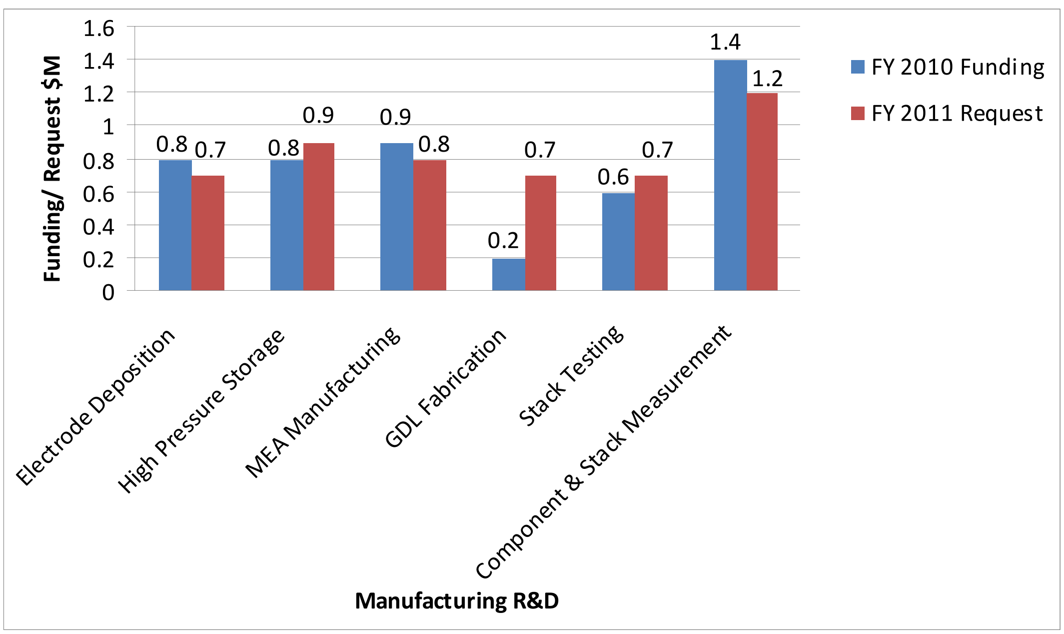
2010
Manufacturing R&D
Summary of Annual Merit Review of Manufacturing R&D Sub-program

Summary of Reviewer Comments on the Manufacturing R&D Sub-program:

The Manufacturing R&D sub-program develops and demonstrates technologies and processes to reduce the cost of components and systems for fuel cells, hydrogen storage, and hydrogen production, to enable the growth of a strong domestic supplier base. The activities focus on near-term cost goals for early market applications. In FY 2010, eight new manufacturing projects were reviewed. These projects addressed fuel cell membrane electrode assembly (MEA) manufacturing and fabrication of catalyst-coated membranes. In addition to new manufacturing R&D on low-cost, durable MEAs, the sub-program added work on gas diffusion layer production and fuel cell stack in-line testing. One project addressed lower-cost manufacturing of high-pressure containment vessels for hydrogen storage.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was level for FY 2009 and 2010 at approximately $5 million per year. All current projects are scheduled to continue through FY 2010 with future efforts subject to appropriations.



Majority of Reviewer Comments and Recommendations:

Manufacturing projects were rated high to average with seven individual projects rated 3.1 or higher. Overall ratings ranged from 3.6 to 2.7. All projects were judged to be relevant to the DOE Hydrogen Program's activities, with good or adequate technical approaches employed. In most cases, project progress and accomplishments were judged as satisfactory; however, several projects were observed to have approaches that needed improvement in terms of modeling/testing integration, concept validation, or industry input. Project teams were judged to be strong for most projects, with partners having demonstrated experience and expertise in the required technical disciplines. In general, reviewers felt that more effort should be devoted to quantifying and validating potential cost reductions. Lower manufacturing costs were judged to be an important rationale for continuation of the projects in the future.

The highest ranked (3.6) project was "Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacturing." Reviewers considered this project to be highly relevant, with an excellent approach, substantial progress, and strong technology transfer and collaborations.

The lowest ranked (2.7) project was "Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage." This project was judged to be relevant, but it was observed that the approach (if fully successful) will have a low impact on reducing the storage system manufactured cost.

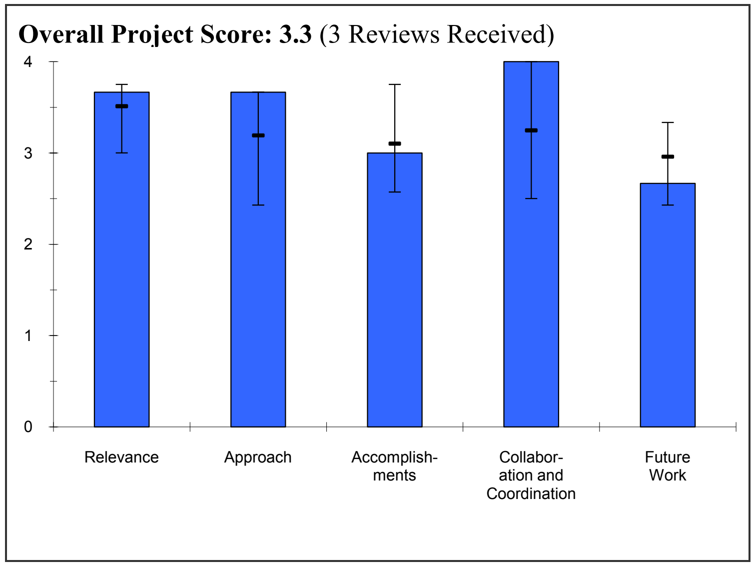
In summary, manufacturing R&D was considered to be a key element for fuel cell and hydrogen technology commercialization. The Manufacturing R&D sub-program was judged to be well-managed, well-organized, and focused on addressing programmatic performance targets.

Project # MN-01: Fuel Cell MEA Manufacturing R&D

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project

The project objectives are to 1) evaluate and develop in-line diagnostics for membrane electrode assembly (MEA) component quality control, and validate in-line, 2) investigate the effects of manufacturing defects on MEA performance and durability to understand the accuracy requirements for diagnostics, and 3) validate and refine existing Lawrence Berkeley National Laboratory MEA model for new application predictions of the effects of defects.



Question 1: Relevance to overall Department of Energy (DOE) objectives

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

- The need for lower cost repeat components is extremely important, as is the need for quality assurance/quality control processes.
- This project seems to be generally in alignment with DOE objectives, but would be better if it were not so disjointed. For instance, the way in which modeling is to be used to make practical improvements has not been clearly described. I do not suggest stopping the model development activity, but rather indicating how models are to be realistically validated, parameterized, and implemented to guide application of inline diagnostics.
- MEA cost and performance have been critical to competitiveness of fuel cells.

Question 2: Approach to performing the research and development

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

- The approach is valid and should be followed.
- Conceptually, this is a good approach.
- There is an outstanding team of stakeholders involved in the process.

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

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

- The accomplishments to date are as should be expected per the timeline.
- Given the time and financial support so far, it seems like the implementation of useful techniques is somewhat far away.
- The diagnostics development is focusing on key problem areas of fuel cell materials performance and cost.

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

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

- The list of collaborators is impressive.
- There is a strong group to provide vertically integrated input.

- The National Renewable Energy Laboratory (NREL) has assembled an outstanding team of stakeholders including both private industry and research institutions.

Question 5: Approach to and relevance of proposed future research

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

- The proposed future work makes sense for this exercise.
- See comments above. The project should include a clearer description of how the separate components of this program are combined to result in cost effective application of the diagnostics in an inline environment.
- It is good that NREL is looking at growth rates to try to understand how possible "defects" degrade. It is also good that NREL is expanding into high-temperature proton exchange membrane (PEM).

Strengths and weaknesses

Strengths
- The list of collaborators is good.
- The team did good work on coupling the simulation of defects to the use of diagnostics to test sensitivity. It also did well with the real world demonstration plans.
- This is a team of highly skilled experts.

Weaknesses
- There is a lack of stack testing to detect and interpret the signals for the various defects.
- They need to integrate the model with hardware diagnostics and create an overall plan to provide a feedback loop.

