might be viewed as "due diligence" by DOE to confirm that the Hydrogen Program has ultimate commercial viability.
- While providing some level of insight as to what cost reductions might be necessary to meet DOE cost targets, those insights are somewhat obvious (e.g., catalyst and GDL costs) and do not require such an intricate analysis. In other words, there is little need to price out (study in detail) the 2% and 3% costs when the major 20%, 30% and 40% costs are obvious (see slide #17).
- These types of studies are imperative to ensure that there is a reasonable path to meeting the cost targets of this significant application.
- These studies should also yield what particular improvements or technologies are required to meet the DOE targets.
- Few things are more relevant to DOE objectives than an understanding of fuel cell cost drivers.
- A detailed projected cost breakdown of present, 2010, and 2015 is very helpful in guiding future work.
- Even though much of the effort seems to duplicate the TIAX study, it provides valuable additional insight.
- In general, the task of estimating fuel cell system costs is highly relevant to DOE targets.
- This cost study adds to its relevance by identifying a matrix of technology levels versus expected volume.
- There is just one failing with regard to relevance – the scope of the project is limited to describing catalyst application techniques that will almost certainly be obsolete by the time of fuel cell vehicle commercialization (assuming all other targets remain relevant and that fuel cell vehicle strategy has not changed).
- Extremely important to do long-term DFMA cost estimates of the fuel cell system for the DOE's knowledge.
- Companies do their own studies, but these are proprietary, and DOE needs to have its own, independently generated estimates.

Question 2: Approach to performing the research and development

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

- DFMA approach is good.
- Systematic analysis of manufacturing costs for each step.
- Used the key technical targets from DOE targets to conduct the analysis.
- Used the current technology and component cost for FY2010 target analysis and used future technology and component cost for FY2015 analysis.
- Different technological approaches to manufacture same components were used in the cost analysis.
- Very practical approach of using present technology and not to anticipate the benefits of future technology.
- The presentation described the approach as "detailed, rigorous, and consistent." In fact, projections out to 2010 and 2015 cannot possibly be rigorous.
- The approach could be better described as "best guess."
- As was pointed out during the Q&A, and as confirmed by the presenter, the "best guess" methodology used combined the lowest cost options for various components even though they didn't work well together. That is, more realistic systems might pair a lowest cost option in one component with a more expensive option for another component.
- The presentation demonstrated a relatively good degree of research and detail, and a rather transparent process that spelled out the assumptions.
- The transparency of the methodology used here is highly appreciated.
- Looking at the impact of different volumes and different technologies is very good as well.
- Overall, a very good systematic and well-considered approach.
- Takes into account many possible improvements in technology (higher temperature, reduced humidity, lower pressure, etc.) but does not provide for possible step-changes such as truly mass-manufactured, low catalyst loaded MEAs.
- Combines lowest cost components and processes, which may not be compatible for a complete and workable system.
- The approach is exactly what is needed – a matrix of volume versus technology levels.
- The use of proven and public manufacturing cost estimation techniques is detailed, specific, and adjustable.
- The approach allows for evaluation of competing technologies.
- The approach has one major failing: the mixture of technologies that are not amenable to each other (e.g., stamped metal plates with UTC-prescribed conditioning). Presenting alternatives (e.g., molded plates) helps to alleviate this concern.
- DTI uses extensive knowledge of fuel cell systems and design for manufacturing analysis (DFMA)
- Please investigate a larger variety of system design and material options that have different effects on costs.
- UTC's bipolar plate design is based on carbon and is self-humidifying. Steel plates may be cheaper in your long-term cost estimates, but could not achieve the same self-humidifying mechanism that UTC uses.
- The industrial reaction to this type of study (from Nissan and UTC) is that a series of very optimistic assumptions are made, which results in very low mass-produced costs. Is this the most useful approach for the industry? What about adding probabilities of success/ failure with one vs. another production design or material selection choices.

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

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

- Thorough analysis of the components and assembly process of stack system have been conducted.
- Individual component costs were analyzed carefully.
- The system cost estimate assuming 2015 technology is almost double the DOE 2015 target.
- Correctly identified the GDL cost impact and its importance.
- All the smaller aspects, such as stack conditioning time, were considered in the calculation.
- The calculation method is receptive of any future changes that may happen in technology or material front.

- The contractor performed well in their process research, manufacturing insight, and distillation of estimated costs.
- Good results for this point into the project.
- Gathering the input information and processing with known (and accepted) procedures to arrive at the results shown represents excellent technical accomplishments.
- The study provides the most detailed understanding we have thus far of what fuel cell costs will be in the future.
- Individual analyses of MEA components are highly detailed, although there is some room for improving the compatibility of these components.
- GDL manufacturing process should be validated with an industrial partner.
- Very thorough, technically knowledgeable analysis.
- UTC can not use stamp-printed steel bipolar plates with its MEA and system designs. One catalyst application technology may not work with another technology (like the electrolyte).

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

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

- The data will be available to all fuel cell manufacturers.
- Significant input has been taken from different stack and fuel cell component manufacturers.
- Ongoing open relationship with fuel cell manufacturers will help in developing robust cost analysis method.
- The model will be shared with DOE, which eventually will be shared with all DOE partners.
- By its nature, this project requires extensive collaboration with industry in the research phase, in order to obtain insight and data.
- The accumulated data and conclusions of this project would be best reviewed by opening them to validation by all stakeholders (i.e., as part of the formal process).
- Claim that they have interacted with many suppliers and OEMS, but no list was provided. Hopefully, a complete list of contacts will be included in the written report, so that one can see if key parties are being consulted.
- While there was a lot of input from industry, there didn't seem to be much true collaboration.
- While collaborations exist for the study to be produced, there are specific areas where collaboration could help. GDL production is one example.
- There is too much reliance upon patents. Patent holders should be contacted in order to understand what is really described in the patent and whether the technology in question is applicable to the assumptions of the study.
- Collaborated with the Fuel Cell Tech Team and others extensively (slide 2).
- Tremendous amount of work trying to understand sensitive information from a host of industrial participants.

Question 5: Approach to and relevance of proposed future research

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

- Low cost non-platinum catalysts will be considered.
- Annual updates will capture any new changes in material cost or process cost.
- Factors for any change in technology and material cost will be updated.
- The PI proposes to better cover some areas (e.g., non-precious metal catalysts, bipolar plate passivation).
- The PI proposes to use the analysis to date as a starting point to see how costs might be driven down.
- Notwithstanding the above, future research is of limited relevance to the overall program because its major conclusions would still be obvious and it would be further refining estimates of mere 2% and 3% cost components. That is, DOE effort would be better spent on overcoming barriers in its technical program.
- Good plan, but I would also recommend analyzing what subsidies would be required (to make FCVs reasonably cost competitive) under different adoption-rate scenarios. DOE should have some idea of the subsidies required to cross the "valley of death." These subsidies may be shared by industry and the government, but some order-of-magnitude estimates would be useful here. Additionally, one could include the impact of early-market volumes (non-automotive).
- The only future work mentioned was possible annual updating of results until 2011.

- Annual updating is likely important but it seems that fundamental changes in some models might be necessary to keep up with potential changes in the "best" system design, major materials, or manufacturing processes.
- The need to explore alternative fabrication techniques and to refine the BOP costs is shown and is well understood by DTI.
- There is considerable refinement that DTI can bring to other details of the technology. The reliance on patents should be replaced by further collaboration with technology developers.
- Please add probabilities of success or failure with one technology, process, or materials choice vs. another.
- Please show cost estimate final results based on carbon bipolar plates as well, not just steel.

Strengths and weaknesses

Strengths

- Very practical consideration of all the component, assembly and manufacturing costs.
- Comparisons of present (FY2006) and future (FY2010, FY2015) are very realistic.
- Good comparison of present and future component/assembly costs.
- The project satisfies some measure of "due diligence" in estimating the commercial viability of the research program (e.g., by estimating costs and comparing them to DOE targets).
- The project provides some measure of insight as to the major costs of a fuel cell system, and hence where the greatest opportunities for cost reduction might be.
- The project demonstrates a good level of performance in research, analysis, and transparency.
- Transparency of the methods and assumptions used.
- Looking at the cost at different annual volumes.
- Well organized.
- Well executed.
- Important area of study.
- Systematic approach.
- Incorporation of competing technologies in evaluation.
- Detailed analysis of each stack and system component.
- Literature search.
- Cost estimation techniques.
- Knowledge of PI and his team on design for manufacturing analysis and fuel cell system design.
- Highly detailed and transparent study.

