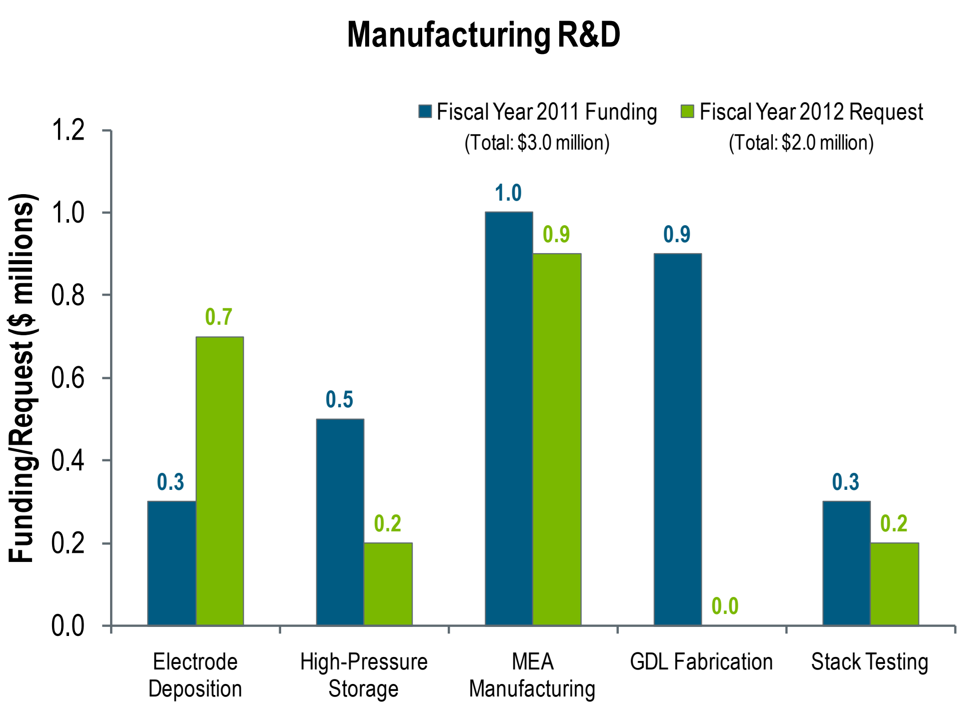
2011 — Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

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

The Manufacturing R&D sub-program was judged to be well-managed, well-organized, and focused on addressing programmatic performance targets. In fiscal year (FY) 2011, eight manufacturing projects were reviewed. These projects addressed fuel cell membrane electrode assembly manufacturing, fabrication of catalyst-coated membranes, gas diffusion layer production, fuel cell stack in-line testing, and manufacturing of high-pressure vessels for hydrogen storage. Reviewers observed that plans for addressing issues and challenges could have been presented in more detail and that gaps in high-volume manufacturing technologies and processes are somewhat difficult to characterize because most manufacturers are far from reaching high-volume production. In general, reviewers stated that the Manufacturing R&D sub-program is addressing key issues for fuel cell and hydrogen technology commercialization. The reviewers noted that the diagnostic projects carried out at universities were good but they would only be useful if the diagnostics are used by industry component manufacturers.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was $3 million for FY 2011 and $2 million was requested for FY 2012. The FY 2012 request level funding will continue existing manufacturing R&D projects, but at a slower pace. The gas diffusion layer project has been completed.



Majority of Reviewer Comments and Recommendations:

Eight Manufacturing R&D projects were reviewed and the maximum, minimum, and average scores for the projects were 3.7, 2.9, and 3.3 respectively. All projects were judged to be highly relevant to the DOE Hydrogen and Fuel Cells Program's activities, with good to very good technical approaches. In most cases, project progress and accomplishments were judged to be very good; however, several projects made less than average progress. It was not clear to some reviewers how some investigations would lead to improved quality control and reduced

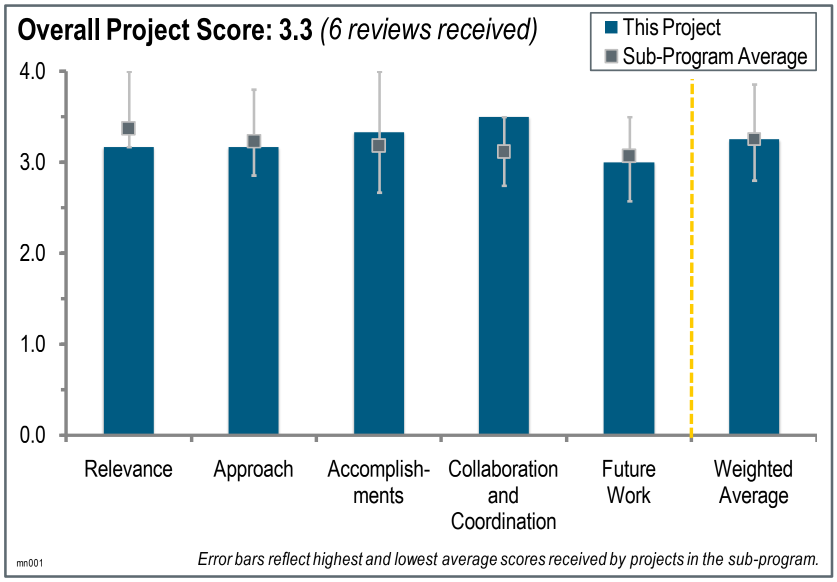
component cost. Project teams were judged to be strong for most projects, with partners having demonstrated experience and expertise in the required technical disciplines. In general, reviewers felt that more effort should be devoted to quantifying and validating potential cost reductions. Lower manufacturing costs were judged to be an important rationale for continuation of the projects in the future.

The highest-ranked projects (3.7) were considered by the reviewers to be highly relevant, with an excellent approach, outstanding accomplishments, and strong technology transfer and collaborations. The reviewers found the projects with the lowest scores (2.9) to be relevant but observed that the accomplishments were not adequately presented and it was difficult to assess the contributions from collaborators.

Project # MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

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) integrate Lawrence Berkeley National Laboratory (LBNL) modeling to support diagnostic development and implementation. The National Renewable Energy Laboratory is additionally providing up-to-date analyses of the manufacturing capabilities and readiness of the fuel cell industry to further support the U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to DOE objectives.

- This project focuses on quality control related to fuel cell manufacturing. It is very relevant to the DOE Hydrogen and Fuel Cells Program objectives as the technology is moving into the early commercialization phase.
- The ability to diagnose for defects in membranes, gas diffusion layers (GDLs), and catalyst layers in-line is well aligned with Program objectives for manufacturing. If the infrared (IR)/reactive flow-through diagnostic can be adapted to be an in-line process such as the IR/DC (direct current) diagnostic, that would be valuable to the Program.
- This activity is relevant in the overall scheme of things. The task consists of evaluating, developing, and validating in-line diagnostics for MEA component quality control; investigating the effects of manufacturing defects on MEA performance and durability to understand the accuracy requirements for diagnostics; and integrating LBNL modeling to support diagnostic development and implementation.
- Defect identification is important to economic delivery of MEAs and GDLs. This work is very important in helping the fuel cell manufacturing industry develop standard in-line flaw detection techniques.
- MEA cost and loading reduction efforts are significant opportunities for polymer electrolyte membrane fuel cell cost reduction in both the near and long term.
- Diagnostics for large-scale manufacturing are important. How the segmented cell testing will help with manufacturing is unclear.