Specific recommendations and additions or deletions to the work scope

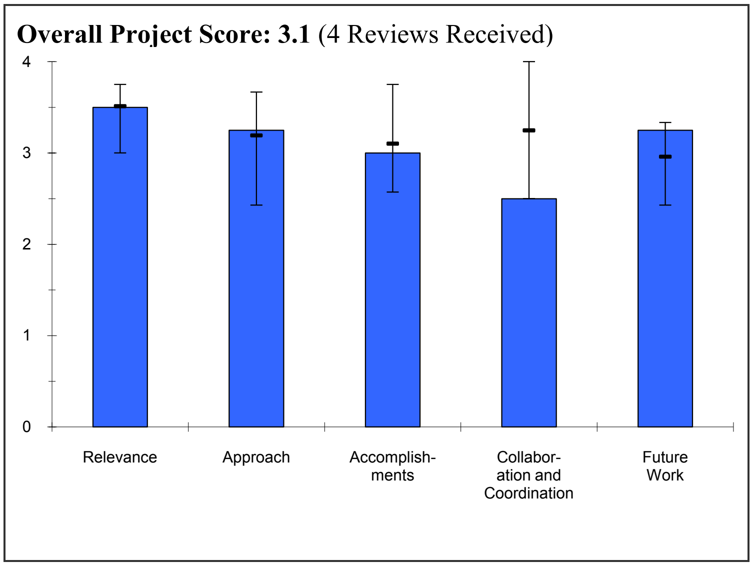
- The reviewer suggests the PIs evaluate their ability to do systems testing.

Project # MN-02: Reduction in Fabrication Costs of Gas Diffusion Layers

Jason Morgan; Ballard Material Products

Brief Summary of Project

The overall objective of this project is to reduce the fabrication costs of gas diffusion layer (GDLs) by 1) improving product quality through the use of online tools, 2) increasing the manufacturing efficiency by reducing the number of process steps and producing material at a wider width, 3) reducing process losses by improving Web-handling equipment, and 4) eliminating scrap through improved product uniformity. The goal is to produce high performance GDLs at lower cost at high volumes in the near-term.



Question 1: Relevance to overall DOE objectives

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

- This project is related to polymer electrolyte membrane (PEM) fuel cell cost reduction (reducing the cost of GDLs) and improving performance/cost by understanding the relationship between process parameters and critical GDL properties, as well as identifying GDL requirements for improved performance.
- Cost reduction and optimal water transport are critical to commercialization of PEM fuel cells.
- It is exactly this type of real-world, real-scale installation that will allow fuel cells to reach commercial viability and acceptance. Good job! All of the cost models in the world do not compare to having to do the actual implementation of the process equipment and produce large quantities of usable material. This type of real-world project for further understanding of process problems and variables should be supported even more by DOE.
- The project is relevant to DOE goals. However, the inability to share microporous layer thickness and specifics regarding the GDL that the group is making does limit the usefulness and relevance to the general community.

Question 2: Approach to performing the research and development

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

- The team's use of cost breakdown and development of new, lower cost process technology is good.
- The team showed good management, timeline, and progress. This project is very practical, yet critically needed.
- The approach is good in general. However, the group should be performing more *in situ* fuel cell experiments to validate the manufacturing changes made to the products to get better feedback throughout the project. From the way it was presented, it seems that the investigators will vary parameters first and then run all fuel cell experiments later, but this should be a more integrated process.
- It is not clear how acceptance standards for GDL materials have been established and what those standards are. It appears that the only customer involved is Ballard Power Systems (BPS). This project would benefit significantly from the involvement of other customers besides BPS.
- The team used a good approach to addressing critical processes and equipment that affect GDL quality and limit production capacity. However, since there was little detail shown concerning what defects the online inspection systems are addressing, it is difficult to assess whether the proposed approach is adequate.
- This project recognizes the need to develop a deeper understanding of the relationships among critical process parameters, the performance of the resulting GDL, and the modeling effort that should be underway if showing progress in that direction.

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

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

- This project has a large degree of "trust me" information because these statements and accomplishments are not backed up with any data.
- Much of this project is hard to grade because there is little information on many portions. For example, this project has made GDL substrate improvements. However, there is no data to document the improvement, the amount of improvement, or to show that these are state-of-art materials. The materials are not available to other developers, so there is no independent verification of these improvements, nor even polarization curves, thermal conductivity data, porosimetry, or permeability data.
- There are clear improvements in process conditions and process changes to eliminate micro-cracking.
- The team has shown cost reductions to $14/kW for the GDL at 1/5th the volume of the commercialization target. The PIs state that there is a roadmap to get to the DOE target, but it is unclear what this roadmap is. It also appears that these cost estimates only include materials and labor and not capital costs and overhead. These cost estimates are not consistent with the methodology used by, for example, Directed Technologies Inc. (DTI).
- If the DOE goal is truly to have 500,000 fuel cell vehicles in production per year, more investment into exactly this type of project is needed. There is very good progress made here and very good hands-on knowledge development.
- The technical accomplishments towards cost and process were good.
- The project would have been more interesting if more data could have been provided (like microporous layer thickness) and fuel cell experiments were run.
- The team showed good progress in reducing GDL costs toward the established DOE goal of $4/kW.
- This project appears to be on track to meet its next critical project milestone.
- It is not clear to what extent online measurement and inspection tools will be used for real-time process controls.

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

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

- There is some minor collaboration with Hickner/Pennsylvania State University —otherwise this project is entirely BPS.
- The collaborations seem lacking. The lack of an existing market for this quantity of MEAs is worrisome. Who is going to buy all of these MEAs or all of this GDL material?
- The groups worked well together.
- The collaboration among project partners appears to be well coordinated. However, this project would benefit from additional input from other customers and potential customers.

Question 5: Approach to and relevance of proposed future research

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

- The team's future work includes more inline methodology and reducing the number of individual processing steps.
- Their future work plan is in line with current and continued progress.
- The proposed plan seemed good, but the specifics of the plan were limited.
- The plan going forward is well thought out and consistent with addressing the critical barriers to cost-effective, high-volume production methods for paper GDL.

Strengths and weaknesses

Strengths

- Real-world application development is sorely needed in the industry. Good job to BPS and DOE for funding this project!
- This project addresses critical barriers to successful commercialization of fuel cells, namely cost-effective, high-volume manufacturing capacity and effective online inspection and measurement techniques to improve GDL product quality.
- The integration of online measurement and inspection tools, and models of the relationships among material properties and performance, should lead to improved process controls and product quality.

Weaknesses

- The team could use a partnership with an auto manufacturer or another external MEA/stack supplier as an outlet for products.
- There is no other customer besides BPS involved in this project, so the acceptance standards established by BPS may not satisfy other customers' needs for GDL materials. The addition of at least one outside customer to evaluate product quality and performance would add significantly to the credibility of the project's results.

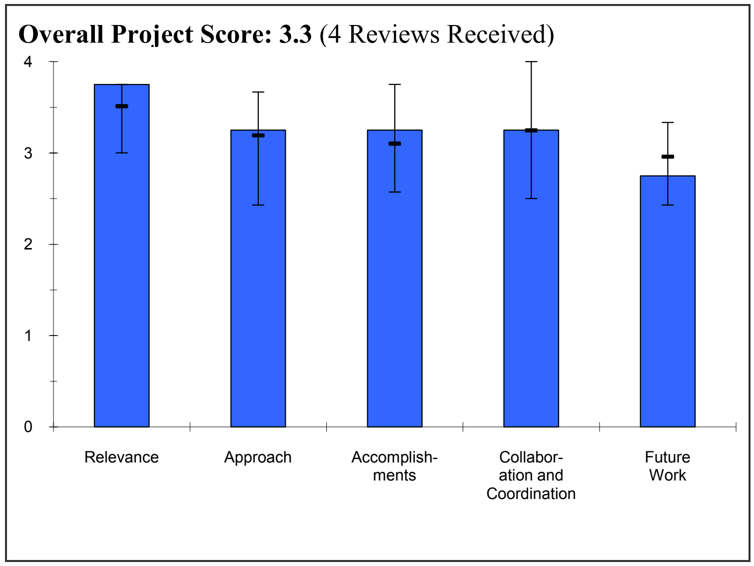
Specific recommendations and additions or deletions to the work scope

- More data need to be shown to back up the statements made.
- There should be independent verification of statements, such as statements about improved GDL materials or, at minimum, polarization curve comparisons.
- It is recommended that one or more external customers be added to the project team to provide additional input on product acceptance standards and assess the resulting GDL quality and performance.