Weaknesses

- The assumptions on perfect integration of the best products of different component technologies is not a good approach.
- This project has limited impact because it generates little new qualitative information (as opposed to generating quantitative estimates for that which was previously known qualitatively) that would affect management decisions on the course of the research program.
- Elevation of educated guesswork to "rigor."
- The learning curve for assembly costs appears to be unbelievably flat (e.g., hardly any change in system assembly cost going from 1,000 to 500,000 units per year is not realistic). Some "learning curve" for assembly costs should be considered. Realistically, manufacturing efficiencies are typically learned with experience (i.e., one's idea of how to make 500,000 per year today is probably wrong).
- It seems too tied to predetermined configurations and processes that don't necessarily "mesh."
- A combination of the least costly components and processes may or may not ever represent a workable system.
- Lack of compatibility of different technologies.
- Greater need for industrial collaboration.
- Different scenario analyses of different materials usage were not investigated. For example, only two designs assumed – either carbon OR steel used for bipolar plates – this was the only scenario variation considered for the design.
- No change in assembly costs between 30,000 and half a million – robotic assembly assumed for both – realistic?
- What is the differentiating feature of this DTI study compared with DTI's other DFMA stack studies?

Specific recommendations and additions or deletions to the work scope

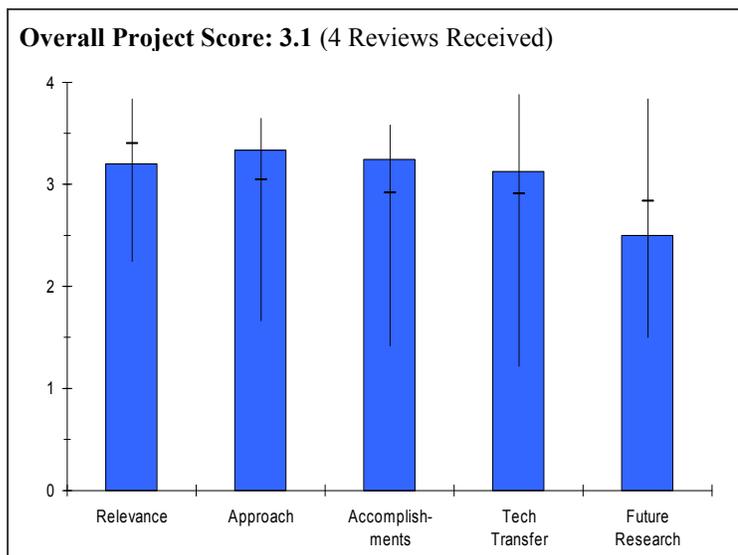
- Components from a working stack should be considered for the study to reflect the actual manufacturing cost.
- Components, such as membrane, GDL, catalyst etc., from different sources should be factored in the calculation to assess the practicality of the cost calculations.
- Consider adding some flexibility to the configuration and processes.
- Evaluate alternative catalyst application technologies including catalyst materials with alternative supports beyond high surface area carbon. Even though this is intended to be the assignment of the TIAX study, the TIAX study does not contain the approach and the rigor that DTI shows.
- Heightened contact with industry.
- DOE should not only allocate more funding for these kinds of studies, but also require industrial participants that it funds to provide data, advice, and feedback on these kinds of studies.
- More scenario analysis within the study – different costs of different design pathways.
- Make the models accessible in the Macro Systems Model so that industrial participants can do scenario analyses of different designs they may develop. For example, an industrial participant should be able to use the model to see the financial difference between using 1) a platinum-based catalyst and 2) a platinum-alloy based catalyst.

Project # FC-29: Platinum Recycling Technology Development

Stephen Grot; Ion Power, Inc.

Brief Summary of Project

The objectives of this project are to 1) assist the DOE to demonstrate a cost effective and environmentally friendly recovery and re-use technology for platinum group metal (PGM) containing materials used in fuel cell systems and 2) to use new processes that can also separate and recover valuable ionomer materials. DOE 2010 targets for membrane costs indicate membrane has value equal to the PGM. To achieve the project objectives, solvents will be used to “dissolve” ionomer and physically separate catalyst from ionomer solution in 1-5 sq-meter batch sizes. A best attempt to re-manufacture catalyst coated membranes with recovered materials will be made. Additionally, failure modes of membrane electrode assembly (MEA) materials used in fuel cells will be learned.



Question 1: Relevance to overall DOE objectives

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

- Pt recovery is an important aspect of the overall fuel cell life cycle - it addresses both environmental issues and important cost issues that could ultimately impact the net costs of fuel cell systems. This project addresses important DOE goals, targets and objectives.
- Nafion recovery is not critical for meeting DOE objectives.
- Value of Pt recovery to the DOE program is unclear.
- Remaking Nafion into membranes is not critical for meeting DOE objectives - may be more expensive than making fresh material.
- High relevance to the success of PEM fuel cells.
- Recycle (reuse) of expensive materials (perfluorinated ionomer and PGM catalyst) should be incorporated in the fuel cell cost model.

Question 2: Approach to performing the research and development

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

- The project has focused on a solid technical approach which explores reclamation of both the PGM and the ionomer membrane material.
- The PI of this project clearly understands the problem and has effectively structured the research program to address the DOE goals in this area and has identified and assessed risks involved in at least three potential solutions of the problem.
- Batch process seems reasonable to recover Nafion.
- Centrifuge shows good Pt recovery.
- May have difficulty when working with unitized assemblies.
- Technique may only be applicable for Nafion.
- Both catalyst and ionomers are taken into account.
- Don't see a reason for looking after MEA failure modes in point of view recycling of the components.
- Important to analyze the limits of separation technologies.

- Also important to calculate the value of the recycled materials.
- Need to identify material specification to be reused (application) and clarify technical metric and criteria for success of this process.
- Need to pursue cost analysis to identify economical model of this recycle process.

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

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

- Excellent progress has been made to date - the project has demonstrated a high degree of PGM recovery and has also shown that Nafion membrane material can also be separated and recovered, although "enrichment" will be required to fully reuse the membrane material.
- Some scale-up of the process has been demonstrated.
- It was not clear that economic analysis of the proposed reclamation process has been conducted with the subsequent impact on fuel cell life cycle costs.
- Demonstrated scale-up of Pt recovery process - lost recovery.
- Recovered Nafion not in form suitable for recasting into membranes.
- No progress shown on understanding durability issues of MEAs.
- Good progress in scaling up the process.
- EOL Nafion similar to BOL Nafion, great result for recycling method.
- Not only the recycling process itself is reviewed, also the cost and the energy the process needs.
- Propose only 2% loss in catalyst recycling.
- Progress was shown, however, need to clarify metric and criteria for this process success. Recycled material specification should be identified to develop metric and criteria.

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

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

- A number of collaborations were reported – apparently the collaborators provided important guidance and direction to the PI – it seems that most of the work was done in-house, however Delaware State and DuPont have, or will, play important roles in the execution of the work.
- Plans to work with DuPont on Nafion recasting, but nothing shown.
- Excellent partnerships between institutes and industry.
- Good collaboration to collect used materials.
- Industry collaboration is recommended to develop material reissue application and identify material specifications for these applications.
- Also, industry collaboration will be benefit for process scale-up.

Question 5: Approach to and relevance of proposed future research

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

- Given the degree of completion (reported to be 70% complete) of this project, the future plans appear to be reasonable. It will be important to complete the remaining project tasks to assess fully the potential of the recovery process.
- Increasing collaboration with DuPont on Nafion film reprocessing not recommended.
- Investigating potential for use of recycled Nafion not recommended.
- No plans shown for improved Pt recovery process.
- No work on alloys is planned.
- What about reinforced membranes?
- Hydrocarbon membranes?

Strengths and weaknesses**Strengths**

- Developed scaled-up process for Pt recovery.
- Interactions with stack suppliers as well as component suppliers.
- Development of IP to make the Nafion solution less dilute.
- Membrane material handling.