Question 2: Approach to performing the work

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

- The approach to the diagnostic development has been a good, stepwise, and logical process. Hopefully the team is planning to look into possibilities of integrated diagnostics to service a common stack component manufacturing line.
- The approach expounded upon appears to be rational. It would be difficult to recommend an alternate approach and still succeed.
- Several approaches to detecting flaws and uniformity of MEAs are being investigated. Each of the techniques is IR-based and makes a real measurement rather than a point image that needs to be averaged across and down web. The goal is to make the measurements on a web line on a continuous basis rather than at discrete time intervals. If the development is successful, one or more of these techniques has a good chance for more widespread deployment in fuel cell manufacturing lines.
- The effort is approaching defect identification and quantification through a variety of means. More clarity is needed in quantifying potential cost savings as well as the relationship between defect characteristics and performance and/or durability (i.e., maximum acceptable defect characteristics).
- Heavy reliance on IR/DC will limit defect identification.
- The main objective is development of diagnostics to help large-scale manufacturing by developing in-line processing diagnostics. Diagnostics of optical reflectometer and IR, and segmented cell testing to study defects is stretching the relevance.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.3** for its accomplishments and progress.

- Demonstration of IR/DC is excellent, with analysis ranging from defect size to measurement time analysis.
- Good demonstration of the in-line diagnostics.
- The technical accomplishments are good but progress towards cost reduction goals needs to be better quantified through both cost analyses and establishment of maximum acceptable defect values.
- The progress on this project is appropriate for the expenditures to date. The IR/DC method appears to be limited to gross defects. Holes of one mm^2 (millimeter squared) are not likely to be detected.
- The IR/DC diagnostic has been nicely done. The reviewer was uncertain about the in-line implementation with high throughput catalyst coated membrane given the 1 second or so heat-up time of the catalyst layer. That is not conducive to small roller separation for the layer to heat up before it gets into the measurement area. The assumption used in the IR/DC accomplishment slide, that there is “little effect of bare spots [in a less than] <10% active area,” is not indicated by the approximately 150 mV (millivolt) loss in the adjacent polarization curve. That is not a little effect.
- This project has a number of components that all have the objective of assisting industry in scaling up MEA manufacturing to higher volumes. The IR/DC diagnostic is the furthest along the development path. A correlation between defect detection and initial performance needs to be developed to prevent rejecting materials that have little impact on performance. The limits of defect detection need to be established and the minimum size defect determined that has an impact on performance.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.5** for its collaboration and coordination.

- Collaborations with many companies and universities appear strong. Industrial collaborators have contributed sample MEAs with known defects to further develop the diagnostics discussed in the presentation.
- The project incorporates a number of useful collaborators from both industry and academia.
- The list of collaborators is suitable.
- Collaboration shown with 3M, Colorado School of Mines, Ballard, and Hawai’i Natural Energy Institute. Collaboration was only mentioned with LBNL.

- Collaboration with manufacturers was cited. Critical input from industrial partners should be sought and implemented.

Question 5: Proposed future work

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

- These techniques can be highly valuable in identification of hidden flaws and should be vigorously pursued.
- The IR/DC diagnostic looks like a valuable in-line diagnostic but needs further and better validation. This tool really looks at carbon loading, not platinum loading. The reviewer asked if there is a way to distinguish variation in the catalyst. Some developers are intentionally introducing cracks into catalyst layers to increase mass transport. The reviewer asked if this technique is valid for that MEA manufacturing approach. The technique to date is looking at relatively thin MEAs. This technique needs to be validated for full active area MEA rolls. The proposed work using the segmented cell system belongs in a durability project, not in a manufacturing project. This system (segmented cell) has no utility for this project.
- The proposed future work appears appropriate.
- Implementing the diagnostics on a web line would confirm the feasibility of these techniques to enable on-line quality control in the MEA manufacturing process. If adopted by manufacturers, this would represent a major accomplishment and provide a good return on the DOE investment.
- The segmented cell that will be utilized to study the initial and long-term effects of defects seems a little out of scope for a project providing manufacturing assistance. Resources would be better spent on further diagnostic development.
- The reviewer was looking forward to results from the 121-segmented-cell system and was glad to see the continued and increased use of the modeling effort to guide the diagnostics, at least for the IR/DC approach.
- Further efforts relative to defect effects need to be identified. Additional cost-related work should be performed.
- More clarity regarding decision points and success criteria should be provided.

Project strengths:

- Good identification of intentionally introduced flaws. The IR/DC technology has been brought to continuous process application.
- The application of commercially available hardware from other industries to this specific application.
- There are strong collaborations and promising results from initial development efforts.
- The IR/DC diagnostic is good. Generally the diagnostic hardware development for the whole project is a strength.
- A variety of potentially useful defect evaluation methods is being developed.

Project weaknesses:

- The IR/DC technique needs to be applied to actual process flaws. Additionally, a better understanding of actual process flaws needs to be developed so that the IR/DC technique or other non-destructive examination techniques can be developed.
- The project has a good partner list, but is not utilizing all partners.
- The current sensitivity levels for holes may not be sufficient for mass production: holes of 1 mm^2 are not likely to be detected.
- IR/DC diagnostic relies on DC excitation causing an increased temperature. Defects that do not have a thickness variation or IR losses will not be detectable. Anomalies in non-precious group metal catalyst systems may not be detectable with these techniques.
- Defect thresholds need to be better identified and cost implications need to be evaluated.

Recommendations for additions/deletions to project scope:

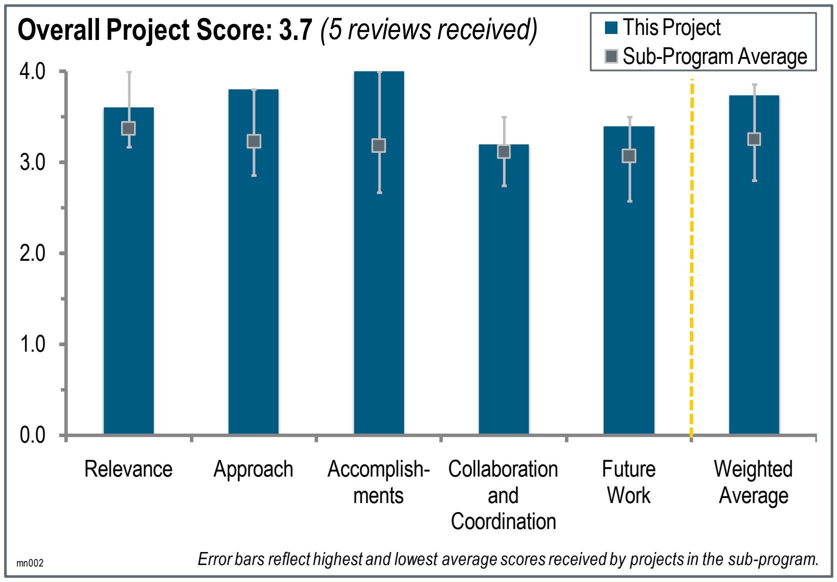
- Apply the IR/DC technique to an actual process line to determine flaw detection capability and utility in increasing process line economics.
- While segmented cell testing is a good tool, it does not seem relevant for this project. Incorporating this system into a manufacturing project is clearly a stretch, especially when future plans are to conduct durability testing. The diagnostics need further refinement to understand if they are applicable to full width production and other types of variations in manufacturing including materials, different ionomers in catalyst layers, and intentional catalyst layer cracking. The project needs to incorporate the modeling into the project.
- Work to detect all hole sizes.
- Limits on the smallest detectable defect and what size defects matter to fuel cell performance need to be determined. Software needs to be developed for the IR systems.

Project # MN-002: 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 (GDL) products by: (1) improving product quality through the use of online tools, (2) increasing 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 for a lower cost at higher volumes in the near term.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.6** for its relevance to U.S. Department of Energy (DOE) objectives.

- This activity directly supports the DOE Hydrogen and Fuel Cells Program and is focused on reducing the fabrication cost of GDLs to meet DOE targets.
- The project directly addresses DOE objectives of increasing production rates, decreasing production costs, and identifying materials that will reduce cost and/or improve performance and durability.
- GDL cost reduction efforts are a good opportunity for polymer electrolyte membrane fuel cell cost reduction in both the near and long term.
- High volume GDL manufacturing reduces costs.