Project # MN-03: Modular, High-Volume Fuel Cell Leak-Test Suite and Process
Ian Kaye; UltraCell Corporation

Brief Summary of Project

The project objectives are to 1) design a modular, high-volume fuel cell leak-test suite capable of testing in excess of 100,000 fuel cell stack per year (e.g., 50 fuel cell stacks per hour), 2) perform leak tests inline during assembly and break-in steps, 3) demonstrate fuel cell stack yield rate to 95%, 4) reduce labor content to six minutes, and 5) reduce fuel cell stack manufacturing cost by 80%. The objectives for the past year were to 1) develop leak-test methods and 2) design and fabricate a leak-test suite prototype.



Question 1: Relevance to overall DOE objectives

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

- Although repeat components are currently the major cost driver for the stacks, as the component costs drop the labor costs will become significant. Starting the development of methods to reduce labor cost at this point in time is appropriate.
- Leak testing has high potential to reduce manufacturing costs and support high-quality manufacturing.
- The concept of online quality control is an important cost-reduction topic. This project is an initial step towards reducing the burn-in time and increasing the throughput of the production process.

Question 2: Approach to performing the research and development

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

- The approach is sound and innovative.
- The testing process and protocols appear to be thorough.
- The testing appears to be focused on the system only after it has been fully assembled, which raises the question of whether there would be any potential benefits of testing done prior to the final system assembly.
- Project feasibility is relative to progress as the project proceeds. The reviewer thinks that for this project, feasibility is primarily based on cost savings and processing rates. Since this presentation is the second report on progress, the reviewer would have liked to see data supporting the feasibility of the original/overall objectives of the project.
- Leak detection is only performed after the system is fully assembled, meaning that rework could be a major contributor to cost.

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

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

- The accomplishments to date are appropriate and impressive.
- Assuming a high-volume scenario, the type of testing appears to be so time-consuming that there would be a potential for a lot of faulty units to be manufactured while a defect was being identified and assessed. This would translate to the risk of a high level of scrappage and cost.

- This project appears to be very specific to an UltraCell product. The reviewer questions how transferrable this would be to other technologies.
- Software development by CTS in support of the leak-test suite and the controls necessary for automating the process seem very impressive. The mechanical analysis and modeling done by the Pacific Northwest National Laboratory (PNNL) also appear impressive, but it was not clear how this information was being used in the leak testing/assembling process.
- The objectives for the last year as stated in the presentation (slide 3) were met, but with respect to the milestones on the next slide, it would appear that a major objective over the last year would be the go/no-go decision based on the feasibility of 50 parts per hundred (pph), if 5 pph was achieved by February 2010. This objective is not listed for the past year and progress towards the 5 pph goal was not provided, nor was a suggested revision given to this date on the go/no-go decision. The objectives achieved and not achieved should be addressed.
- Progress is being made and the PIs appear to be meeting their objectives. We should ask the question, "Are they on the right track to reach high-throughput, low-rework quality control?" The approach does not include identification of defects prior to assembly, which is a flaw in the analytical method.

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

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

- The collaboration is adequate and suitable for this type of project.
- The team has good partners, but they appear to be specific to UltraCell's needs.
- The team is working with PNNL, but the speaker was unable to discuss or explain the results of the model. The modeling results should be explained. There was no explanation of what Mound Technical Solutions, Inc. does for the program.

Question 5: Approach to and relevance of proposed future research

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

- The future work plan is rational and appropriate.
- The speaker spent very little time on future work, though he had plenty of time left to discuss.
- The future work, as stated, includes a plan to test/evaluate and validate leak-test suite. However, on the last slide under the summary, the progress section stated that they had already tested the leak-test suite. What is the difference between testing done and testing planned?
- This section does not include anything with regards to finalizing the leak-test suite (e.g., components, tests, and procedure components) as stated verbally during the presentation.
- There was nothing listed that directly supports achieving the quantitative objectives of the project.
- The future work discussion was poor even though the speaker had time left.

Strengths and weaknesses

Strengths
- The process is much better than that used prior to this project.
- It is extremely important to increase quality and reduce fabrication costs. Therefore, this project's deliverables are very relevant to DOE objectives if enough procedural information is provided that the entire industry can benefit.
- This approach has improved the prior quality control processes and increased throughput.

Weaknesses
- The reviewer questions whether this fixture and testing process would be used in a high volume scenario. This is very good as a transitional tool specific to UltraCell's needs and priorities.
- The PI admitted not understanding the analysis or modeling work done by PNNL, but he should be able to explain conclusions derived from each effort and how this information is being applied to the leak testing/assembly process.

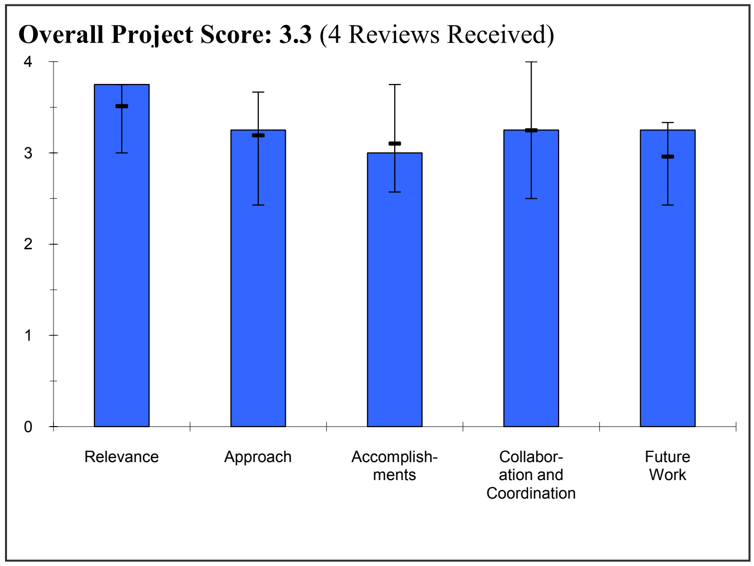
- The reviewer would suggest a time analysis of each component in the process flow chart on slide 5 as a driver for procedure revision and optimization as well as serving as a metric for the parts per hour goals. The PI said the process is dominated by the burn-in/break-in process and that the criteria for achieving this point is subject to argument, which further justifies the need for a time breakdown. What will be considered acceptable by UltraCell before a product goes out the door?
- The approach can lead to extensive rework of the process, but it is valid for the limited performance and durability of their application. The process does not appear to be valid for automotive or stationary processes and there are potential problems with the start/stop degradation with their approach.

Specific recommendations and additions or deletions to the work scope

- The reviewer would recommend they work on assessing the transferability to other products and technologies. Perhaps PNNL could have addressed this better than UltraCell had someone from PNNL been part of the presentation.
- A suggested addition would be to develop an approach for accelerating the break-in process, since this appears to be a potential bottleneck for achieving process rates.
- The team should consider how to reduce the rework process and should demonstrate that they do not introduce start/stop degradation. The PI should find a way to demonstrate that it is valid for larger (i.e., greater than 5-kW) fuel cell power systems.

Project # MN-04: Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies Engineered for Rapid Conditioning
Colin Busby; W.L. Gore

Brief Summary of Project



The overall objective of this project is to develop unique, high-volume manufacturing processes to produce low-cost, durable, high-power density, three-layer membrane electrode assemblies (MEAs) that require little or no stack conditioning. This objective includes 1) a manufacturing process that is scalable to fuel cell industry MEA volumes of at least 500,000 systems per year, 2) a manufacturing process that is consistent with achieving the $15/kW$_e$ DOE 2015 transportation stack cost target, 3) the product made in the manufacturing process should be at least as durable as an MEA made in the current process for relevant automotive duty cycling test protocols, 4) a product developed using the new process must demonstrate power density greater or equal to that of the MEA made by the current process for relevant automotive operating conditions, 5) a product of three-layer MEA roll-good (anode electrode + membrane + cathode electrode), and 6) a stack break-in time that is reduced by at least 50% compared to the product made in today's process and break-in strategies employed must be consistent with cost targets.