Weaknesses

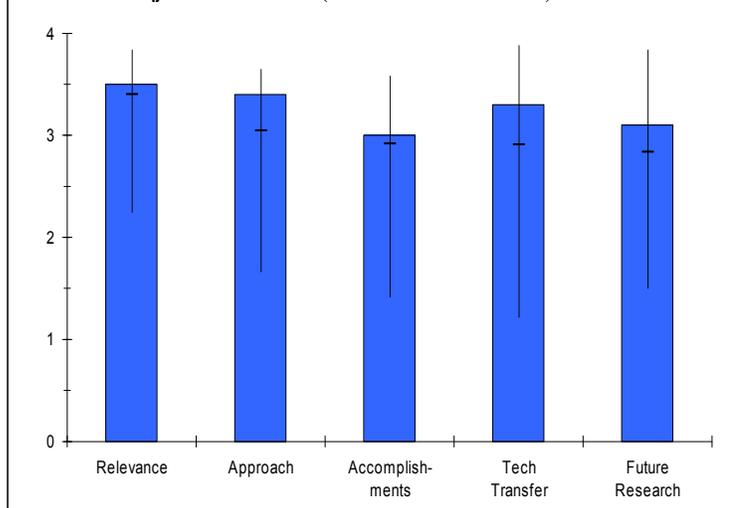
- Too much focus on Nafion recovery – likely low value effort.

Specific recommendations and additions or deletions to the work scope

- It is important to complete at least a preliminary economic analysis of the proposed project.
- Investigate how recovery process must be done for a unitized assembly including seals, gaskets, adhesives, etc.
- Do economic analysis on value of recovering Nafion.
- Assuming Nafion recovery is not economically viable, focus on Pt recovery and stop work on Nafion recovery.
- Also work on alloy recycling.
- More study for application of recycled material is needed. Develop metric and criteria for process target.
- Develop cost model to be incorporated into fuel cell cost model.
- Industry collaboration for process scale-up approach.

Project # FC-30: Platinum Group Metal Recycling Technology Development*Larry Shore; BASF***Brief Summary of Project**

The overall objective of this project is to develop and demonstrate a process for recycling of polymer electrolyte membrane (PEM) fuel cell membrane electrode assemblies (MEAs) without hydrogen fluoride (HF) emission. The objective for 2006-2007 is to re-design the process so that catalyst-coated membranes (CCMs) and Gas diffusion electrodes (GDEs) are processed together. Accomplished last year, a simple environmentally-benign, 'universal' process to recover Pt from fuel cell MEAs was developed with the following features: 1) no organic solvent required; 2) no need for combustion; 3) removal of gas diffusion layer (GDL) from membrane no longer necessary; 4) applicable to both CCM and GDE architecture; and 5) high yield with base metal-alloyed cathode catalysts indicated.

Overall Project Score: 3.2 (5 Reviews Received)**Question 1: Relevance to overall DOE objectives**

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

- Pt (PGM) recovery is an important aspect of the overall fuel cell life cycle – it addresses both environmental issues and important cost issues that could ultimately impact the net costs of fuel cell systems. This project addresses important DOE goals, targets, and objectives.
- Addresses the main barrier for fuel cells – cost.
- High relevance to the success of PEM fuel cells.
- Project is focused on DOE goal to reduce cost of fuel cells due to platinum recycling.
- Without Pt recycling, fuel cell costs will be prohibitive.

Question 2: Approach to performing the research and development

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

- A solid technical approach has been taken in this project which was exploratory in the initial stages.
- Several potential reclamation processes have been surveyed and eliminated.
- The PI of this project clearly understands the problem and has effectively structured the research program to address the DOE goals in this area and has identified and assessed risks involved in at least three potential solutions of the problem. It appears that the project has been focused on the approach that is most likely to succeed.
- Approach to develop a widely applicable (both GDE and CCM) and environmentally sound recycling process is the only approach that would make business sense. Have developed processes which work with future alloy catalysts.
- Good approach to process CCMs and GDEs together.
- It's fine for me that they are focusing mainly on the catalyst.
- Approach is well-thought and focused on environmental-friendly processes for platinum recovery.
- Team has considered many recycling options and is willing to discard those that seem to show little promise.

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

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

- Significant progress has been made to date - however there is much remaining to be done in this project which was reported to be 85% complete.
- It will be important to complete the economic analysis and prototype process demonstration - it is not clear that enough time is left to complete these important tasks.
- Have developed a recycling process which avoids combustion and eliminates organic solvents and does not require preresmoval of GDL.
- Have developed a process which is applicable to GDE and CCMs.
- Have achieved >98% recovery of the Pt with both CCM and GDE.
- Established a simple process without organic solvent, etc. and that's important to reach the DOE goals.
- Combustion process seems to be not useful for alloys due to Ru loss.
- Significant progress toward identification of the the most efficient process to recycle both CCMs and MEAs.
- Environmently friendly process was identified.
- Encouraging that the GDL does not have to separated first from the membrane.
- Environmental impacts of acids chosen for leachate procedure should be addressed. There must be some waste streams from the leachate to deal with. While it is true that PI has stopped further consideration of the VaTech method and its evolution of HF, I question the waste liquids generated by the acid leaching procedure. Need to understand this better.
- What is the target for %Pt/precious metal recovery?

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

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

- A number of collaborations were reported – apparently the collaborators provided important guidance and direction to the PI – it seems that most of the work was done in-house at BASF (with the possible exception of Virginia Tech which assisted in one of the discontinued recovery processes).
- Working with membrane, catalyst, and MEA manufacturers. All the needed players are involved.
- It would be useful to have a collaboration with membrane manufacturer.
- There is a long list of collaborators, but it is unclear what they have brought into project (except materials).
- Collaboration with Virginia Tech was mentioned, but it is not on the list of collaborators.
- Although the NRL catalyst was tested, ONR instead of NRL was mentioned during presentation.
- Should talk to fuel cell stack manufacturers as well. Some of the packaging plans may add to the costs of the proposed recycling system.

Question 5: Approach to and relevance of proposed future research

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

- Given the degree of completion of this project, the future plans appear to be reasonable. It will be important to complete the remaining project tasks to assess fully the potential of the recovery process selected by the PI.
- Proposed work includes economic study which will be important. Scale-up and demonstration is planned.
- Important to do the process economic analysis.
- What is the impact of alterative catalyst structures/compositions on the chosen recycling procedure? What about the 3M alloy – will it work on that?

Strengths and weaknesses**Strengths**

- Extensive knowledge of catalysts and recycling of them.
- Fast identification of non-promising processes followed by redirection of the project.

FUEL CELLS

Weaknesses

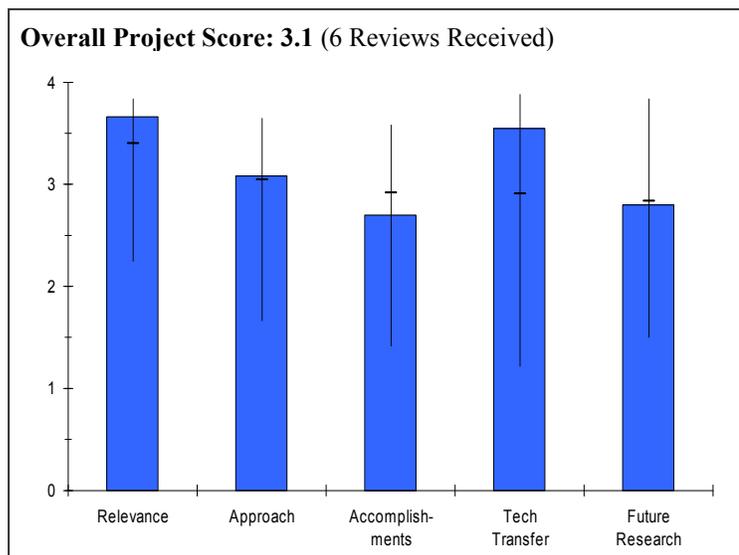
- Deeper look at membranes needed.
- No cost analysis for cryo-grinding .
- Sources of MEAs, GDLs, and catalysts should be mentioned on slides.
- Should have a go/no-go decision point prior to proceeding to build recycling plant prototype.

Specific recommendations and additions or deletions to the work scope

- Environmental impacts of acids chosen for leachate procedure should be addressed.
- It is important to complete the economic analysis and prototype process demonstration.
- Include quantification of CO₂ emissions from energy usage in the process.

Project # FCP-01: Component Benchmarking*Tommy Rockward; LANL***Brief Summary of Project**

The objectives of this project are to 1) provide technical assistance to fuel cell component and systems developers as directed by the DOE; 2) include testing of materials and participation in the further development and validation of a single cell test protocols with the U.S. Fuel Cell Council; and 3) provide 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 assistance includes making technical experts available to the Tech Team 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 **3.7** for its relevance to DOE objectives.