Question 2: Approach to performing the work

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

- The approach is very good and gets to the heart of the issue by concentrating on the ink mixing process and the coating processes to prepare the final product. The approach involves continuous mixing of the ink and binders and coating multiple layers at the same time. These process modifications were aimed at eliminating batch processing and multiple passes down the web line.
- The approach is stepwise, well structured, and organized with well-defined measures of success. DOE might use this as a model to give other projects.
- The project is addressing cost reduction through several avenues: process simplification, inspection and testing, yield improvements, and part optimization.
- The approach uses rolled goods and coating techniques, and removes batch processing techniques.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **4.0** for its accomplishments and progress.

- Very good progress has been made and there is a good discussion of those factors that are outside the specifications and an explanation of why the factors are outside targets. This discussion projects confidence and the researchers have an understanding and pathway to success.
- Significant cost reductions have been achieved and improvements are being made in several areas.
- There is good analysis and presentation of costs. Researchers show low variability in their validation of the continuous mixing and coating processes. However, the polarization performance is substantially lower than state-of-the-art. There are no details on what the other materials and operating conditions (such as platinum loading, membrane, and stoichs) are given. Ballard has better performing membrane electrode assemblies (MEAs) than the polarization curves show. The reviewer questioned whether this was an effect of GDL, MEA, or operating conditions. The reviewer asked about showing validation with good performing MEAs and operating conditions for better evaluation of the GDL materials. At higher performance, the GDL operation is more critical. The axes in the graph on slide 11 needs tick labels.
- A significant accomplishment was in relating critical GDL properties to specific process steps and operating parameters.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Excellent subcontracting from Pennsylvania State University (PSU).
- Collaborators are making good contributions towards the project’s accomplishments.
- Good coordination between PSU and Ballard. This project could use more collaboration with different fuel cell developers to explore different stack operation on the process.
- Ballard Material Products (BMP) collaborated with Ballard and with PSU to provide material specifications and on-line process diagnostic capability, respectively.
- More discussion on the efforts by PSU and Ballard Power Systems would be helpful.

Question 5: Proposed future work

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

- The planned work tasks are logical extensions of current activities.
- The project is nearly over with a few additional activities planned; however, they are significant: in situ testing in stacks, process improvements based on initial results, production of full-scale rolls of GDL materials, and design of a green field facility to reach the DOE cost target. If these activities can be accomplished in the remainder of the project, they will be significant accomplishments and mark a successful project.
- The project is 85% complete. Most of the future work appears to be process optimization, nominally for only one fuel cell developer.
- It would be optimal to validate the outcome versus the DOE program target at targeted mass production volumes.
- The proposed future work appears to be a continuation of the present efforts. The reviewer questioned where the effort is to characterize the cause of the problems that the particulates in the coating inks were causing.

Project strengths:

- Excellent progress toward aggressive goals.
- This is a multifaceted approach towards cost reduction.
- The manufacturer undertook this work rather than a research organization. Having a fuel cell manufacturer enabled the PI to keep the focus on improving an existing process and reducing the cost of a current commercial product rather than focus on a hypothetical exercise for a material that does not currently exist. The record of accomplishments during this project is very good.

- These are good projects; however, there needs to be information related to capital. Rolled goods clearly have a lower processing cost.

Project weaknesses:

- It is unclear how capital cost is taken into account in the cost projections.
- A domestic source of low weight carbon fiber paper that met BMP cost and quality requirements was not identified.

Recommendations for additions/deletions to project scope:

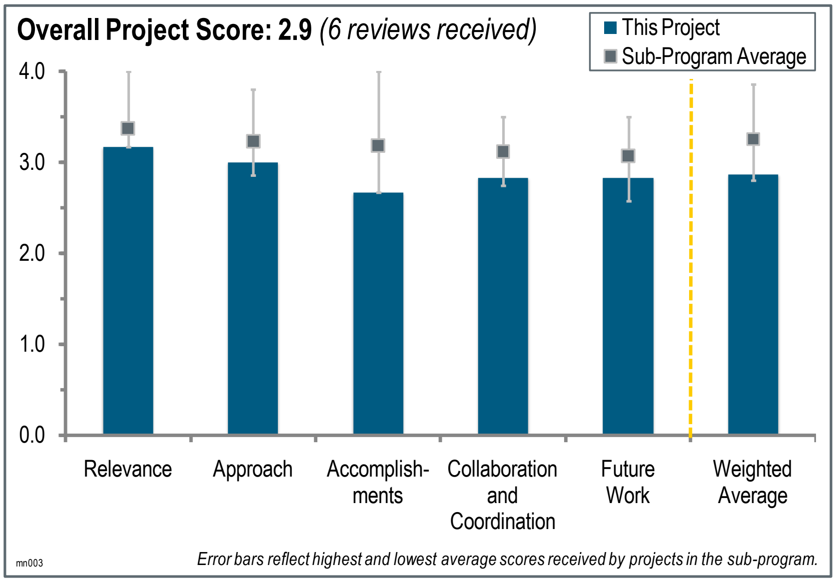
- This is an excellent project.
- Additional information on the potential process flexibility (such as if the process makes MEAs with variable Teflon® poly-tetrafluoroethylene loading in the microporous layer [MPL] or substrate, incorporating different carbon blacks into the MPL) is needed to allow the process to suit different manufacturers using different stack operating conditions. Researchers should show GDL performance with higher performing MEAs where the GDL performance is more critical.

Project # MN-003: Modular, High-Volume Fuel Cell Leak-Test Suite and Process

Hugh McCabe; 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 stacks per year (i.e., 50 fuel cell stacks per hour); (2) perform leak tests in-line during assembly and break-in steps; (3) demonstrate fuel cell stack yield rate up to 95%; (4) reduce labor content to six minutes; and (5) reduce fuel cell stack manufacturing cost by 80%. The objective for the past year was to test and evaluate the lead-test suite prototype.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is outstanding in terms of direct methanol fuel cell relevance, but it is unclear if the project would translate to other fuel cell technologies.
- Leak detection is an important need in volume fuel cell manufacturing activities.
- Although repeat components are currently the major cost driver for the stacks, as the component costs drop the labor costs will become significant. The development of methods to reduce labor cost is appropriate.
- The project partners developed a physical system and process that can reduce the pressure testing time during stack assembly; however, it is important that the test hardware and process is easily adaptable to stacks from other manufacturers and high and low temperature polymer electrolyte membrane stacks.
- Automated quality control elements, such as leak testing, are important fuel cell cost reduction elements.
- The project defines a method of reducing the cost of quality control and break-in of the fuel cell system. Reducing the number of break-in steps will accelerate the process for qualifying a fuel cell system for delivery.

Question 2: Approach to performing the work

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

- The approach is sound and innovative.
- Teaming with Pacific Northwest National Laboratory (PNNL) and Cincinnati Test Systems (CTS) makes for a well-rounded collaboration.
- The approach to developing an automated leak test apparatus is sound but cost analysis elements are lacking.
- The approach demonstrates systematic evaluation of the leaks through pressure decay and the measurement of voltage decay and crossover currents. The break-in stage measures the open-circuit voltage decay and evaluates the performance. All of these are important factors. The criteria for success were not discussed with sufficient detail although graphs of normal behavior were given.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.7** for its accomplishments and progress.

- The accomplishments to date are appropriate and impressive.
- The labor minutes for the test suite were significantly reduced; this is the type of achievement that the project should deliver. The number of failures due to leaks was greatly decreased. The capability of the pressure drop test is demonstrated.
- The presentation needs to better highlight the importance of the successful outcomes of the project, including cost, quality, and performance of the product.
- Based on the presentation (slide 9), the leak test time seems to have been reduced at the time of touch labor as well as the leak failures. However, it is not completely clear how that occurs or how repeatable the results would be for a larger test population or different stack design.
- Leak test cycle time improvements were not adequately described. A reduction of failures due to leaks may not be entirely attributable to new processes but may arise in part from previously inadequate manual processes. The path to 50 parts per hour (pph) presumes that a pressure test alone will be adequate to identify all leak root causes.
- This project met most of the objectives.
- The presenter was very difficult to understand and most of the questions were answered by someone other than the presenter. UltraCell has closed their large manufacturing facility in Ohio, so it is difficult to discern if adequate testing for high-volume processes can be achieved. Four of five tests in the second validation and two of three systems in the third validation passed exit criteria.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- The combination of PNNL, UltraCell, and CTS seems to be the complementary mix that is needed to execute this project.
- The collaboration is adequate and suitable for this type of project.
- The collaborators are adequate and appropriate but there is insufficient information to assess their contributions.
- Collaboration partners (PNNL, CTS) are good. If this leak detection suite helps the fuel cell manufacturers at large, there should be specific steps to demonstrate or provide information to them as well as incorporate some of their high-volume metrics.
- The collaboration with the other institutions (e.g., CTS) was not reviewed on the charts and their contributions were not clearly evident. If this was completed in the first year and no longer part of the activity, UltraCell should have stated such and explained what the previous contribution was.

