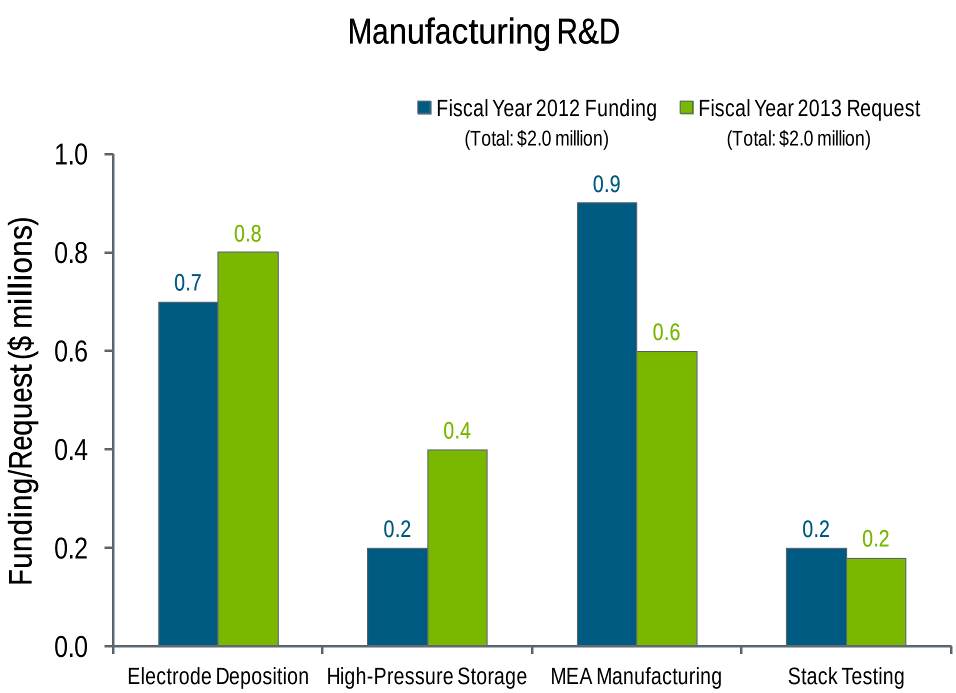
2012 — Manufacturing Research and Development (R&D) Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

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

The Manufacturing R&D sub-program was judged to be well managed and well executed. Reviewers stated that the overall goals and objectives of the sub-program were clearly defined and that the projects in the sub-program were highly relevant to these goals and objectives. Reviewers also stated that the manufacturing sub-program projects are rather mature, well-conceived, and are delivering quality results. Reviewers noted that the issues and challenges that remain have been clearly identified and a plan exists with the only limitation being availability of funding. In fiscal year (FY) 2012, six manufacturing projects were reviewed. These projects addressed fuel cell membrane electrode assembly manufacturing, fabrication of catalyst-coated membranes, fuel cell stack in-line testing, and manufacturing of high-pressure vessels for hydrogen storage. Reviewers noted that there were no projects for low-cost, high-volume manufacturing of gas diffusion layers (completed in FY 2011) and no projects to facilitate high-volume assembly of stacks.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was $2 million for FY 2012 and $2 million was requested for FY 2013. The FY 2013 request level funding will continue existing manufacturing R&D projects. The ultrasonic membrane electrode assembly (MEA) sealing project has been completed.



Majority of Reviewer Comments and Recommendations:

Six Manufacturing R&D projects were reviewed and the maximum, minimum, and average scores for the projects were 3.4, 3.0, and 3.3, respectively. All projects were judged to be highly relevant to the DOE Hydrogen and Fuel Cells Program's activities, with very good technical approaches. Project progress and accomplishments were judged to be extremely good. Project teams were judged to be strong; participation and contribution from industry partners was judged to be useful and coordinated. For most of the projects, reviewers felt that more details needed to be presented for future work.