- Testing and training at LANL is valuable to material and component developers.
- The program addresses the testing of catalyst and development of test protocols to be used by PEM fuel cell developers. The benefit is achieving uniform procedures for the different fuel cell developers.
- This project nominally concerns various "benchmarking" activities in which test methods are developed and applied to determine the properties and performance of various fuel cell components and system attributes.
- This project provides outside access to experts and facilities at Los Alamos National Laboratory in support of various issues in fuel cell development, e.g., in a capacity similar to that of a consultant.
- LANL is gluing together many different components across industry and academia, both nationally and internationally. This is important work for keeping metrics/standards in fuel cells.
- This project is relevant to the DOE program and mission. The National Labs need to take a leadership role in aiding in technology transition. Part of the reason for their overall existence is to provide technical expertise to aid in the development of American industry and technology.
- LANL's work on fuel cells is on target regarding support for the H₂ Fuel Initiative.

Question 2: Approach to performing the research and development

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

- The protocols listed should be valuable to component developers.
- An extensive list of visitors to LANL was identified. It is not clear what topics were important to the visitors. The presentation should have provide some examples of the type of data exchange.
- Testing protocols were reviewed for the EU. The results of this review were not provided and it would help the reviewer if examples of the type of contributions were given.
- Los Alamos' strength in a "benchmarking" project should be in the use of its laboratory facilities as a competent and unbiased reference. But instead, the presentation emphasized the development of consensus test methods in various collaborative fora in which Los Alamos' contribution and impact was often unclear. That is, beyond

merely reviewing and commenting on proposed test protocols (within the technical capability of many industrial participants), in what ways did Los Alamos provide solutions based on its unique resources?

- It was difficult to determine exactly what this project entails – exactly what resources were being made available (and how they were being utilized).
- The written poster indicates extensive involvement in many technical areas, but answers to questions seeking additional detail were not so detailed.
- Overall approach is very good and leverages LANL's years of expertise.
- Not really clear the role that LANL is playing in each role – for instance, in catalyst stability protocols, each company has a method and it's not clear how LANL is integrated with those other protocols and whether they have compared them.
- Participating in meetings, setting up workshops and tutorials, as well as working collaboratively with U.S. researchers and industry are an important role the national labs need to fill.
- LANL has an understanding of fuel cell fundamentals second to none.

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

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

- LANL has had many visitors and given lots of talks.
- No information of test results given (not even numbers of samples evaluated).
- No experimental data were presented by the organization; the program appears to be advisory and not part of a testing effort.
- LANL participates as a member of a team on the USFCC Durability Protocols. It appears they reviewed the protocols but did not contribute to their development. With LANL's experience, I would expect that they would lead in the development of protocols and provide experimental data.
- The presentation lacked data showing results of benchmarking exercises. For example, in a "round robin" type of test one would normally show the different results from different testing laboratories (coded for anonymity) on the same object. In performance testing, one would show the measurements made on different samples (coded for anonymity) made by a single reference laboratory (or a group of well-coordinated reference laboratories).
- The presentation lacked description of specific technical achievements attributable to Los Alamos that advanced the ability of industry to conduct testing. How did Los Alamos advance the art and science of performance testing in the laboratory (and what experimental data demonstrates such advances)?
- Not really clear if all 21 invited presentations can be claimed for this one program – 21 presentations seem to be from many LANL programs (\$570K/yr).
- How much of leadership role is LANL playing?
- Obviously the technical accomplishments and progress from this program are largely proprietary. Nonetheless this program is interfacing with a wide variety of researchers and industry.
- Support for development of durability and catalyst durability protocols has been great.
- LANL could do more to speed up the development of test protocols for H₂ quality. We are still waiting for the results of the round robin baseline testing among LANL, University of HI, Clemson, and U Conn. H₂ quality testing is of critical importance to complete as soon as possible.
- Impurities in the H₂ are more problematic—whose responsibility are they?

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

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

- LANL has lots of collaborators.
- Lack of data makes it impossible to determine value of these collaborations.
- The LANL fuel cell training class is planned but has not been held and may fit under future work.
- A long list of visitors is provided: LANL could provide a list of the information they transferred as part of a collaboration and this would be helpful for the reviewer and maintain a record of LANL's achievements.

- LANL reports they worked on a proprietary catalyst, but it was not clear if this was for a outside party that developed the catalyst or whether the proprietary catalyst was developed by LANL.
- The presentation contains an impressive list of collaborators, covering three slides, and presentations made, covering two slides.
- The extensive list of purported collaborators is disproportionate to the technical work described on the subsequent slides, in which principle interactions appear to be discussion participation within large consensus groups.
- The number of collaborations is truly astonishing!
- To ensure the best use of this program, the PI needs to take additional steps to ensure more researchers know that the program is available and the capabilities are available at LANL.
- Lots of training, tours, collaborations, presentations, etc.
- Excellent ties to USFCC, FreedomCAR and Fuel Partnership, and others.

Question 5: Approach to and relevance of proposed future research

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

- No future research was proposed.
- The future work is the training course.
- LANL will continue to advise the USFCC.
- LANL will continue to participate in the WG12.
- The presentation indicated that future activity would include participation in various round robin tests; otherwise it implied that the future would be more of the same.
- Overall very good plan to keep doing the same activities—presumably no program plans are listed.
- The future research is dependent on outside researchers and industry seeking out LANL and its resources.
- More a support project coordinated with USFCC and others, so future efforts are guided by a body outside LANL.

Strengths and weaknesses

Strengths

- Good test facilities and personnel.
- LANL has a very strong reputation in fuel cell technology. The researchers and facilities at LANL should provide a strong basis for research and development.
- It is valuable to the fuel cell development and testing communities to have access to Los Alamos' facilities and expertise.
- The presentation indicates extensive outreach and networking with many potentially interested parties.
- LANL is providing a welcoming facility/resources to help unite measurement capabilities within the fuel cell community.
- Outreach to researchers and industry is an important component of the National Lab mission. These types of efforts need to be given additional resources.
- Vast collaboration network.
- Community education on fuel cells. The tutorials that LANL puts on are useful to train new people.
- Detailed understanding of fuel cell fundamentals.

Weaknesses

- Lack of any statistical information on test reproducibility.
- Very little data were made available. The project is conducting reviews but little evidence of experimental activity is given.
- I think the presentation was weaker than the actual activities at LANL. A better description of the experimental activity should be provided.
- The presentation had undue emphasis on paper exercises (i.e., "review and comment") that did not utilize Los Alamos' laboratory facilities and other technical strengths (e.g., those not otherwise available in private industry).

- The presentation lacked experimental data providing technical justification for recommendations or decisions made in establishing testing protocols.
- LANL has a small amount of "not invented here" symptoms and they may want to update SOME of their methods, or at least validate their traditional methods against emerging ones.
- Additional advertising of upcoming workshops/events needs to occur. This program also needs to do a better job of communicating the capabilities that are available.
- Lacks sense of urgency.

Specific recommendations and additions or deletions to the work scope

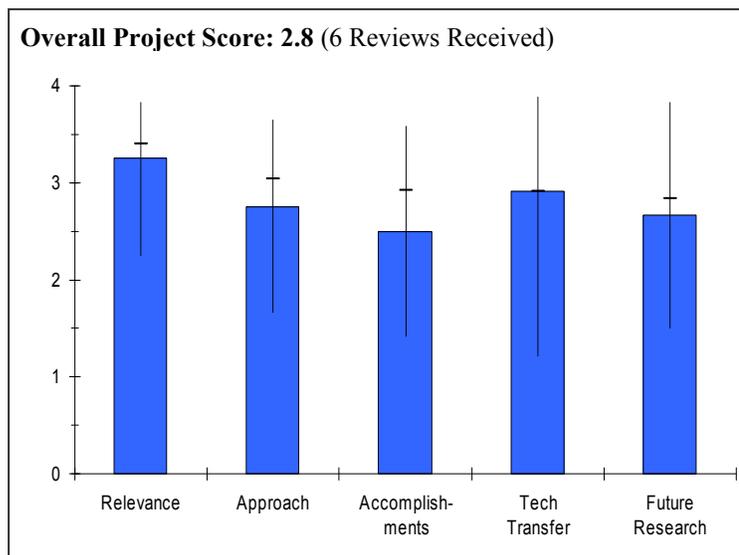
- Show data for non-confidential materials.
- Do a statistical analysis of durability test results.
- Draw some conclusions from the data.
- At the very least, list the number of samples tested for each protocol. Then maybe a proper evaluation can be made.
- Increase the disclosure of data and information. The lack of reporting does not provide the fuel cell community with helpful information.
- This project had a 2003 start, yet the "Objectives" describe general areas of activity that the project "is expected" to entail. This project should be of sufficient maturity that the PIs should be able to articulate short and specific objectives that indicate exactly how they intend to (1) apply the technical strengths of Los Alamos to advance and to add value to the testing efforts otherwise being organized by the community, and (2) proactively use benchmark testing as a tool for advancing DOE program goals (that is, its role as a means rather than as an end).
- This program should definitely be continued as it is of broad service.
- The project needs to investigate new routes to advertise its existence.
- Recommend putting significant resources and timeline commitments on the impurities work. It seems to be moving too slowly.