Question 5: Proposed future work

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

- The future work plan is rational and appropriate.
- The future work is consistent with moving the successful aspects of this program into their pilot production line.
- The PI did propose future work that makes sense. However, it is still not clear how this technology will be pervasive without more sharing with other fuel cell original equipment manufacturers.
- Future work is reasonable, but lacks any cost savings analyses.
- Based on uncertainties in the ability of this year's results to conclusively demonstrate a general 5 pph capacity in the prototype suite, the plan to fabricate, integrate, test, and evaluate a 50 pph suite may be overly optimistic.

Project strengths:

- UltraCell is systematically establishing the qualification test and break-in procedure as part of their production facility.
- This is an important area to manufacturers.

Project weaknesses:

- Detection of only 95% of the defects, while sounding impressive, is inadequate. Detection rates of 99.9% or better are required for a goal of six sigma.
- UltraCell no longer has their large-scale manufacturing facility from which to test this suite at large volumes. It was hard to discern progress based on the charts and presentation. Full correlation between leaks detected and fuel cell failures has yet to occur.
- The PI did not discuss the implications of a successful cost and performance outcome. The perception is that this could be a great help, but it would be helpful to the reviewer if this would have been further discussed.
- The presentation lacked a cost analysis and detail in the presented results.
- The presentation, and especially the charts, did not provide a complete view of the process. Only during the discussion did it become evident that the break-in period was seven hours long, which is promising but not a given. A Gantt chart for the process would have been helpful. The key benefit appears to be the reduction in labor time, which is very good, but a full perspective of the qualification/break-in process should have been presented. The failure of a cell, by a process that was not discussed, was a problem. The failure should have been discussed and explained. If the failure was outside the scope of the project effort, it should have been stated.

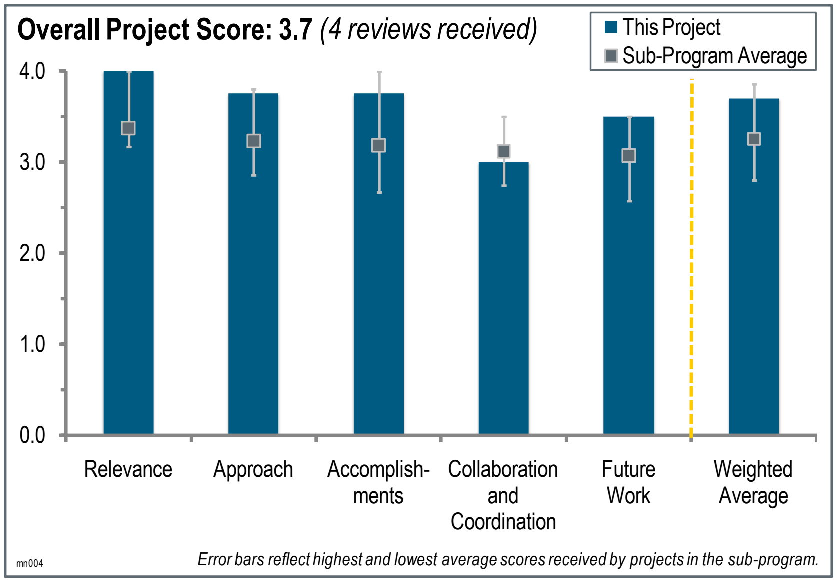
Recommendations for additions/deletions to project scope:

- Work on getting the detection rates up.
- The project needs to highlight the implications of a successful outcome on cost and performance.
- Potential cost savings need to be analyzed to assess adequately the usefulness of the effort.
- The full process for qualification and break-in should be discussed and the contributions of the project to the full process should be identified.

Project # MN-004: 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 that will 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/year, (2) a manufacturing process that is consistent with achieving the $15/kW U.S. Department of Energy (DOE) 2015 transportation stack cost target, (3) a product that is at least as durable as an MEA made in the current process for relevant automotive duty cycling test protocols, (4) a product that demonstrates a power density greater or equal to that of the MEA made by the current process for relevant automotive operating conditions, (5) a product form of 3 layers of MEA roll-good (anode plus membrane plus cathode), and (6) a stack break-in time that is reduced to four hours or less.

Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **4.0** for its relevance to DOE objectives.

- Low-cost, high-quality MEA manufacturing is required for polymer electrolyte membrane (PEM) fuel cell commercialization.
- Cost reductions to MEAs are very important to meeting DOE targets.
- The objective of developing a low cost MEA is consistent with the goals of DOE. The analyses identify the thermal and water management characteristics of the project. A reduction in the thickness of the membrane could reduce conductivity losses and improve redistribution of water.
- MEAs are a large cost driver and Gore has proposed a project to address a means to substantially reduce these costs.

Question 2: Approach to performing the work

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

- Changing the manufacturing process to eliminate additional material costs and streamline production are both approaches consistent with the goals of DOE. Increasing durability of the MEA is a goal; although it was not clear if the objective for this effort was to meet the previous durability goals with the new, lower cost MEA. The explanations of the approaches used in the program were excellent.
- The project is very focused on status versus performance metrics.
- Gore has a very strong technical approach to accomplish the work proposed. Using United Technologies Corporation (UTC) for stack validation can help confirm results from the W.L. Gore work.
- Gore has “de-emphasized” break-in as a priority with the current protocol of 2 hours versus a target of 4 hours. It is unclear why the original goal was four hours; no break-in would be an ideal goal. The modeling efforts, while

valid to understand PEM fuel cells, do not correlate with this project's goal of a low-cost MEA manufacturing process.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.8** for its accomplishments and progress.

- Significant progress was made to minimize waste of materials. This project has good process control for direct coated anodes and cathodes.
- The progress toward the goals and benefits of the project were clearly identified. The costs and benefits were not identified and it is assumed these are considered proprietary. Gore has not only improved the manufacturing process, but also led to improved performance of the MEA. It is impressive that the membrane thickness was reduced without a major penalty in crossover. The modeling efforts appear to be slower and behind the experimental activities.
- Gore has met most of their objectives, with the University of Tennessee-Knoxville (UTK) being the only possible exception. This project shows potential to eliminate intermediate backer materials. Gore met the go/no-go criteria of a projected 10% reduction in cost. There is a potential for benefits to five-layer MEAs. Gore updated their 2009 results and realized additional cost savings projections. Much of the savings were achieved through membrane thickness reduction, reduced scrap, and process elimination.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The list of collaboration with other institutions was presented; however, the discussion of some of the activities of the collaborators was not very detailed. The interaction with UTC Power and the National Renewable Energy Laboratory and how they would help this effort needs to be explained further.
- This strong team consists of University of Delaware (UD), UTC Power, and UTK. It is not clear how well Gore will communicate results to other MEA manufacturers in this highly competitive area.
- Slides were presented from the partners on this project; however, there does not seem to be any real collaboration. It does not appear that the UD modeling or UTK modeling has anything to do with the manufacturing process or will have an effect on the manufacturing process. These 2 modeling tasks appear irrelevant to the project's success. Also, the principal investigator listed for UTC is no longer at UTC.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- There is high confidence of a successful outcome on this important project.
- The future work is at an appropriate scale for the remainder of the term, which is about one year.
- Future work is a continuation of the project activities.