Question 1: Relevance to overall DOE objectives

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

- The objectives are well-aligned with the Hydrogen Program objectives for commercialization, including high-volume manufacturing of low-cost, durable MEAs.
- The scale-up, cost durability, high-volume cost model for MEA production was relevant.
- Projects such as this are critically needed for future commercialization of fuel cells in general. Kudos to W. L. Gore and Associates and DOE for funding this work!
- Reduced cost seems likely via this approach. Overall, the plan is well thought out including increased understanding of the underlying physical processes limiting manufacturing improvement.
- This project addresses stack manufacturing cost by reducing process steps, scrap, and non-reusable materials (liners). Investigators should quantify the potential for process rate improvement of the direct, two-sided coating over current methods. The investigator claims durability and stack-conditioning time improvements. These must be substantiated going forward.

Question 2: Approach to performing the research and development

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

- This project has a solid approach to reduce MEA and stack costs. The project is clearly on the appropriate development path with the high-volume, full-width MEA production with minimal coating passes.
- This project also includes what can be considered peripheral or side projects including modeling of heat and water management and modeling of mechanical membrane and electrode properties for MEA stress prediction related to temperature and relative humidity cycling scenarios. It is very unlikely that these side projects will affect the outcome and development of the main project (Gore) and there is little/no information about how these projects will feed back into the core project for MEA production.

- The project showed good use and combination of modeling with real-world application.
- Successful implementation of direct coating should reduce catalyst coated membrane cycle time. Investigators have identified an alternative path, if the primary path is not successful, although improvements based on an alternative path must be quantified. The technical challenges of an alternative path, such as membrane-membrane bond cycle time and interfacial strength, must be quantified if this path is taken. The incorporation of mechanical and transport modeling should aid development. Investigators should verify the relevance of uniaxial stress testing to stress conditions during fuel cell operation.

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

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

- Most of the results to date appear to be performance-related verification with little information on the progress for cost reductions. Most of the performance-related data appears to be on Pt loadings significantly beyond the 2010 DOE targets, but not approaching the 2015 DOE targets, and there is no path forward shown on how the PI intends to get to the target loading.
- The team is still somewhat early in project cycle, but the members are making good progress in getting equipment designed and installed, models in place, and the initial testing done.
- No miracles have occurred, but the progress is well within target expectations.
- Equipment installation and commissioning is a big step forward. Two-sided coating has been demonstrated, which is an impressive accomplishment. Performance testing looks to be headed in the right direction if transport issues can be solved. Investigators should work toward an understanding of the cause of the transport issue (e.g., electrode porosity, hydrophobicity, gas diffusion layer (GDL) properties).

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

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

- The work with Pennsylvania State University (PSU) and University of Delaware was discussed in terms of approach, but no results from other partners were offered.
- I do not understand why parts of this project exist. This project's objective is to reduce MEA production costs. However, two partners are exclusively modeling either durability or mass transport. There are much bigger, more complete projects in these areas and there were specific calls for those types of work. How do these efforts fit in with a manufacturing proposal? These efforts, while they may be good, should have been proposed through the specific calls from DOE for durability work and water management modeling.
- There appears to be little collaboration achieved to date. However, project collaborators will likely come in now that the baseline setup and validation is nearly complete.
- Even though the number of collaborators is fairly small, the effort seems very well coordinated. There also do not seem to be wasteful activities by partners with weakly related tasks.
- The team's collaborations appear to be appropriate and the partners exhibited good use of modeling and university participation.

Question 5: Approach to and relevance of proposed future research

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

- Stack testing and water management measurement and testing are very good plans. The reviewer is looking forward to seeing real-world production data and analysis!
- This project addresses the current issue of water management. The reviewer hopes to see examples of uses of models at the next review and would also like to see more detail on the implementation of new processes.

Strengths and weaknesses

Strengths
- The team showed a good approach and plan.

- The team had a clear target, method, and integration.
- The project looks to advance process technology and thereby reduce manufacturing costs. Modeling efforts support the main process development task. In particular, investigators should be praised for bringing on new project partner (PSU) to address the emerging issue of water transport.

Weaknesses

- There appears to be weak collaborations to date, but that may be better defined as the project progresses.
- There are no large weaknesses. The risk is moderate, but this seems appropriate for this sort of program.
- The potential rate improvement of new processes should be addressed. In other words, a 25% cost reduction is laudable, but it does not by itself address scale-up to high volume (i.e., the barrier listed in the Overview slide).
- Improvements in durability and conditioning time must be verified.

Specific recommendations and additions or deletions to the work scope

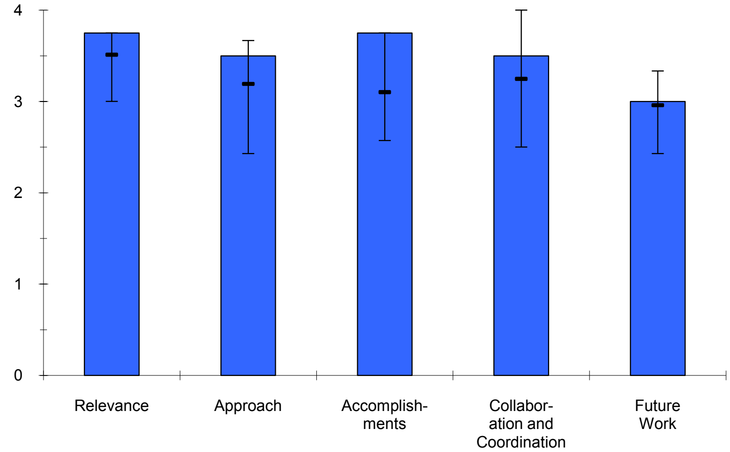
- This project includes what can be considered peripheral side projects, such as modeling of heat and water management and the mechanical stress modeling. While these are fine tasks, they do not seem to fit in with the solicitation call for manufacturing technologies. There was a separate call for water management studies. It is unlikely this work will lead to a manufacturing cost reduction in the short period of this project.
- This project needs to move quickly to DOE target loadings for 2010 and 2015. The work shown is at loadings significantly beyond DOE targets. Regardless of other improvements, this project will not meet long-term cost targets for MEAs.
- The investigators did not address the variability in electrode uniformity or changes in requirements for quality control as a result of the new process, particularly when higher rates are achieved. Therefore, the investigation of quality control needs is warranted.

Project # MN-05: Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacture
Raymond Puffer; Rensselaer Polytechnic Institute

Brief Summary of Project

The high-level objective of this project is to enable cost-effective, high-volume manufacture of high-temperature (160º-180ºC) polymer electrolyte membrane (PEM) membrane electrode assemblies (MEAs) by 1) achieving greater uniformity and performance of high temperature MEAs by the application of adaptive real-time process controls (APCs) combined with effective *in situ* property sensing to the MEA pressing process and 2) greatly reducing MEA pressing cycle time through the development of novel, robust ultrasonic bonding processes for high-temperature PEM MEAs. This year, the project will focus on process optimization, initial APC implementation, stack testing, and low-temperature ultrasonics.

Overall Project Score: 3.6 (4 Reviews Received)



Question 1: Relevance to overall DOE objectives

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

- This project demonstrates a great application of new technology to fuel cell MEA manufacturing. The reviewer gives kudos to Ray Puffer, Rensselaer Polytechnic Institute (RPI) and DOE for funding and working on a project with real-world benefits to fuel cell commercialization.
- This project has potential to support a substantial cost reduction in MEAs.
- High-temperature PEM MEAs will likely play a major role in fuel cell system commercialization. The adaption of manufacturing and quality assurance methods relevant to phosphoric-acid-doped polybenzimidazole (PA-PBI) membranes and MEAs will provide an important contribution to DOE's and the industry's commercialization goals.
- APCs have the potential to increase MEA manufacturing quality and, therefore, reduce cost.
- The project would have more relevance if it had a low-temperature MEA supplier as a member of the team.
- The project is focused on solving critical issues for PEM and high-temperature PEM fuel cell manufacturing. The project targets one of the most important bottlenecks in the production of PEM fuel cell systems.