Project # FCP-04: Kettering University Fuel Cell Project*Joel Berry; Kettering University***Brief Summary of Project**

The overall objectives of this project are to 1) develop novel proton exchange membranes (PEM) for fuel cells and 2) develop a computational fluid dynamics (CFD) porous flow model for PEM fuel cells for improved water and thermal management. The objective for 2006 was to develop a low-cost, high performance membrane that includes experimental testing and performance validation.

Question 1: Relevance to overall DOE objectives

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



- The relevance of this particular approach to the DOE objectives was not clearly stated.
- The project is highly relevant to the DOE's objectives and supports the President's Hydrogen Fuel Initiative.
- The topic of the project fully supports the DOE RD&D plan.
- This project involves development of new polymeric membrane materials that prospectively might have superior properties.
- Though not yet reported, this project involves development of a new computer model (computational fluid dynamics) for the multiphase analysis of water and its vapor flowing through a fuel cell.
- Good effort that addresses DOE goals for membrane cost and performance.
- Project appears to be similar to research done by others.

Question 2: Approach to performing the research and development

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

- A rationale was not given for the choice of polymers and why these particular polymers will improve the membrane properties relative to Nafion.
- The method used for determining proton conductivity, diffusion of protons determined by pH change of aqueous solutions in contact with the membrane, is not relevant to fuel cell conditions.
- The technical approach for the program is good. The tasks are clearly presented.
- The testing setup for measuring the membrane proton exchange capacity is questionable because the membrane diffusion capability due to acidic concentration (pH) difference across the membrane is not an indication of its ionic conductivity. Instead, an electric circuit should be established such that protons crossing through the membrane is assured and the membrane ionic conductivity is appropriately measured.
- The membrane dimensional change in the x, y, and z directions, due to water uptake, should be determined with a relatively accurate non-contact measuring technique that utilizes optical or laser methods.
- The project is technically feasible.
- Commercially interesting membrane materials should also be judged on their chemical stability, their ability to bind and stabilize dispersed catalyst, the temperature range of their operation (e.g., to run hot to avoid CO poisoning of the catalyst), etc.
- The presentation did not propose that membrane conductivity is a limiting factor for fuel cell design. The electrochemical reaction at the cathode is generally regarded as the rate-limiting step.

- Increasing the conductivity of the membrane could perhaps lead to smaller fuel cells of equal power (e.g., higher power density), but only to the extent that protons crossing the membrane could react more quickly with the oxygen.
- Decreased cost is also cited as an advantage of the new membrane material, but no data is provided on either (1) prospective costs of the traditional and prospective membrane materials, or (2) the extent to which the cost of the membrane might influence overall fuel cell system costs.
- Innovative approach that leverages collaborator expertise to develop inexpensive membrane technology.
- Approach provides highly flexible platform for continued improvements using broad range of previously developed and/or new polymer chemistries.
- Though project claims to be addressing manufacturing costs, it is not clear how this is/will be addressed.

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

This project was rated **2.5** based on accomplishments.

- Technical progress has been slow considering the funding level and that this is a two-year project.
- No results presented for the CFD modeling effort.
- The project was started July 2006. It is too early to make a judgement for technical accomplishments at this time. However, the project progress is good.
- The project is eleven months in progress with no evidence that supports the accomplishments as indicated by the PI: Task 2: Chemical modification – 80% completed, Task 3: Thermal stability and Water Management – 70% completed, Task 4: CFD Multi-phase model for PEM fuel cells – 40% completed.
- The presentation showed an impressive amount of data for a project of such maturity and level-of-effort.
- Large number of materials already screened, and several of the most promising are undergoing additional evaluation.
- Need to evaluate membranes at temperatures above 60°C.
- Significant progress in developing the theory and correlating it to their experimental results, at least for the more promising materials for which data was shown.
- The project claims to have discovered an "advanced" membrane manufacturing procedure; it is not described.
- Should show clearly the alignment of progress to technical targets.

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

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

- The inclusion of a catalyst company and a polymer company on the team is excellent. It is unclear, however, what participation these team members have thus far.
- The project was started July 2006. It is too early to transfer technology to industry at this time.
- Collaboration with two industries namely, Bei Tech and Umicore Fuel Cells were mentioned by the PI.
- The PIs collaborate with a German fuel cell manufacturer and a minor player in polymer membranes.
- Project strongly leverages expertise and prior technology demonstrations of the two identified collaborators.
- Strong working relationship with both collaborators, who continue to make valuable contributions to the program.
- Bei Tech and Umicore are mentioned as partners, but their roles are not clear.

Question 5: Approach to and relevance of proposed future research

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

- Without full characterization of the materials developed thus far, it is premature to state that the future research should include improvements on the membrane properties (e.g., cross-linking). The first step in future work should be full characterization of the existing materials to determine if they hold any promise.
- Based on the presentation information, the future research work is clearly presented and technical approaches are reasonable.

- Good plan for the proposed future research work.
- Future research is described as, "seek answers by identifying factors limiting PEM fuel cell performance". Better focus is required both on general grounds and specifically because such a broad scope would require an extensive technical capability that the PIs do not have.
- The PIs plan to integrate their new membrane material into a working fuel cell and to measure its performance, a natural and appropriate extension of work completed to date. However, it is still not clear how this new material would advance the state-of-the-art.
- Very ambitious based on FY08 funding level.
- While the future plans for this project may lead to some additional knowledge being gained, these plans should focus more on overcoming barriers.

Strengths and weaknesses

Strengths

- The approach to membrane development may have some promise, but this needs to be demonstrated with the correct characterization techniques.
- The PI and co-Pi have good R&D experience for polymer membrane electrolyte chemistry.
- Good overall objectives that are complemented by well planned future research work.
- The quantity of experimental work completed to date is impressive for a project of this scale.
- Good theoretical and experimental research that is making good progress toward DOE goals.

Weaknesses

- Lack of characterization of the polymers. If Kettering does not have the correct equipment for evaluation of the membrane properties, then they should utilize the capabilities of their stated partners or request help from either BekkTech or the high temperature membrane project coordinator, the University of Central Florida.
- Improvement in the measuring methods and techniques for the proton exchange capacity and membrane dimensions change due to water uptake is necessary. The project's rate of progress should increase to match the project two year duration plan.
- It's not clear what hypothesis the PI is trying to test or what specific technical barrier the PI is trying to overcome.
- Indicated that they had applied for a follow-on program, but could not articulate what they expected to demonstrate by the end of the current effort and what the focus of the follow-on program would be. Essentially said "just further exploration".
- Difficult to assess the extent of Edisonian versus good fundamental research since the process is proprietary. Makes it difficult to determine at what point membranes from this effort should transition.
- It is not clear that this project is doing anything unique.

Specific recommendations and additions or deletions to the work scope

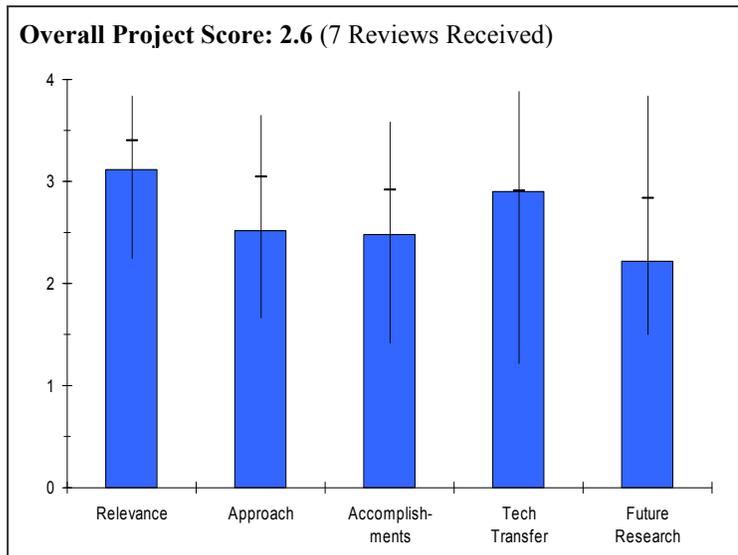
- Increased interaction with the North American fuel cell industry is encouraged.
- Full membrane characterization and participation in DOE's High Temperature Membrane Working Group for direction in correct membrane characterization protocol.
- This project just started the second year, project progress is good. No action is need at this time.
- Focus work on overcoming key barriers.