Project strengths:

- This project's strength lies with Gore and its product line and processing knowledge.
- The project strength is targeting a major manufacturing cost driver, reduction in materials (backer). reduction in conditioning time and costs, and minimized use of solvents.
- The robust approach that leverages the skills and strengths of its collaborators is a strength of this project.

Project weaknesses:

- There is little real collaboration in this project.
- It appears the modeling effort needs to be increased.

Recommendations for additions/deletions to project scope:

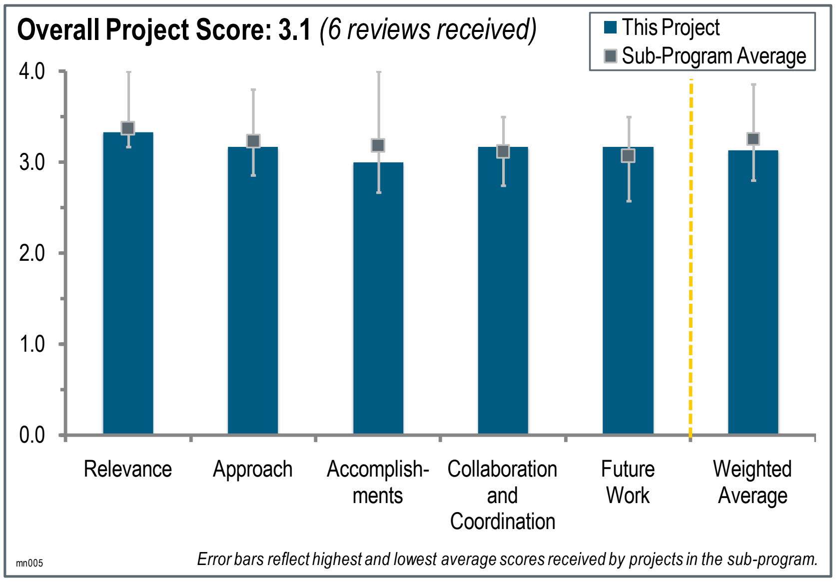
- Gore needs to expand the process to rolled goods.
- Gore should state when the results of this effort will enter the marketplace.

Project # MN-005: Adaptive Process Controls and Ultrasonics for High Temperature PEM Membrane Electrode Assembly Manufacture

Raymond Puffer; Rensselaer Polytechnic Institute

Brief Summary of Project:

The objective of this project is to enable cost-effective, high-volume manufacture of high-temperature (160°–180°C) polymer electrolyte membranes (PEM) and membrane electrode assemblies (MEAs) by: (1) achieving greater uniformity and performance of high-temperature MEAs by applying real-time adaptive 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 (U/S) bonding processes for high-temperature PEM MEAs.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Advances in high-quality stack manufacturing are very important to the economic deployment of PEM fuel cells.
- Adaptive process control and ultrasonic sealing for MEA fabrication have the potential to improve MEA manufacturing quality and therefore reduce costs.
- The reduction of the manufacturing time and improvements in MEA properties directly improves the MEA and is well within the scope of the DOE goals.
- This project is developing production diagnostics and techniques for moderate temperature operating fuel cells (160°–180°C). These fuel cells have an application for combined heat and power, but not for transportation. If these manufacturing techniques can be expanded to lower temperature PEM fuel cells for transportation, they will have increased relevance. This work appears to be recently initiated.
- The project now includes investigations for both high-temperature and low-temperature PEM analysis.
- It was difficult to see the relevance of the project because the speaker did not define the quality control issues of MEAs with current methods and address how APC or U/S welding improves MEA uniformity, as asserted in the presentation. Additionally, no data were shown to justify the decrease in cost with the new method. A table was attached in the back-up data but not discussed or addressed during the presentation. In general, the speaker did not provide enough data to justify his statements or relevance of the project.

Question 2: Approach to performing the work

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

- The approach was expanded because of the promising success for U/S sealing of high-temperature MEAs to include low-temperature MEAs. The manufacturing improvements were systematically applied to the fabrication of MEAs and the principal investigator will test these improvements in a real fuel cell system that is fully instrumented to evaluate the operational characteristics of the new MEAs. The adaptive process control coupled with quality control is an outstanding research approach that couples manufacturing with the physical property specifications of the MEA.

- The effort is guided by a thorough project plan, incorporating appropriate elements of modeling, experimental design, testing, and cost analyses.
- The use of on-line alternating current impedance to measure the quality of MEA construction was very interesting. However, it seems counter-intuitive to make a series of MEAs and then wait to test for uniformity with in situ fuel cell stack testing. It seems that other quicker and cheaper methods of characterization would be utilized to monitor the quality of the MEAs prior to in situ testing. Additionally, there does not seem to be a plan to understand mechanistically why the current MEA formation methods are so variable or why the proposed methods in this project would be an improvement.
- Both the ultrasonic bonding and adaptive process control of MEA sealing are very promising. Little attention is paid to micro-level effects of bonding.
- This project appears to be pressing MEAs with sensors and controls. Pressing of individual MEAs does not appear to be a manufacturing technique that most manufacturers are exploring.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.0** for its accomplishments and progress.

- This is a very successful project. The APC concepts have improved the MEAs while reducing the manufacturing time. This is an example of an outstanding research and development success. The importance of scale-up recognized by the researcher is not recognized by most research and development activities. A 90% cost reduction for sealing is phenomenal.
- Significant cost reductions have been identified.
- Adaptive process control efforts indicate improved cycle times with no loss in part performance; ultrasonic sealing can greatly reduce cycle time. Cost savings in the sealing process need to be translated/incorporated into a cost savings for the delivered MEA.
- The results are very promising to date on a macro-scale; however, no evidence of micro-level understanding has been demonstrated. This deeper understanding is necessary to understand the durability of these seals.
- Polarization curve performance is far below other developers (recognizing that these are different membranes operating at 160°–180°C). There is little quantifiable information presented, including catalyst loading, durability, and membrane conditions.
- There seems to be a lack of characterization other than putting MEAs in stack, e.g., lack of microscopy.
- It was difficult to gauge the progress because data were not shown to contrast current results with previous findings. The polarization curves and data shown looked interesting and promising, but the presentation was data-light.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There is good collaboration across universities, labs, and industry that will help assure a good understanding of the process and its results.
- The project has good participation and contribution from industry partners.
- Rensselaer Polytechnic Institute (RPI) is working with the leading industrial organizations in both high-temperature PEM and low-temperature PEM. This is a good decision by RPI.
- Ballard was added as a collaborator in the past year.
- The formal partner via a subcontract on the project is Arizona State University, but there did not appear to be any collaboration. It is unclear whether all the partners listed have really contributed to the project, other than BASF. Ballard and the National Renewable Energy Laboratory look to be just initiated.

Question 5: Proposed future work

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

- Future work efforts are appropriate and have the potential to validate current process improvement efforts.

- Proposed work will build on the early phase successes of this project. The proposed work in the rest of this project is well organized.
- In general, the proposed plan is good; however, this reviewer would recommend doing some ex-situ work to characterize and understand the differences in sample prep techniques.
- The sealing of larger MEAs and durability testing appear to be critical components of future work.
- Durability testing may require more emphasis in order to validate the conclusions of the study.
- Very little detail is given to future work or how previous technical accomplishments will be built upon. More macro-level work will lead to a limited understanding of APC and ultrasonic sealing.

Project strengths:

- A macro-level understanding of seal integrity and single-cell performance is a strength.
- The project gets better with every update.
- RPI is making good progress towards the project goals and is well designed and executed.
- The primary strength is the experience of the researchers at RPI and their ability to collaborate with fuel cell industry leaders.

Project weaknesses:

- Lack of micro-level understanding of sealing is a weakness.
- The manufacturing process and application to other types of fuel cells are unclear. Pressing individual MEAs is not a low-cost process compared with coating rolled goods.
- A higher level view of cost impacts would be helpful.