Question 2: Approach to performing the research and development

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

- Technical barriers were well addressed. It is somewhat unclear how scale-up will work and if the technology is applicable to roll-to-roll processes.
- The project hopes to improve the uniformity and performance of UltraCell's high-temperature MEAs through adaptive process control over the hot pressing cycle. A second objective is to reduce the cycle time for the pressing operation through the use of ultrasonic welding techniques. UltraCell has had difficulty in achieving consistent performance from its fuel cells and it is not clear that this effort will improve the consistency of the fuel cells. A better understanding of the cause of the performance variability is needed.
- The approach is correct and addresses high throughput in the manufacturing of high-temperature PEM fuel cells. The PI shows an excellent understanding of the manufacturing process and the approach correctly addresses the manufacturing issues for MEAs.

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

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

- The project has made very good progress and results so far, especially since the project is still relatively new.
- Ultrasonic welding can be transformative in terms of MEA cost.
- The project has demonstrated the feasibility of ultrasonic welding with a cycle time of less than one second as compared to about one minute for thermal bonding.
- BASF Fuel Cells (BASF) has identified the reasons for the slight departure of the ohmic region of the polarization curve; this was due to test fixture variations.
- The cost analysis showed potential cost savings from the ultrasonic fabrication process.
- The durability of MEAs made with an ultrasonic process needs further confirmation.
- The technical accomplishments are very good. Many of the program targets are met or the program will meet these targets in the near future.

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

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

- There are good collaborators for high-temperature phosphoric acid fuel cells. It makes sense given that the technology is seeing some success now. The team could use better collaboration with major low-temperature PEM/MEA manufacturers as well. Perhaps this could be a future goal as lab-scale work is completed on low-temperature PEM sealing.
- The project has a strong team of partners.
- A solid list of industry and academic partners are on this team. BASF Fuel Cells is an important team member because they supply the high-temperature MEAs for UltraCell.
- The program has established a good team of collaborators. Many of the collaborators have only started their efforts and most of the work load has been done by RPI.

Question 5: Approach to and relevance of proposed future research

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

- It is not clear how this technique will scale to larger MEAs. Is it applicable to roll-to-roll processing or is it limited to a stop-and-go, continuous batch (stamping) process?
- The project's proposed future research is appropriately directed.
- A schedule is not presented. A more detailed look at future work could help to dispel the comment that the project is too long.
- There is little indication of the timing of and interaction between future work elements, particularly for low-temperature MEAs.
- It is still not clear why the project is four years long.
- The proposed future work is consistent with the objectives. The performance and durability of the ultrasonically welded components will be a measure of the success of the program.

Strengths and weaknesses

Strengths

- There is real potential to greatly reduce MEA preparation cycle time, which would lower MEA processing costs and introduce online testing capability.
- The results to date have been strong and very relevant to meeting DOE targets for cost and performance.
- This team showed good organization. The ultrasonic welding technique may be applicable to low-temperature MEAs if it proves successful at reducing cost.
- Early results look promising.

- The PI and the facilities at RPI are the primary strengths of the program. The experience at this facility makes it the leader in manufacturing R&D for MEAs and high-temperature PEM components.

Weaknesses

- There is a lack of low-temperature fuel cell or MEA supplier information to confirm applicability of these techniques to low-temperature systems.
- The *in situ* impedance measurement technique needs further confirmation of its applicability to high-rate manufacturing.
- There are no obvious weaknesses.

Specific recommendations and additions or deletions to the work scope

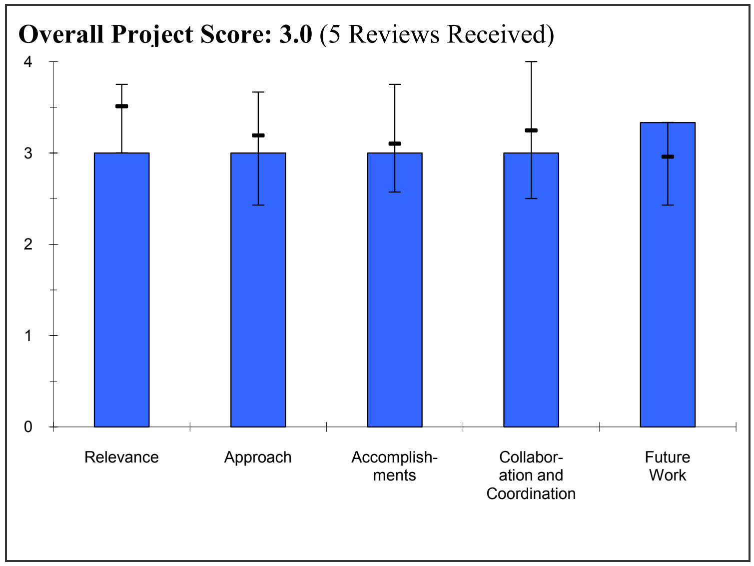
- The reviewer suggests adding a low-temperature MEA manufacturer as a collaborator.
- The team should provide a better definition of scale-up plans and risks.
- The team should have a dialog with low-temperature MEA suppliers to determine the feasibility of adapting this process to their systems.
- The project is having early success. If the rate of achievement continues, DOE may wish to revisit the objectives and funding and increase both.

Project # MN-06: Metrology for Fuel Cell Manufacturing

Eric Stanfield; National Institute of Standards and Technology

Brief Summary of Project

The objective of this project is to develop a knowledge base of engineering data relating performance variation to manufacturing process parameters and variability. The approach is to fabricate experimental cathode-side flow field plates with various well-defined combinations of flow field channel dimensional variations. Then, it quantifies the performance effects, if any, and correlates these results into required dimensional fabrication tolerance levels.



Question 1: Relevance to overall DOE objectives

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

- This project was separated into three separate tasks: P1, P2, and P3. P1 was "Cause-and-Effect: Flow Field Plate Manufacturing Variability and its Impact on Performance." P1 missed the mark by sticking to 25 psi and did not measure appropriate feedback that would be useful to the industry. P2 was "Non-Contact Sensor Evaluation for Bipolar Plate Manufacturing Process Control and Smart Assembly of Fuel Cell Stacks." P2 is a generic look at existing measurement devices, so there is some usefulness for newcomers to the industry. P3 was "Optical Scatterfield Metrology for Online Catalyst Coating Inspection of PEM (Fuel Cell) Soft Goods." P3 seems to be the most useful project. The project appears to support the overall objectives of this program.
- The project has relevance to the DOE program objectives to reduce the cost of fuel cells. Successful completion of the project could establish the link between component (i.e., plate and catalyst coated membrane [CCM]) characteristics and performance and durability of a cell or stack.
- This project is likely to provide pre-competitive information that the entire industry can use to help achieve DOE's ultimate objectives.
- The initial part of the project characterizes the performance of the PEM fuel cell as a function of the design of flow fields. It is not clear that this is a measure of manufacturing capability. If this data can be correlated with quality control measurements, then the project is relevant.
- The development of quality control sensors is important. The work has to progress to full-size systems.

Question 2: Approach to performing the research and development

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

- P1 shows inadequate test parameters to generate a useful design table. It had a good intent at the outset, but it lacked industry input into what should be measured and varied. P2 shows good work was done to evaluate a range of equipment and focused on feasible techniques that industry can use.
- P3 shows that technical barriers are being well addressed, and this project could have a great impact if inline operation can be achieved. The activities are science-based and appear promising. The main suggestion here is that the overall perspective be better spelled out. Some activities seem to have limited impact, perhaps because of insufficient order of magnitude analysis such as the aspect ratio limitation.
- This project is a collection of three separate tasks that may not have a great deal of interaction, but success in any one of the areas will improve manufacturing processes for fuel cell components.
- The non-design-specific nature of the work is good.