Project # FCP-08: University of South Carolina Fuel Cell Design Project

John Van Zee; University of South Carolina

Brief Summary of Project

The objective for Project 1 (non-carbon supported catalysts) includes developing novel materials (e.g., Nb-doped) for improved corrosion resistance and improved fuel cell components. The objective for Project 2 (hydrogen quality) is to develop a fundamental understanding of performance and durability losses induced by fuel contaminants. Project 3 (gaskets for PEMFCs) plans to develop a fundamental understanding of the degradation mechanisms of existing gaskets and the performance of improved materials. Finally, the objective for Project 4 (acid loss in polybenzimidazole (PBI)-type high temperature membranes) is to 1) develop a fundamental understanding of acid loss and acid transport mechanism and 2) predict performance and lifetime as a function of load cycle.



Question 1: Relevance to overall DOE objectives

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

- The project on hydrogen quality seems to be the most likely to have an impact by this team, while phosphoric acid research is not particularly compelling for the HFI.
- The primary work reported focuses more on modeling of flows, which can be related loosely but doesn't do much in terms of advancing any of the four research directions.
- The project is highly relevant to DOE's objectives and supports the President's Hydrogen Fuel Initiative.
- The program addresses critical needs for the development and advancement of PEM technology.
- The hydrogen quality program is critical for achieving durability of the PEM fuel cell and assuring the cost of hydrogen is not excessively high.
- Gasket materials are critical for PEM fuel cells. Developing stable gaskets with high durability is a PEM fuel cell need.
- Acid loss is a critical problem of the PBI-type membrane and suggests that PBI is a matrix for holding phosphoric acid and not a membrane in the sense of perfluorinated sulfonic acid membrane. This is an issue that needs to be fully understood.
- The project is in complete agreement with the overall DOE objectives.
- A collection of disparate project areas that broadly support fuel cell development.
- The main projects of this program directly address the top three barriers of durability (catalyst supports, gaskets), performance (impurities) and cost (not sure how this is directed at reducing costs).
- The program also appears to cut across the transportation and stationary lines.
- Project appears to address some key barriers, but is not clear aligned to the Hydrogen vision.

Question 2: Approach to performing the research and development

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

- The approach of this group is very disconnected with no real synergy between the four different research areas.
- Within any given research area, the approach tends to be very vague on specifics and no progress has been made. More often than not, this degree of unorganization or lack of insight leads to poor progress.
- The technical approaches for the program are reasonable.

- The approach thoroughly analyzes the design of the conventional and optimized PEM fuel cell flowfields.
- From the data developed by this program, optimized designs of the flowfields and modeling of hydrogen purity effects for various PEM fuel cells will be possible.
- The degree to which the technical barriers are addressed is not fully described by the PI during the poster session and this could be attributed to the following: (1) The project just started two months ago and will continue for another 20 months. (2) The project consists of four subprograms that are not yet completely developed. (3) Most of the co-PIs of this rather large project did not participate in the poster session.
- The catalyst support corrosion issue directly addresses a critical limiting characteristic of current carbon supported catalysts.
- Determining the tolerance to hydrogen quality will presumably directly impact the cost associated with hydrogen production, but not necessarily the cost of the MEAs or stack fabrication.
- The various projects appear to be unrelated from the information presented, and as such, for a two year program of this size, it is a concern that the degree of progress on any one will not be very deep.
- Too many sub-projects within this project.

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

This project was rated **2.5** based on accomplishments.

- At this time, the only real progress is limited modeling on massively parallel flow channels that won't be used commercially. These are being used as the basis for doing impurity studies, but the models haven't been validated experimentally and its unlikely that they can be to the level that is necessary for the way they are hoped to be applied.
- No supporting/past work in this area has been presented to suggest that success should be expected from this work.
- The project was started February 2007. It is too early to make a judgement for technical accomplishments.
- The modeling of the current density distributions in the conventional cell and the ideal cell provide a basis for understanding the overall performance of PEM fuel cells.
- The water modeling and hydrogen distribution will greatly help understanding the PEM fuel cell hydrogen quality experiments.
- The thermal modeling as a function of flowfield design will provide additional understanding with regard to the durability of the membrane. This is a bonus from this program and is not included in objectives.
- The project is showing a reasonable rate of progress.
- This project is just getting started and most of the work to date has focused largely in the area of modeling of cell current density distributions and temperature gradients. This type of work has been done many times before by many others, and there is really nothing new here.
- Better clarification should be presented as to how the MEA current density uniformity is related to hydrogen impurity – is the modelling done just because it can be or is there evidence to support it is a strong factor determining the stack response to fuel impurities?

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

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

- Interaction with industry, centers/panels is important. This has not been demonstrated by the project yet or at least is unclear.
- Significantly more interaction with leaders in the field would significantly strengthen the project.
- Hard to rate technology transfer because program has just started up. Collaboration with Plug Power is a strong tech transfer effort.
- The detail and quality of the data reported at the review is outstanding.
- The project has identified Plug Power and 14 companies as collaborators, but there is little evidence of meaningful input or interaction so far.
- The opportunity for dissemination of results through the NSF IC/UCRC appears good. Direct interaction with Plug Power and probably UTC will also be beneficial.
- Though 14 companies are mentioned early in the presentation, there is no other explanation of collaboration in this project.

Question 5: Approach to and relevance of proposed future research

This project was rated 2.2 for proposed future work.

- Plans to pursue sealants/gaskets and novel supports don't suggest that advancement of the state of the art is likely.
- Phosphoric acid loss/migration is not currently the limitation in the commercial deployment of these systems.
- The work on hydrogen quality is necessary, but the use of the model developed and parallel flow channels to evaluate impurities is unlikely to improve insight into hydrogen quality specifications.
- The task plan identifies the future work and the program is well-structured.
- The project did not clearly show any proposed future research work.
- The workplan is well-structured and carefully laid out.
- No slide was included to specifically state the future work.
- Since project has just started most work is still to come, so should consider splitting project into multiple projects with more focus.

Strengths and weaknesses

Strengths

- The PI has a good experience for the fuel cell R&D experience.
- Well-organized modeling effort.
- Top PEM researcher leading effort.
- The project interactions/collaborations include 14 Companies of NSF I/UCRC Center for Fuel Cells, DOE H₂ Quality Team and Plug Power partners.
- The project consists of four subprograms that are in complete agreement with the overall DOE objectives.
- Good modeling and interactions with partners.
- Project appears to be well-funded.

Weaknesses

- Little experience and no demonstrated performance in the area. Unlikely to supply much benefit to the program or advance the HFI.
- Based on the presentation information, only one PI for the program. The risk is high for the program. The program needs more co-PIs or coworkers to accomplish the projects.
- Program should address cross-flow flowfields.
- The project duration is too short for the large amount of work that needs to be accomplished.
- Very diverse topics which might stretch the resources too much to enable solid progress on any one project.
- PI is attempting to take on too many topics.

Specific recommendations and additions or deletions to the work scope

- Should focus effort on one key area.
- Hydrogen quality has needs that can be met by this team, but focusing on performance and diagnostics rather than modeling would be a better approach. Close coordination with others in the program in this area is necessary to make sure that meaningful contribution is added.
- Data supporting the potential of novel supports needs to be demonstrated to justify funding.
- Sealants/gaskets work needs to be guided by fuel cell developers or the studies may prove valueless.
- Phosphoric acid studies should be abandoned.
- The PI should add a co-worker to the project.
- Does DOE provide \$1,655,000 for one PI only? The funding is too much for one PI (20 months). The funding for most university projects is ~\$300K per year.
- Program should compare PBI fuel cell to phosphoric acid fuel cell using silicon carbide for matrix. Which of the two reduces the phosphoric acid vapor pressure and will extend the life of the fuel cell is a critical question.

Project # FCP-09: Development of a 5 kW Prototype Coal-based Fuel Cell

Steven Chuang; University of Akron

Brief Summary of Project

The overall objective for the project is to design a 5 kW prototype coal-based fuel cell and fabricate a small scale coal fuel cell system including coal injection and fly ash removal ports. The objective for 2007 is to fabricate and test a small scale coal fuel cell system. To achieve the objective, an improvement of the anode catalyst structure and the interface between electrode and membrane will be made. Refinement of the techniques for fabrication of the fuel cell assembly will also be needed. Interconnect materials for the coal-based fuel cell will be selected and tested.