Recommendations for additions/deletions to project scope:

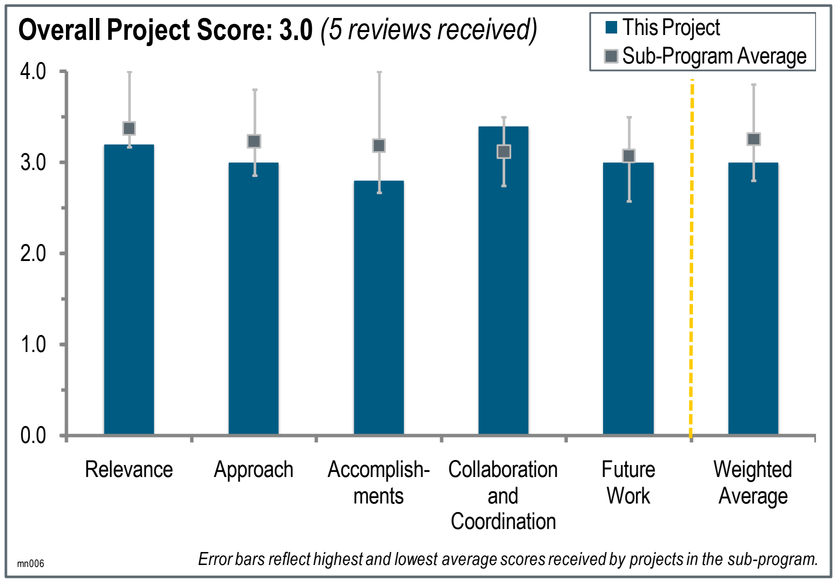
- Researchers should thoroughly investigate the seals as a function of process control to understand the end product. This effort can then be compared with durability and stack results to understand the effects of experimental parameters on seal integrity.
- Ultrasonic sealing should be verified for large, active-area MEAs.
- In future presentations, this reviewer would recommend describing the process being used by the team. In looking through both the 2010 and 2011 presentations, there was not a description of the actual process. “MEA welding” can refer to many different processes, from welding plates with MEAs in the middle to making MEAs. As a member of the audience without previous knowledge of the project, it took the full 20 minutes to understand exactly what was being welded.

Project # MN-006: 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 pre-competitive knowledge base of engineering data that relates 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 to quantify the performance effects, if any, and correlate these results into required dimensional fabrication tolerance levels. The project will provide data necessary to make informed tolerance decisions to enable the reduction of fabrication costs.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.2** for its relevance to U.S. Department of Energy (DOE) objectives.

- This project is extremely relevant and interesting. The lack of a high-speed plate control is a large bottleneck for manufacturing fuel cells on a large-scale level. This technique is very applicable in current fuel cell manufacturing. Though the authors did not have time to present on the ellipsometry experiment, it is an interesting technique to perform quick quality control screening for mud cracks, metal nuggets, and other defects in the soft goods. It would be interesting to use the tool, or a similar tool, to detect defects or monitor the state of the plates following durability runs and/or monitor the quality of welds or other post-etching processing. While the investigations into flow-field geometry, plate manufacturing dimensional scanning, and catalyst-coating optical inspection are potentially useful, there is no indication of what kinds of quality or cost improvements could be achieved if these technologies were validated and made commercially available.
- The goal of this project is to provide bipolar plate manufacturers and designers with the data necessary to make informed tolerance-decisions to enable the reduction of fabrication costs. This objective is met by the development of a pre-competitive knowledge base of engineering data relating performance variation to manufacturing process dimensional variability.
- There appears to be some link between the work being done and the DOE objectives, but some of the effort seems to be less critical to near-term success.
- Inflexible quality control (QC) processes can hinder high-volume manufacturing of fuel cells, especially in the United States where relatively higher labor rates exist and significant labor hours cannot continue for QC processes.

Question 2: Approach to performing the work

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

- The approach is very interesting. It is well thought out and executable. This reviewer would recommend looking into the capabilities of the optical scatterfield metrology, or other technologies, to investigate if it is possible to look for evidence of corrosion as a function of location. Additionally, the authors should be focused more on measuring plate variability as a function of pressure drop across the plates rather than electrochemical

performance. Flow field dimensions are designed to provide a specific pressure drop across a plate. Pressure drop changes across 50 cm^2 (centimeter squared) test cells may not produce large changes in performance. Slight changes in pressure drop across 200-500 plates in a vehicle stack will definitely affect performance, water management, and the overall fuel cell system. Currently, original equipment manufacturers measure the quality of plates by measuring the pressure drop across plates prior to building stacks to insure the pressure drop is within specification, a very arduous process. The authors of this work should empirically perform a study to measure the variability within plates and then selectively choose plates with different degrees of variability to measure the effects on pressure drop, generating a chart of the relationship.

- The National Institute of Standards and Technology (NIST) proposes a sound approach for the technology objectives. However, collaboration with only the Los Alamos National Laboratory (LANL) seems too limited. Matching 40% of NIST's mission-funded labor is good. NIST is focused on commercially available, non-contact high-speed scanning technologies. This is better than trying to invent a specific piece of equipment.
- The approach to generating this data base is to use a statistically based design-of-experiments and fabricate experimental "cathode" side-flow field plates with various well-defined combinations of flow field channel dimensional variations; then, through single-cell fuel cell performance testing using a robust protocol, quantify the performance effects, if any, and correlate these results into required dimensional fabrication tolerance levels. This is a sound engineering approach.
- The overall approach of each of these tasks is good.
- This is a good approach for the flow field dimensional tolerance investigation. These kinds of bases are important in identifying allowable manufacturing tolerances. However, it is not entirely clear how critical parallelism or thickness variations are relative to performance and cost. It is also not clear how the use of scatterfield metrology for catalyst coating inspection will aid manufacturers with improving quality and reducing costs.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.8** for its accomplishments and progress.

- The team is on track to meet the goals and objectives of the project.
- The accomplishments to date are appropriate to the effort. The results appear promising.
- Task 1 has shown good progress and should provide key data for understanding manufacturing tolerances. The output from Task 2 is a continuous scanner that can accurately measure channel depth and width at reasonable speeds. Task 3 has shown progress in being able to accurately measure the loading of various catalyst types with acceptable repeatability and accuracy. The overall progress of these tasks is good and the results, especially of Task 3, are promising.
- The flow-field testing showed good repeatability, indicating good control of other factors. While progress was made in all 3 subprojects relative to demonstrating the capabilities of each technology, it is not clear how any of these investigations will lead to improved quality control and reduced component cost.
- This project reduced outlet pressure according to 2010 Annual Merit Review feedback; however, other plate data still must be repeated to confirm the initial results. The videos indicate the ability to scan up to one-half meter per second of assembly line speed.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- The collaboration and coordination is appropriate.
- Each task seems to have a good amount of collaboration and the groups appear to be working well together.
- Collaboration with LANL was identified in future work, but not clearly explained in the work to date. Collaboration in the plate scanning effort appears adequate with reasonably selected partners. Collaborators were identified in the third subproject but their contributions were not explained sufficiently.
- Without good collaboration, NIST does not have a role in this area. Their basis for existing is predicated on significant collaboration with industry.

Question 5: Proposed future work

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

- The proposed new work appears appropriate. The two-phase work looks to be interesting. For low-quality flows, the correlations by C.S. Thom are suggested.
- The scope of the future work fits with the current projects and generally addresses the barriers being targeted.
- The future work efforts identified for all 3 subprojects were appropriate for further validation of the technologies, but none included any assessment of the usefulness relative to quality improvements or cost reductions.
- Phase II looks promising, but the project investigator ran out of time and there was little discussion on this topic.

Project strengths:

- The analytical approach in this project is a strength.
- Task 1 should provide bipolar plate manufacturers with key information for setting tolerance specifications for their processes. Task 2 provides a unique system for measuring channel width and depth and could eventually be useful when manufacturing rates increase. Task 3 is the most useful of the 3 and could provide critical data about the catalyst loading on the catalyst coated membranes or gas diffusion electrodes.
- This is a unique and interesting project. The soft-good ellipsometry work looks very interesting.
- NIST provides an essential role to manufacturers by setting the standards from which measurements and manufacturing processes sorely need.