- An evaluation of non-contact measurement techniques appears to be applicable to plates, electrodes, and membranes.
- Optical scatterfield metrology shows promise for determining Pt in real time.
- There are three tasks in this topic. Two of the tasks, P2 and P3, are in the outstanding category. P1 is a good program. Overall, the rating was outstanding.
- The development of quality control technology is systematic and builds on previous successful experience. The project has a strong focus and should provide a benefit to all MEA and fuel cell component manufacturers.

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

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

- P1 missed the mark because of bad inputs used in design of experiments.
- P2 shows pretty good work has been done to provide newcomers to the industry with an array of techniques; however, it offers no breakthrough work.
- P3 shows progress is going well but a little slow. It would be nice to see more work on calibration. For example, what does this feedback on X wavelength show on a known sample?
- Much activity appears to be ongoing. However, the presentation makes it difficult to assess progress with much certainty.
- There was initial skepticism concerning the applicability of the optical scatterfield technique to measuring platinum loading. The initial results with the scatterfield microscope are in agreement with 3M's in-house analysis for loadings of 0.1, 0.15, 0.2 g Pt/cm^2. The National Institute of Standards and Technology (NIST) has also looked at traditional catalyst layers. So far this technology still holds promise.
- The Optical Scatterfield Metrology is a higher risk activity that can provide great worth. The demonstration of angle-resolved scatterfield microscopy indicates the instrumentation will have sensitivity to 0.01 mg Pt/cm^2. This is a critical milestone, and if it had failed, it would have set the project back or even stalled it completely. The data from the scatterfield microscopy are very promising.
- The non-contact sensor activity shows promise to be a quality control measurement of flow field depth and width. The speed of the process was not discussed and is an important factor.

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

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

- P1's lack of broad industry support on inputs was a miss.
- P2's evaluation of existing instruments was well performed. P3 shows good leverage of different organizations. It is good that informal interactions seem widespread. However, it is not clear how deep the interactions are, how beneficial to the project they are, and whether feedback exists.
- The collaboration is good, with numerous interactions with manufacturers.
- This is a good team for P1. It was unclear who the collaboration was with for P2, which looked like a shopping list of organizations.

Question 5: Approach to and relevance of proposed future research

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

- On P2, it seems like not much breakthrough going on. There is a lot of inspection equipment available. It would have been nice to determine the most important parameters to measure, and which needs less measurement, as a means of speeding up throughput. Overall, the effort is pretty well thought out and can help newcomers to the industry.
- P3 is the most interesting project. P1 seemed to miss the mark on what could have been a noble project.
- More specificity would be very helpful in evaluating the plan. That said, it appears that the next goals are well considered.
- The proposed future work is clearly laid out and includes relevant go/no-go decisions points. The reviewer gives kudos for the clarity of the presentation in this regard.

- The future work continues the successful efforts already achieved by P2 and P3. Future work for P1 does not open new doors, and it is not clear if the subtle differences in flow fields will be observed in this level of test.

Strengths and weaknesses

Strengths
- On P3, the optical online metrology for catalyst coating inspection is a strength. It seems interesting and could have a huge impact. Some further information on estimated process times and equipment costs should be provided, as well as how the implementation on inline process could be accomplished. A comparison of the project accuracy with known values or to what the manufacturers say is there would be interesting to know. It would also be beneficial to know if this can pick out size distribution.
- The project uses a science-based approach and focuses on eventual application of technologies.
- NIST is the most logical place to develop online metrology instrumentation in a pre-competitive environment. Successful outcomes would benefit the entire fuel cell industry.
- The presentation was very good. It clearly delineated past progress (FY 08) from more recent accomplishments. The performance schedule with appropriate milestones and decision points was well done.
- The primary strength is NIST, which is a high-caliber, well-focused laboratory. The PI has assembled an innovative approach for developing inline quality control. The approach and the overall program are well focused.

Weaknesses
- On P1, regarding the cause and effect of manufacturability on the cathode, it is important to touch on the impacts of real-world cathode conditions. The 25 psi pressure is not realistic, and lower pressure could have a huge impact on cathode design or even under different utilizations. It seems like many manufacturing-induced issues, such as roughness and warping, are not included, nor are the measured parameters (ones that would be critical to systems integrators) collected. These parameters include pressure drop and correlation to different geometries such as serpentine, parallel, etc. The reviewer does not think this will result in a useful design table for bi-polar plate manufacturers.
- The overall approach and risks were not well presented. The speaker attempted to cover far too much information with the result that much information was lost. In the future, please speak more clearly and spend a bit of time on context.
- Progress has been sporadic due mainly to funding issues.
- P1 should be reviewed. It is not clear that the sensitivity of the electrochemical methods used will be sufficient for subtle changes in the flow fields.

Specific recommendations and additions or deletions to the work scope

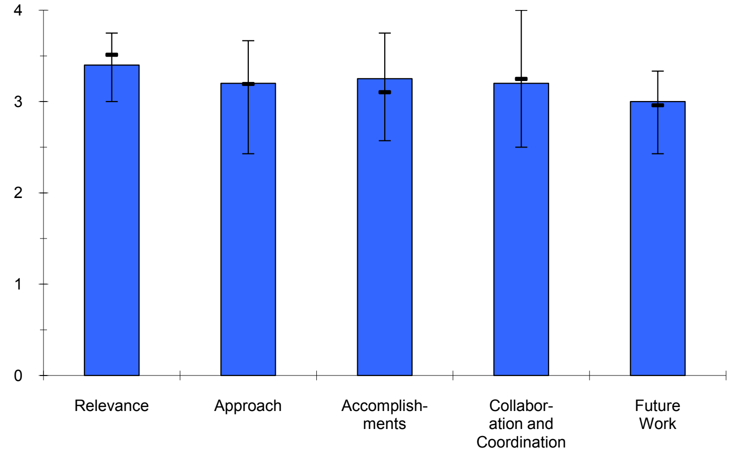
- P1 should try to add lower pressure cathode and solicit more information on required feedback parameters from industry.
- P2 should publish a summary for the use of measurement techniques for general industry use into industry manufacturing publications.
- For P3, be sure to keep industry in the loop so as to not repeat the mistake in P1. It would be good to provide some idea of how an inline process would look along with cost. Be sure to map out "the machine showed X, Y on the following: manufacturer supplied gas diffusion electrodes (GDEs) with A, B loadings," and see if catalyst particle size distribution can also be determined.
- The project should start to consider full-size bipolar plates and plates that may be slightly warped. Teaming with a research laboratory that can do segmented cell research may improve P1.

Project # MN-07: High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies
Emory De Castro; BASF

Brief Summary of Project

The overall objectives of this project are to 1) reduce cost in fabricating gas diffusion electrodes (GDE) with a focus on GDEs used for combined heat and power (CHP) generation, 2) relate manufacturing variations to actual fuel cell performance to establish a cost-effective product specification within six-sigma guidelines, and 3) develop advanced quality control (QC) methods to guide realization of the first two objectives. The objectives for FY 10 are full-length roll coating and online measurement of Pt level and distribution (advanced QC).

Overall Project Score: 3.2 (5 Reviews Received)



Question 1: Relevance to overall DOE objectives

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

- This project is related to polymer electrolyte membrane fuel cell (PEMFC) cost reduction (reduce cost of GDEs and membrane electrode assemblies (MEAs)) and improving performance.
- Cost reduction of the MEA/electrodes is critical to commercialization of PEMFCs. This project appears to be concentrating on a technology specific to BASF, which is phosphoric acid-imbibed PBI. So, it has limited impact for the rest of the fuel cell community.
- This project is very well aligned to DOE objectives, assuming DOE objectives are to promote and implement mass-production of high-quality MEAs. Effective and fast inline QC testing will be critical.
- This project addresses mainstream needs for improved cost and quality metrics set by DOE.
- The work outlined in this program is required to meet the performance and cost targets for fuel cell commercialization. Specifically, it is critical to have uniform Pt distribution, especially as the overall loadings are decreased.
- This project supports the DOE program objectives. Its success would lead to manufacturing cost savings.