Question 1: Relevance to overall DOE objectives

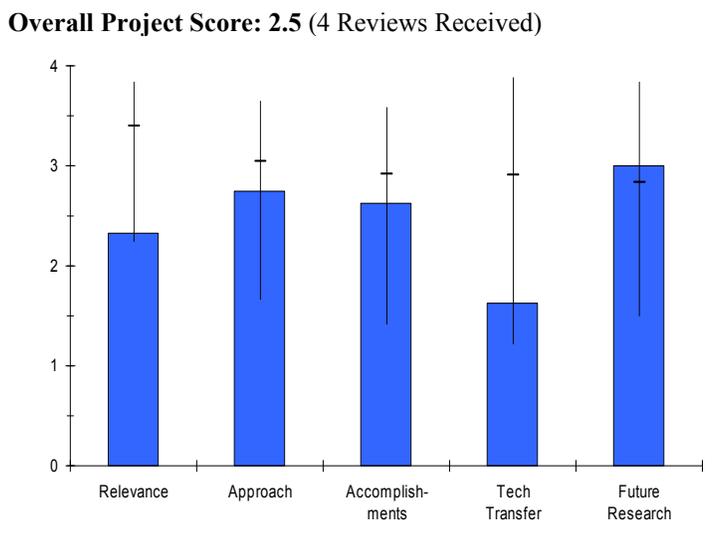
This project earned a score of **2.3** for its relevance to DOE objectives.

- It is not clear how a solid oxide fuel cell utilizing coal as a fuel is supporting the Hydrogen Fuel Initiative.
- Project to generate electricity directly from coal. In the long term, it is difficult to understand how this fits into the overall DOE program and what long term advantages it offers.
- Fuel cells utilizing coal directly could utilize the existing domestic coal resource on a small scale at high efficiency close to the load, saving line losses and enhancing reliability at the point of use. This is a strength of the topic.
- The lack of integration of the process with sequestration detracts from its benefits.
- Although this is not a hydrogen production topic, its electrical generation focus is consistent with DOE RD&D goals of high efficiency and domestic fuel use.
- To be more consistent with DOE RD&D goals of reduced CO₂ emissions, sequestration could be added to the process topic.
- Addresses DOE barriers for SOFC work.

Question 2: Approach to performing the research and development

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

- Given the low cell voltages and the lack of any emission control for the effluent of the SOFC, the approach should be justified by calculation of overall system efficiency and comparison with coal to electricity via combustion.
- The approach to improving cell performance on this high sulfur fuel is very good.
- Approach appeared to be very naïve. Very much an academic effort but without very much detail and very limited data to support the effort. There are many analytical/spectroscopic techniques that should be used in this program that are absent. One specific program goal was the removal of fly ash from the cell during operation. There was no indication that this technical objective is being pursued.
- Although the "fly ash" is supposed to not adhere to the anode, the "fly ash" removal methods were not successful in removing the "fly ash". This should remain a high priority.
- What will be done with the CO₂ emissions?



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

This project was rated **2.6** based on accomplishments.

- This is a very challenging project and the short-term performance on coal is impressive.
- Showed several graphs that indicate that a cell is capable of converting coal into electricity. Overall efficiency very low. No indication of potential cost or efficiency improvement.
- Current accomplishments include interconnect development, successful operation on coal, verification of loose "fly ash", and comparisons with other systems. These are significant accomplishments.
- The development of a "fly ash" removal method may be difficult. Without development of a "fly ash" removal method, the advantage of loose "fly ash" might not be utilized to its full potential value. This topic needs to be stressed in the near term.
- The current project scale is extremely small, compared to the project goal of 5 kW. Some assessment of the path to larger size demonstrations (and up to the project goal of 5 kW) could help to ensure that the project goals are met within the project contract terms. This is a suggestion for additional emphasis by the project manager.
- If the durability is proven out, the achievement of 750-800°C operation is a significant achievement.
- What is the overall efficiency of converting coal to electricity for THIS fuel cell? I saw some general statements, but they were all generic. What is the efficiency target for this system?

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

This project was rated **1.6** for technology transfer and collaboration.

- No outside interaction is evident.
- Did not appear to have any tech transfer opportunities or collaborations.
- Need to get some industrial partners if they ever hope to commercialize the system. Maybe GE?
- This is a university operating in a vacuum. The only real-world development tie is the Ohio Coal Development Office. Needs more collaboration.

Question 5: Approach to and relevance of proposed future research

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

- The proposed future research addresses the issues of taking the initially promising small-scale single cell results to the stage of demonstration of a stack.
- Beyond simple stating that the cell efficiency needs to be improved, there did not appear to a well defined future research plan. There were not details given even on the proposed path to higher efficiency.
- Future work planned is appropriate, with emphasis on the goals of the research.
- It is time to bring in a collaborator with industrial engineering expertise.

Strengths and weaknesses

Strengths

- Prior work is well documented and the current project builds upon prior experience. This is a strength of the project. The project tries to reduce the impact of "fly ash" on the fuel cell anode. This is a good goal and some progress has been made.
- The graphical evidence provided is helpful in understanding the technology topic.
- The PI is very knowledgeable about SOFCs and has identified what issues need to be addressed to demonstrate them.
- The project emphasizes the use of a domestic resource – coal – in a highly efficient and customer supportive way.
- The project builds on prior experience and work.
- The project has accomplished many of their goals.

Weaknesses

- Analysis of system efficiency and system design is missing. This type of analysis would illustrate if this approach for converting coal to electricity makes sense.
- The project could really benefit from some collaborations with the larger community capable of using a variety of spectroscopic techniques to understand the cell/material function and performance in this approach.
- The project could be improved by coordinating and fully integrating sequestration issues into the project and into the technology development process.
- The project size is very small now, compared to the goal of a 5-kW system.
- The project accomplishment, of showing that "fly ash" does not adhere to the anode, may be hard to take advantage of without an effective "fly ash" removal technique.
- System performance degradation, ostensibly due to "fly ash" build-up, is probably too severe to allow use of this technology on a commercial scale. Degradation needs to be improved - ostensibly by implementing a "fly ash" removal method.
- System is optimized for a particular coal from Ohio. What about other coals? Will it work for them? Especially with different sulfur content.
- Need a plan for fly ash management.
- Need a partner with a business and scale-up focus. Otherwise, unanticipated problems in making a commercial product could doom the work to failure.

Specific recommendations and additions or deletions to the work scope

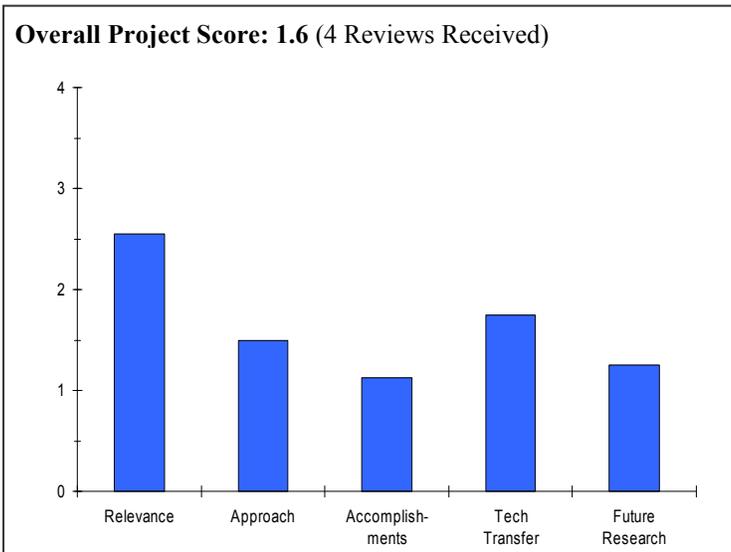
- Additional future work is suggested to fully include sequestration of CO₂.
- For coal resources to support the DOE RD&D goals of lower CO₂ emissions, this project must be integrated with sequestration. It is suggested that this integration be accomplished now, while the project is in progress, to ensure that the technology developed here is compatible with sequestration.
- The poster included several technologies, some of which were for comparison with the technology of interest. Although this is helpful for comparison, it may also be confusing to some readers. It is suggested that in the future, the comparisons be separated out to avoid confusion with the topic of interest.
- The project could be improved by making the graphs consistent in terms of scale and units.
- Without a successful "fly ash" removal method, the advantage of the "fly ash" not adhering to the anode could be lost. This should be a topic for future high priority work.
- Suggest system design and efficiency analysis.
- Project is quite specifically tied to Ohio's coal industry. Expand to the national interest and get away from only Ohio coal operation. Or, explain that Ohio coal (sulfur content, ash content, moisture, and all the rest) are similar to other coal sources—I think it is not.