Project weaknesses:

- The accurate analysis of two-phase cooling may be a challenge.
- Task one is useful, but limited in its current form. Expanding on the channel design and operating conditions is a good way to address this weakness. Task 2 is a good accomplishment, but the impact on near-term fuel cell applications seems minimal.
- The overall project seems too focused on things one could do and not focused enough on whether they should be done.
- The presenter was unable to describe the overarching benefits of the work. The presentation included too many technical details. The second presenter was severely limited in time due to the first presenter going too long.

Recommendations for additions/deletions to project scope:

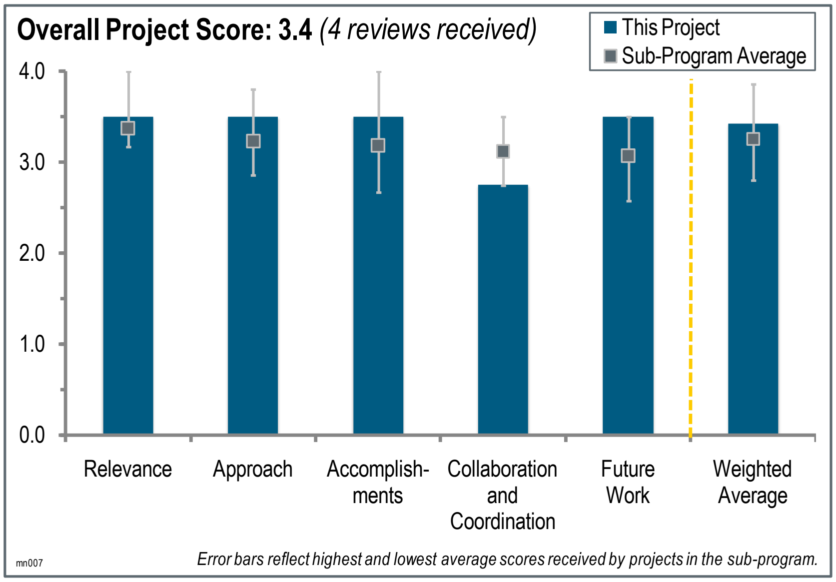
- For task one, there may be some benefit to teaming with a stack supplier in the future to observe the results of variations as opposed to single cells. For Task 3, continue to work with the industry to ensure that the accuracy and measurement speeds are sufficient for their processes. This reviewer recommends re-focusing the plate work to focus on the effects plate variability has on pressure drop as well as on defects from processing and durability runs such as the consistency of welds, evidence of corrosion, or consistency of plate surface treatments following durability runs.

Project # MN-007: 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 the cost of fabricating gas diffusion electrodes (GDEs) with a focus on GDEs used for combined heat and power (CHP) generation, (2) relate manufacturing variations to actual fuel cell performance in order to establish a cost-effective product specification within six-sigma guidelines, and (3) develop advanced quality-control methods to guide realization of the first two objectives. The objectives for fiscal year 2011 are a two-fold speed increase, or equivalent, on cloth and proof-of-principle coating on non-woven paper.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.5** for its relevance to U.S. Department of Energy (DOE) objectives.

- The objectives of this project and barriers addressed fully support DOE objectives.
- The work done in this project can significantly decrease the manufacturing costs of GDEs for high-temperature polymer electrolyte membrane (PEM) applications.
- BASF is developing low cost GDEs for PEM fuel cell CHP. BASF is using platinum/carbon supported catalysts, but there is no information on the type, loadings, durability, or membrane. With the membranes the company is using and the associated issues and performance, these materials will only work for CHP and not for other applications, such as transportation. It appears that most PEM fuel cell developers have moved away from GDE to catalyst coated membranes (CCMs). Developing inks for use with paper gas diffusion layers (GDLs) versus cloths is the correct approach; however, other developers are long past this step.

Question 2: Approach to performing the work

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

- The principal investigator (PI) has a solid approach to addressing key technical barriers. Increasing the throughput rate and platinum utilization, while also improving the uniformity, is a critical to reducing the long-term fabrication costs.
- The PI is working on a moderately high-temperature fuel cell, which has advantages for CHP. The project is moving in the correct direction in terms of paper GDLs, inks, and roll-coating goods.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **3.5** for its accomplishments and progress.

- The overall progress of this project is good. The improved uniformity of platinum distribution was particularly interesting. If they are valid, the results with missing platinum are also interesting. The overall loading of the control sample seems to be higher in general, but there is not any real performance improvement. The reviewer asked if the overall loading could be reduced more, leading to less passes overall.
- The improvement in the rheology of the ink suspensions with a surfactant to improve roll coating and reduce time was good work. In general, the results so far helped to removing the barriers, at least for high-temperature PEMs.
- Progress on improved inks with viscosity that is independent of shear force was made. The production of full-length roll coating with a double coating speed shows good progress.
- It would be helpful to provide a dollar value in terms of cost reduction. It also would be helpful to comment in terms of applicability to other technologies.

Question 4: Collaboration and coordination with other institutions

This project was rated **2.8** for its collaboration and coordination.

- There seems to be good collaboration between the partners in this program.
- Collaborations include XOS for X-ray fluorescence (XRF) mapping and a newly started collaboration with Rensselaer Polytechnic Institute (RPI). It is difficult to measure the success of these collaborations and determine whether XOS simply put several GDEs in a scanning XRF and made a platinum map (approximately 2 hours of work), or if there is real interaction. No results from the RPI interactions were presented.
- It seemed like the RPI collaboration was somewhat informal.
- It is not clear if Case Western participated in this year's effort.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed work is clearly defined and should lead to further cost reductions and improved materials.
- All plans for future work look good, particularly the potential for non-woven, on-roll coating. Increasing capacity on anode production coater is promising.
- Work on carbon papers will increase line speed.

Project strengths:

- This project clearly addresses DOE's goals of reducing costs and increasing manufacturing capacity. The end result of this project should be a dramatic decrease in the manufacturing costs of GDEs for high-temperature PEM fuel cells.
- High-temperature operation is good for CHP, but may be a weakness for any other applications.

Project weaknesses:

- Although there has been some progress in achieving effective improvements, it seems critical to be able to reach higher coating speeds with uniform loadings. Efforts in year two have moved away from that goal, but hopefully will return in year three.
- There is very little quantifiable information presented, including catalyst loading, durability, and membrane conditions. Polarization curve performance is far below other developers in terms of voltage current. (It is recognized that these are different membranes operating at 160°–180°C.)

Recommendations for additions/deletions to project scope:

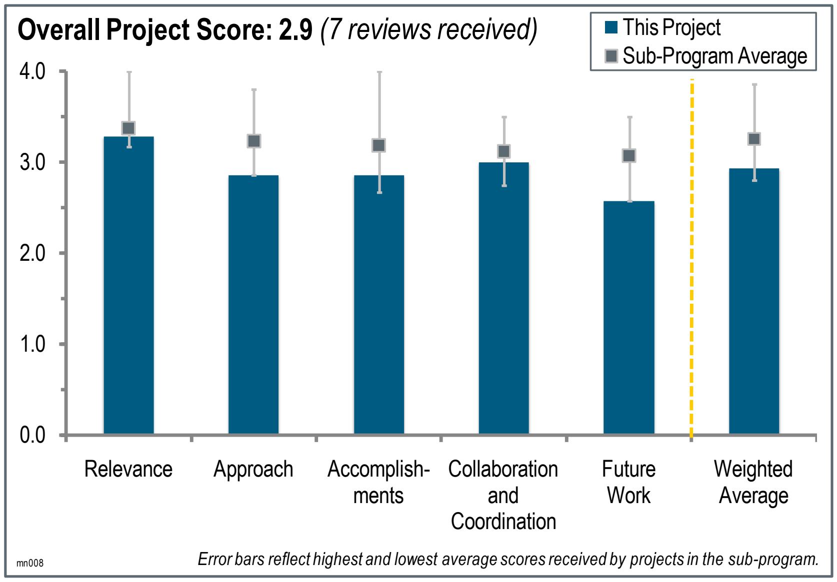
- Researchers should apply manufacturing techniques to other materials, specifically CCMs. This project could use a cost analysis trade-off between the lower performance of these materials versus the higher operating temperature.
- It would be helpful to address the impact on performance and reliability.
- This reviewer would recommend examining the effect of reducing the overall platinum loading based on the performance with missing loading.