Question 2: Approach to performing the research and development

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

- The approach includes developing high-speed, continuous production and incorporation of inline sensors for quality. The focus is on GDEs for CHP applications, which limits the applicability for other larger sectors such as transportation.
- This project has a very good approach. X-ray fluorescence (XRF) is a very powerful tool if applied and calibrated correctly.
- This project shows a good mix of scientific metrology improvement and practical demonstration of process improvement.
- The overall approach of improving line speed and quality control is solid and should be effective. It would really be helpful to understand how tight of a coating tolerance is needed to balance performance and cost. For example: a report chronicling the cost difference if the loading is 1% high, 5% high, or 10% high would be helpful to know. The impact on performance if the loading is 1% low, 5% low, or 10% low would be very interesting to note, as well.

- The approach is to develop the capability for inline measurement of Pt level and distribution, and porosity.

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

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

- Modified XRF technology for inline Pt analysis for quality measurements is an accomplishment and shows progress.
- This project has made very good accomplishments so far and exceeded expectations for Pt measurement in a real fashion by XRF. It has already demonstrated sensitivity down to a Pt loading of 0.0017 mg/cm^2, which is well below DOE target loadings. The assumption is that the system works even better at higher Pt loadings.
- It appears that the individual tasks are on schedule and have good prospect of success.
- Considering that it is early in the program, there has been a significant amount of progress. Reaching the design goals of speed, accuracy, and operator safety is a great accomplishment. There appears to be some work left to improve the uniformity of the coating, but the overall progress is good. It will be very interesting to the see the results of the modeling work on how defects in Pt coating will impact cell performance.
- Measurement of Pt loading down to 1.7 g/m^2 has been achieved ahead of plan. BASF believes that they can measure down to 1 g/m^2 with parameter optimization. This was accomplished with modified optics on commercial XRF units.
- The project identified an additive that stabilized cathode ink and reduced agglomeration, resulting in more uniform coating.

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

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

- The PI is collaborating with Case Western Reserve University for modeling of variation and defects, a baseline model was done.
- Other collaborations appear to be just starting.
- Collaboration is fairly good, and there seems to be more of a supplier/customer interaction, particularly with the supplier of the XRF system.
- Collaboration with other government laboratories and industry is appropriate.
- The roles of each partner are clearly defined and it appears that they are working well together.
- Two collaborators were identified; both play a significant role in the project activities.
- Some informal collaboration is indicated between BASF and Rensselaer Polytechnic Institute (RPI)/Center for Automation Technologies and Systems (CATS).

Question 5: Approach to and relevance of proposed future research

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

- Concentration of online analysis methods for production is recommended.
- The PI needs information on project cost and cost reductions.
- PI has a very good plan. The on-roll porosity measurement could be very beneficial as well. The PI has a good plan to test for the effects of defects. The PI could add testing of alternate materials including catalyst coated membranes (CCMs) or other GDE materials.
- The overall plan still seems reasonable and can be accomplished in the proposed timeframe.
- Overall, the future work is clearly defined and should be effective in reaching goals. From the talk, it sounds as though the program may require some work on improving the ink mixing process for commercialization, which was not specified as a future goal.
- Future work for next year appears appropriate and, if successful, will demonstrate a doubling of line speed on a full roll. Accomplishing this is a critical go/no-go decision point.

Strengths and weaknesses

Strengths

- The project directly addresses DOE's goals and the overall goal of practical, commercially-produced fuel cells.
- The project has a well-integrated mix of high- (or medium-) risk elements and low-risk production improvements. The project is likely to provide overall progress toward DOE goals and may provide significant progress.
- BASF has a strong track record of producing GDEs and their work shows a good understanding of what is required to reduce cost and improve uniformity. The project is structured well, with clear goals and reasonable deadlines.
- The project is a focused one.

Weaknesses

- The team needs information on the projected cost reduction.
- Catalyst loadings are not discussed except for analysis less than 1 mg Pt/cm^2. There needs to be a concentration on meeting the platinum loading targets for 2010 and 2015.
- Collaborations could be stronger. BASF may consider including testing with an external GDE or CCM supplier.
- It is not immediately clear how much the work being done directly impacts cost. It would be helpful to understand where the current levels of production and cost are, and where they will be at the end of this project. It would be helpful to show performance data, especially as BASF attempts to move from carbon fabric to carbon paper.

Specific recommendations and additions or deletions to the work scope

- The team could possibly extend the XRF measurement to other nuclei, F, S, or other metals like Pd or cobalt.
- Is there a possibility to extend this technology to other GDL materials?
- BASF could extend testing to purposely defective GDL material to test the effects of holes, bumps, and other non-uniformities.
- Given the team’s successes, it may be good to include additional collaborators such as the RPI/Puffer project (MN005) for ultrasonic sealing of GDEs into MEAs.
- The project should include some research to determine if the technology could be applied to non-fuel cell applications.
- The reviewer recommends continued collaboration with RPI/CATS.

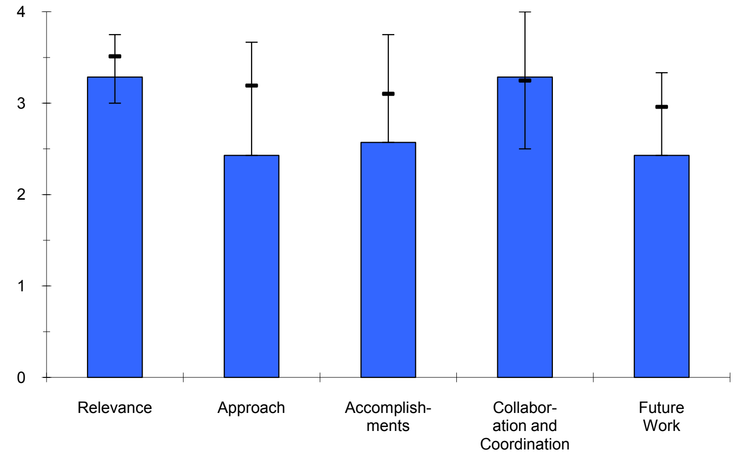
Project # MN-08: Development of Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels

Mark Leavitt; Quantum Fuel Systems Technologies Worldwide, Inc.

Brief Summary of Project

The overall objective of this project is to manufacture Type IV hydrogen storage pressure vessels, utilizing a new hybrid process with the following features: 1) optimal elements of advanced fiber placement and commercial filament winding, 2) reduced production cycle times by adaptations of high speed dry winding methodology, and 3) improved understanding of polymer liner hydrogen degradation. The project goal is to achieve a manufacturing process with lower composite material usage, lower cost, and higher efficiency.

Overall Project Score: 2.7 (7 Reviews Received)



Question 1: Relevance to overall DOE objectives

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

- This project goes straight to improving composite tank efficiency and manufacturing cost by intelligent winding methods and understanding stress-strain relationships for the application of the windings that enable the optimization of the application, while minimizing the material, thus leading to a reduction in cost.
- The project is very relevant to the DOE Fuel Cell Technologies Program as it seeks to reduce the cost of high-pressure hydrogen storage tanks, which is the only technology currently available for storing hydrogen on board a vehicle. Reductions in cost and weight are important, even if the storage density will not be improved much.
- The project is as much a product development effort as a manufacturing process improvement project.
- Cost goals are not clearly defined. The project appears to be of the nature of "let's see how much cost we can take out of our commercial tank."
- Pressurized hydrogen will likely be a long-term option for vehicles, and this project is very relevant in that it can reduce weight and cost below the already adequate values.
- Storage costs are an important element with respect to enabling cost-effective, on-board hydrogen storage and, therefore, hydrogen vehicles.
- The overall aim of the project is relevant, which is a manufacturing process with lower composite material usage, lower cost, and higher efficiency.
- The project addresses increasing the manufacturing rate of hydrogen storage vessels. The project did not appear to address cost reduction of the materials as a major effort even though the materials have the greatest contribution to cost. From chart 13 of the presentation, the materials cost is 97% of the tank cost. That seems to imply that the program only addresses 3% of the cost.

Question 2: Approach to performing the research and development

This project was rated **2.4** on its approach.