Project # CCP-01: Development of Advanced Manufacturing Technologies for Renewable Energy Applications

Charles Ryan; National Center for Manufacturing Sciences (NCMS)

Brief Summary of Project

The National Center for Manufacturing Sciences (NCMS) is working with the U.S. Department of Energy (DOE) and the private sector to identify and develop critical manufacturing technology assessments vital to the affordable manufacturing of hydrogen-powered systems. This project leverages technologies from other industrial sectors and works with the extensive industrial membership base of NCMS to do feasibility projects on those manufacturing technologies identified as key to reducing the cost of the targeted hydrogen-powered systems.



Question 1: Relevance to overall DOE objectives

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

- Partner such as Millennium Cell needs to demonstrate their results from this funding. Partners such as Freudenburg/UTC/Cabot and DuPont may prove more fruitful.
- Manufacturing research and development is an essential component to achieving the cost targets for the PEM vehicle.
- The transition from laboratory to PEM vehicle production will be through several phases including portable and stationary fuel cells. The manufacturing efforts need to address these different applications.
- A broad base of manufacturing efforts will need to be developed to move the PEM technology forward and the program must structure itself for this diversity in manufacturing technology.
- Great titles for the eight projects: "low-cost," "high-reliability," "Manufacturing process," etc., but I could not begin to decipher what the individual projects were about or what they have accomplished. NO CONTENT in the poster.
- The field of manufacturing is highly significant and needs to be pursued and in general the topics sound good on the surface as they were presented. The actual individual programs vary from relevant (projects 1, 4, 7) to nearly irrelevant to the goals of the DOE program.

Question 2: Approach to performing the research and development

This project was rated **1.5** on its approach.

- It would be nice if there were some balance of plant components developers involved.
- The approach attempts to fund too many programs at levels not consistent with being able to complete the R&D effort.
- The approach has a limited prospect of success because the expertise in fuel cell technology at NCMS appears to be limited.
- The federal funding level was at \$4.9 million for 2004 and 2005. It was not clear what the distribution of funding was to the eight projects.
- The presentation should identify what the funding levels and cost share levels are for these projects.

- Having NCMS get monies, then do basically their own solicitation for projects is not an effective way to generate projects that address R&D barriers.
- Low-Cost, High-Volume Manufacturing for PEMFC Power Plants seems to have a few useful aspects. LBNL looking at leachates on what might be called balance of plant could be useful, but there were not enough details to judge. And what is the impact of the leachates? Need better coordination with several fuel cell manufacturers to ensure relevance.
- Need to define targets (including cost and performance) for each of the eight projects.
- In many cases the technical barriers approached are not those where the material science is leading.

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

This project was rated **1.1** based on accomplishments.

- Not clear at all if all partners made any kind of real accomplishments towards a low cost system (real numbers, not percentages).
- Each of the projects report varied levels of success.
- The interview with NCMS's representative was not very productive as he referred me to the individual companies who were not represented.
- It was not clear what part of the activities that were reported were covered by NCMS funding; e.g., the one-step process by Protonex was reported prior to the start of this project; March 2004.
- The "Low-Cost, High-Volume Manufacturing of PEM Fuel Cell Power Plants" did not report any results or participation by UTC Power. What was their contribution?
- Cabot has successfully completed an ATP program with NIST on ink-jet printing. What part of the NCMS program is different from the ATP program?
- Freudenberg and UTC Power have a separate DOE program for a low cost seal. How do these two programs differ? This should have been addressed by NCMS.
- High-Rate Mfg of Carbon Composite Tanks. The OEMs are moving to 70MPa tanks. This work is for 35 MPa tanks. Is the work relevant to 70 MPa? Objective of 6 min cycle time might be relevant, but can they do it for 70MPa tanks?
- Low-Cost, High Volume Ink-Jet. No cost data or estimates, despite the title.
- Low-Cost, High Reliability Seals. No cost data or estimates, despite the title.
- Develop Low Cost MEA3. No cost data or estimates, despite the title.
- Low-Cost, High Volume Manufacturing for PEMFC. No cost data or estimates, despite the title.
- Affordable, High-Rate Manufacturing of Carbon Composite Tanks. No cost data or estimates, despite the title.
- Little valuable progress as far as can be determined since 2004. For example the potentially valuable tank wrapping program still has essentially only concepts to show. The cartridge fuel project has made some progress but it is of limited application, none the less they have apparently made progress though the 1 use concept is clearly unfeasible in mass production. The Stack forming program beat its target but the target is not correlated to the DOE target (it is at about 1/2 current power density). No meaningful progress on testing and it is aimed at the wrong sort of tanks so any progress would likely have no impact on DOE targets and goals. Inkjet process has potential but not at all clear the right testing is being done to verify the results are meaningful to real MEAs. Sealing still not at a degree of progress that might be evaluated really. Project 8 has potential but unclear how good progress actually is.
- Above all there is no cost numbers given; that is what manufacturing lives and dies by.

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

This project was rated **1.8** for technology transfer and collaboration.

- Some collaboration among industry members per project. Very unclear if all the players in this program interact with each other.
- No technology transfer was reported. The program allows individual companies to develop technology and intellectual property without disclosing the technology. Based on technology transfer, the rating is 1.

- The collaborations were high with several teams formed to solve problems. Based on collaboration the rating should be 3.
- I am sure the results are helpful to the companies participating. Whether or not these projects are ever useful to anyone else is hard to judge if no data/results are ever presented at the reviews.
- Essentially individual programs operating in isolation

Question 5: Approach to and relevance of proposed future research

This project was rated **1.3** for proposed future work.

- None was presented.
- The presentation did not report future work for NCMS. The rating would have been higher had they reported future work.
- Individual projects were continuing.
- Because I saw virtually no proposed future research, I cannot comment on their proposed future research.
- Unclear exactly where this is going. In the cases where it is clear I can not see how it will actually advance storage because the work is aimed at things that are clear how to do, not where research is actually needed.

Strengths and weaknesses

Strengths

- A few good partners who are very capable of delivering a good product to support the fuel cell industry.
- Many of the companies are well established in the fuel cell arena and bring strength to the program.
- POTENTIAL collaboration network that NCMS brings to the table. I am not seeing it, though, in the implementation of these eight projects.

Weaknesses

- No real cost data to show the current cost of the system/process to know how much they are closer to a mass market product.
- Discussions with NCMS representative were not productive. Representatives from the companies should have participated.
- The presentation did not follow the guidelines provided by the DOE; no future work identified by NCMS.
- It not clear what value NCMS brings to the program since they appear to not be able to review the technical status of the projects.
- This NCMS "project" has been underway for a couple of years now. It is time to see results. They may have results for some of the eight projects, but we sure are not seeing any results or useful information at the Annual Reviews.
- Participants in all the other DOE projects underway manage to present real results and show progress at the Annual Reviews and at FreedomCAR and Fuel Partnership tech team meetings despite the constraints of showing only non-proprietary information. Why can't NCMS and the eight project partners do this???
- Should be required to develop targets for each of the eight projects, hopefully tied to DOE targets, and show progress towards those targets. Otherwise, impossible to judge the merit of the work.

Specific recommendations and additions or deletions to the work scope

- Real cost numbers should be published. 30% reduction in cost is meaningless unless the final cost is affordable by the customers.
- DOE should work with NCMS to get them more aligned to the reporting of results and following the DOE program guidelines.

- Manufacturing is an important aspect for PEM fuel cell advancement, but NCMS does not appear to have the expertise in fuel cells to directly participate. The expertise of NCMS should be improved.
- Cabot has successfully completed an ATP program with NIST on ink-jet printing. What part of the NCMS program is different from the ATP program?
- Freudenberg and UTC Power have a separate DOE program for a low cost seal. How do these two programs differ?
- I recommend that EACH project team (of which there are eight) be required to present their RESULTS at the next Annual Review. The current process is not working.
- The NDE testing project team should review their project with the Production/Delivery tech team if they have not already done so. Likewise, the Codes & Standards tech team might be interested in a report of progress. Again, though, they need to show some real data and results.