Project # MN-008: 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, using a new hybrid process with the following features: (1) optimized elements of advanced fiber placement and commercial filament winding, (2) reduced production cycle times through adaption 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.



Question 1: Relevance to overall U.S. Department of Energy objectives

This project was rated **3.3** for its relevance to U.S. Department of Energy (DOE) objectives.

- Quantum is developing a new hybrid process for reducing the amount of carbon fiber usage, therefore lowering the cost of pressure vessels. The work is relevant to DOE's goal of reducing the cost of onboard hydrogen storage systems. The team is attempting to increase manufacturing efficiency by distributing automated fiber placement (AFP) and filament winding (FW) operations on different machines. The project aims to understand the compatibility of hydrogen with Type IV high-density polyethylene liner through testing done by the Pacific Northwest National Laboratory (PNNL).
- The project is focused on areas that are important to the adoption of hydrogen technologies in light-duty vehicles.
- Reducing the cost of compressed gas tanks is critical for the commercialization of hydrogen fuel cell electric vehicles. Improving the fabrication process is important, especially for mass production.
- While carbon fiber (CF) cost influences the cost of high-pressure vessels, processing optimization also affects cost to some degree and needs to be optimized.
- Results vary according to industry. Weight reduction and lower cost manufacturing and materials are an immediate benefit.
- The project is focused on the important aspect of reducing the cost of hydrogen pressure vessels, which aligns with the DOE Hydrogen and Fuel Cells Program objectives. The focus on CF usage is important but this project may not have as much potential to reduce costs in comparison to other approaches, such as fiber material cost reduction. It was helpful that the project included a comparison to other alternative fiber options.

Question 2: Approach to performing the work

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

- Letting the industry lead is an excellent approach. This approach has led to other successes in the electric propulsion area and certainly worked here.
- The hybrid approach is creative and has shown good results in cost reduction and gravimetric hydrogen density. The project combines manufacturing testing, physical stress analysis, and financial analysis.

- Considering fiber replacement in the dome area of the pressure vessel is a good approach because this area is typically inefficient in the traditional filament winding process.
- Boeing's AFP is applied to strengthen the vessel domes without adding additional weight to the vessel cylinder. While the approach has the potential to reduce the cost of Type IV tanks by about 10%, it cannot bring down the system cost sufficiently to meet DOE cost targets. Interfacing AFP and commercial FW may still prove challenging because the burst tests show that four of six vessels failed at the AFP/FW interface.
- The cost of CF is a significant part of total cost. There seems to be little room to improve the cost through fabrication. It seems the only possibility is relaxing regulations to reduce the amount of CF to be used for a tank.
- The use of AFP is essential in optimizing load-carrying capability, especially in geometric transition zones. Investigating alternate fibers is probably not useful because the industry has settled on the high strength CF.
- It would be nice to see some work devoted to cryogenic systems as this is the operating regime for essentially all adsorbent material efforts.

Question 3: Accomplishments and progress towards overall project and DOE goals

This project was rated **2.9** for its accomplishments and progress.

- This excellent work is moving down the cost curve. The accomplishments are only limited by the types of materials investigated.
- The project achieved significant cost reductions through advanced fiber placement. The reviewer questioned if there is room for significant improvement in the future.
- The project has made significant progress on cost, weight, and gravimetric density.
- Under difficult situations, such as fixing the cost of CF, it has been well done.
- The project has demonstrated modest progress in weight and cost savings since the previous year's updates. The evolution of cylinder concepts is useful, but may not be progressing at a rate significantly close to the cost gap. The analysis of alternative fibers indicates a CF cost of $14–$15/lb but the cost analysis uses $11/lb without a clear reason for the reduction in material cost.
- There is a need to test the effect of pressure and temperature cycling on the AFP/FW interface.

Question 4: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- There is strong collaboration with Boeing and PNNL.
- The collaboration between PNNL, Lawrence Livermore National Laboratory (LLNL), and Boeing is good; each partner provides solid value.
- The contractor is one of the major manufacturers of composite tanks but still intensively collaborates with other people, which is a good point of this work.
- The current team is well-rounded with laboratories, fabricators, and user representatives. However, no outside interactions were mentioned, such as with fiber producers or the general technical community.
- The laboratories have provided the science needed for industry to progress, which is how it should work.
- The collaboration between Quantum and Boeing appears to be good and attempts to utilize the expertise of both companies. PNNL could collaborate with TIAX, LLC and other sources on cost analysis to ensure a consistent set of assumptions. The presentation did not include the update of LLNL's dry tape analysis.

Question 5: Proposed future work

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

- The plans shown for future work are clear and expected to be well done.
- Using lower cost CF for FW of outer layers and higher strength CF for the dome is a good strategy because the bulk of the cost is in the CF.

- The fiscal year 2012 goal of getting tanks manufactured and putting these processes and materials in the hands of testing labs to corroborate (or not) on developing tanks standards will be interesting to watch unfold. Hopefully that effort will get funding.
- Evaluating and integrating lower cost CF is a good next step. In addition, the project would benefit from a comprehensive manufacturing and process flow evaluation. The processing and transfer of the fiber placement dome to the FW operation may be a bottleneck and needs further development.
- Given that the results of this project so far have been about four times DOE's 2010 target for $/kWh and eight times the 2015 target, it is unclear whether the future work plan will be able to approach these values. The future work seems primarily incremental and may be unable to produce this breakthrough.
- The use of lower cost CF may be useful in the outer layers. More advanced concepts, such as pre-stressing, should be investigated.

Project strengths:

- The researchers have substantial experience in Type IV tanks and CF composites. The project leverages advanced proprietary technology from Boeing to advance the project goals.
- The project has excellent results to date through a creative use of manufacturing techniques.
- One of the manufacturers of composite tanks intensively contributed to the project. The cost reduction is critical to commercializing hydrogen fuel cell electric vehicles.
- Winding and testing capabilities are the key strengths of the project team.
- The industry project lead is a key strength.
- The project appears to have a good balance between analytical and experimental approaches to evaluate the concepts. The cooperation between industry and national labs is a strength of the project.

Project weaknesses:

- There are two issues for the Type IV tank. One is cost and the other is the possible hydrogen bubble formation between the plastic and fibers. The latter was not mentioned even though photos of the boundary between plastic and fibers were shown.
- This project has limited potential to achieve a significant reduction in the cost of the onboard storage systems.
- This project alone will not be sufficient to meet DOE goals. Further funding in the area of low-cost, high-performance fibers is needed on a sustained basis.
- There is an evident lack of understanding of structural materials, especially in relation to controlling the interface between AFP and lay-up. The interface needs to be much better controlled.
- The project seems to consist of several sub-projects and the connection between them is unclear. The cost analysis should be benchmarked against the TIAX analysis, and other sources, since there is an improvement of approximately $20/kWh, which is higher than the TIAX assessment of the current technology at about $19/kWh.

Recommendations for additions/deletions to project scope:

- Researchers should test pressure and temperature cycling of AFP/FW hybrid tanks.
- Hydrogen bubble formation is critical. If it has not been mitigated, it must be included in this project. Codes and standards seriously influence tank specifications and cost. There should be a close collaboration with organizations working on codes and standards.
- The reviewer questioned if gains in cost can be obtained through the investigation of alternate designs for bosses and tank balance-of-plant components. It is important to understand load transfers between layers and its role in tank integrity.
- This project should expand its materials search for something that is recycled.
- The PNNL cost analysis should include the deliverable of comparing and evaluating their assumptions with TIAX. The project could also include future assessments of potential or theoretical areas to further reduce the cost of the pressure vessel.

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