- The application of optimized stress-strain relationships combined with computer numerical control processes that enable precise winding placements is very nice. The scale-up to commercial scale was kept in sight as the project evolved.
- The approach to performing the work is generally rational and appropriate for addressing barriers. However, a clear path to meeting DOE targets was not presented.

- The presentation contains one slide concerning stress analysis, but it is not clear how this analysis is being used to guide development efforts and provide for sufficient safety factors.
- The project will also examine a new approach to tank fabrication being developed by Lawrence Livermore National Laboratory (LLNL). This task was well described, but it is not clear how it integrates into the overall project. Even with a new fabrication process, given the high cost of fiber, it is not clear that a new process will significantly decrease cost to justify this approach.
- Dry tape winding shows good promise for cost reduction. The approach to advanced fiber placement (AFP) with filament winding (FW) is well thought out and executed since last year through a tank test.
- The approaches to storage cost reduction do not seem to have the potential to yield significant progress towards the storage cost targets. It is not clear that liner blistering is a significant problem, and the cost reduction potential of dry tape technology is insufficiently characterized.
- The approach of this project to reduce the cost of a Type IV pressure vessel through advanced fiber placement, dry winding, and liner degradation needs further development to assess the potential and variability in the cost savings. The additional complexity of the fully integrated fiber placement appears to have increased the processing time. The statistical variation of the input parameters should be included in the cost model, including the composite usage ranges for a high-volume production process. The project presentation should identify the clear deliverables and quantifiable goals for each element of the project (i.e., the liner compatibility's contribution to cost reduction).
- The approach is misguided since the program only addresses a small fraction of the storage vessel cost.

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

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

- The technical accomplishments for this project are good. The reviewer thinks more attention needs to be given to techniques to further reduce the costs of the material and quantity (i.e., optimization of windings). If this work were to really achieve its goal of approximately 20% reduction, it would be a significant achievement.
- A cost analysis was presented that showed that material costs dominate. If the cost model that should have been developed by the Pacific Northwest National Laboratory (PNNL) by this time is sufficiently robust, it could be used to guide the effort to promising pathways. This was not discussed.
- Boeing has made good progress demonstrating the AFP technique with their tooling.
- A schedule was not presented and it was unclear whether there are any go/no-go decision points between now and the end of the project.
- The combination of FW and fiber placement trades material cost for capital and processing cost. The analysis shows that the tank cost is projected to be only about 10% lower with the advancements. Any added equipment or processing costs were not described. It really seems questionable whether the cost reduction justifies continued efforts in this area.
- The liner work did not show a clear path to resolving the blistering with cycling results.
- The building and testing of the first AFP and FW tank is a valuable step.
- In reference to the cost analysis on slide 13, additional focus on the composite strength would be valuable, if separate FW and AFP will always be the lower cost option.
- LLNL had a thin-film, aluminum-coated, polymer-lined composite tank 15 years ago. The aluminum coating seems to have been removed in this version, though the coating may alleviate the polymer blistering issue. With a projected cost of more than $20/kWh (and goals set at $4/kWh or lower), the projected cost savings of 11% is clearly insufficient to contribute to reaching DOE targets. The effort has clearly identified material cost as the most significant driver, and reducing the amount of expensive material seems less fruitful than identifying suitable material that costs appreciably less.
- The project shows good results to date regarding the expected manufactured costs of systems.
- The accomplishment of demonstrating a hybrid vessel with the composite usage reduction is very good. The accomplishments in the area of liner compatibility and dry winding appear to have made progress but could have been explained further.
- The technical accomplishments are positive with the AFP showing good results. Tank cost analysis is detailed but demonstrates the problems with this research program. The materials costs are so high that manufacturing improvements will be a minor improvement to cost.

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

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

- The partners appear to be working well together, as they each bring unique strength to this project.
- The team assembled has the technological expertise to carry out the program. Boeing has tremendous experience in fabricating composite structures for the airline industry. Boeing is attempting to adapt and scale down the processes to tank fabrication requirements.
- The inter-dependence of the work by the partners was not entirely clear.
- Very good coordination among team members matching the division of responsibility with the general program progress.
- The coordination between Quantum and Boeing seems well thought out and executed. The efforts by the national labs seem to be disconnected and "thrown in."
- The collaboration with Boeing seems to be appropriate and essential for the AFP task. The role of the other project partners could have been expanded.
- The team is skilled and able to meet the objectives of this program.
- The team does not include a materials manufacturer that would be able to reduce the tank cost significantly.

Question 5: Approach to and relevance of proposed future research

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

- The reviewer would like to see increased emphasis placed on material cost and utilization reduction. While the effort on manufacturing time and utilization of plant equipment represents a small fraction of the overall tank cost at volume, the effort is necessary to improve throughput and eventually reduce cost. This effort should continue.
- While the elements of future work are identified and seem appropriate, there is little indication of the interaction between some of the elements, and timing is unclear. Decision points are not clearly defined.
- The AFP process does not seem to be able to deliver sufficient cost savings. Most of the future work revolves around the AFP process. The only seemingly useful future work item is the evaluation of alternative materials.
- The next steps for the AFP appear focused, though the potential of this method should be further developed and validated prior to extensive physical testing. The future work for the liner assessment and dry winding could include further details.
- The reviewer thinks the effort is misdirected and should address material cost reduction.

Strengths and weaknesses

Strengths

- This project does a nice job in applying science and optimization to the cost reduction of carbon-reinforced high-pressure tanks without compromising functionality (i.e., maximum allowable working pressure and fill time). Continued effort on winding optimization and manufacturing speed will help to reduce the costs.
- The partners appear to be working well together.
- The teaming is strong. There are good and relevant histories for composites and tanks with Quantum Fuel Systems, Boeing, and LLNL.
- The PNNL hydrogen compatibility study can translate to other polymer/composite hydrogen pipeline developments done elsewhere.
- This project could provide incremental improvements in cost and manufacturing of Type IV pressure vessels.
- The strength of this project is the focus on searching for opportunities to reduce the cost of the pressure vessel, which is the main cost of a compressed hydrogen system.
- The manufacturing team is experienced and capable of fulfilling the objectives.

Weaknesses

- The project should focus more of its efforts on those elements that show the biggest promise for continued cost reduction at medium- to large-scale production volumes. Do not stop the efforts on those elements that do not have as significant of an impact, but focus efforts on the big ones.

- So far, the cost of materials dominates the manufacturing cost of the tanks and calls into question the value of pursuing manufacturing improvements that provide only incremental improvements.
- There is minor concern on the accuracy and stability of the cantilevered, full-head access for AFP end wraps.
- The project is only projecting meager cost improvements. The go/no-go point should incorporate a sufficient material hurdle for cost reduction.
- It does not appear from the information provided that Quantum will be able to meet long-term DOE targets.
- The weakness of the project is the lack of theoretical potential analysis prior to the physical demonstration and development. It may have been conducted but simply not included in the project overview.
- The benefits to be developed will not significantly reduce the cost of the hydrogen storage tank. The project does not emphasize material costs.

Specific recommendations and additions or deletions to the work scope

- A better definition of the project schedule and any future decision points is needed.
- Information on permeation through liner materials should be shared between this project and the Lincoln Composites project. It would benefit both efforts.
- Since this project is for the development of a unique, vehicular hydrogen storage pressure tank, the project team should report on the process of industrial practices, codes, and standards that need to be developed for certification of this tank technology and design. It would be good for the team to engage the Department of Transportation or Canadian Standards Association and a nationally recognized testing laboratory in the process ahead of time. If this is not an issue, that is great, but the reviewer suspects it is. If it is, it can be a cost driver and a very serious barrier to commercialization and should be listed as such in the overview.
- The reviewer would recommend scrapping future AFP work and investigate alternative materials.
- The reviewer recommends including an assessment of potential areas of improvement with pressure vessel manufacturing to ensure the project is focused on best potential candidates for cost reduction.
- The program objectives should be evaluated. The benefits of manufacturing improvements should lead to a 30%-50% cost reduction. If the reduction in cost is considerably less than 30%, the project should be terminated and funds redirected to storage programs that can produce a 50% cost reduction.