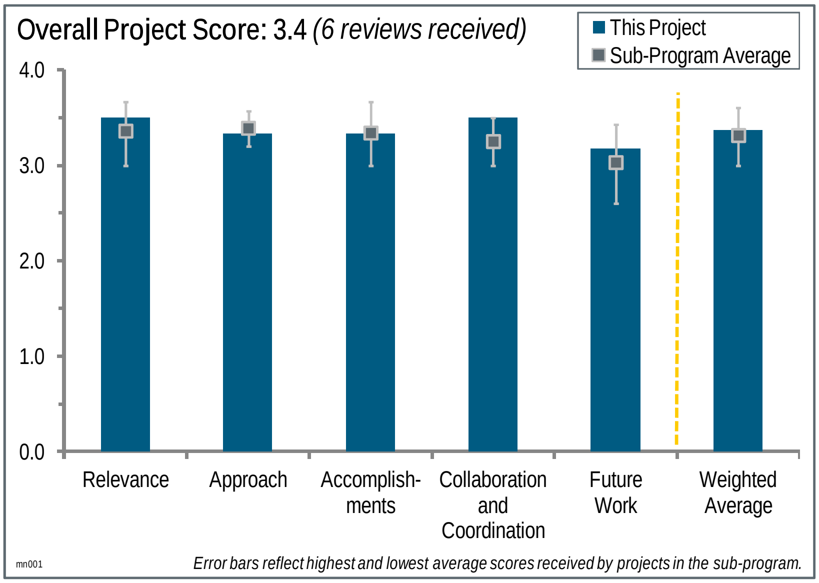
The highest ranked projects (3.4) were considered by the reviewers to be highly relevant, with an excellent approach, outstanding accomplishments, and strong technology transfer and collaborations. The reviewers wondered if the principal investigator of the project with the lowest score (3.0) fielded sufficient test articles to provide an adequate number of samples to achieve statistical significance.

Project # MN-001: Fuel Cell MEA Manufacturing R&D

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to: (1) evaluate and develop in-line diagnostics for membrane electrode assembly (MEA) component quality control (QC), 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's (LBNL's) modeling to support diagnostic development and implementation.



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

This project was rated **3.5** for its relevance to DOE objectives.

- The National Renewable Energy Laboratory (NREL) works to improve manufacturing and QC of Nafion®-based MEAs and gas diffusion layers (GDLs). The emphasis appears to be on measuring and identifying defects, which is a good thing for a national laboratory to be doing.
- This activity is relevant in the overall scheme of things. The task consists of evaluating and developing in-line diagnostics for MEA component QC.
- This is a difficult project to get industry buy-in; it is difficult for companies to share their proprietary QC methods and their yields because yield goes into all cost models. This project seems to be doing a good job of walking that fine line.
- This project is very relevant to the goals and objectives of the DOE Hydrogen and Fuel Cells Program (the Program). This project specifically addresses in-line QC and defect evaluation, both of which are critical as manufacturing volumes increase.
- This project is focused on QC related to fuel cell manufacturing. It is very relevant to the Program. Defect identification is important to the economics of manufacturing fuel cell soft goods.
- MEA cost-reduction efforts are significant opportunities for polymer electrolyte membrane (PEM) fuel cell cost reduction in both the near and long terms.

Question 2: Approach to performing the work

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

- This project is developing various diagnostics that can be used in manufacturing, including at least one diagnostic for all of the internal components (i.e., membrane, GDL, electrode, MEA). NREL is demonstrating the applicability of all these techniques on a manufacturing line speed. This work should be applicable to multiple types of manufacturers. They apply to PEMs and solid oxide fuel cells (SOFCs).
- The approach expounded upon appears to be rational. It would difficult to recommend an alternate approach that would demonstrate similar degrees of success.
- The approach is good, but this reviewer would like to see a broadening of the scope and/or future work to look at further facets of the manufacturing from assembly down to the catalyst level. Understanding these capabilities will give guidance to DOE where the gaps are and what the ultimate limits are in cost with manufacturing scale-up.

- The overall approach of this project has been good because it has had input from a variety of component manufacturers. Most common defects can be detected for the components of the MEA through the methods developed in this project. In addition, the segmented cell analysis can provide key information about the required manufacturing tolerances for these components, which will have a direct impact on cost.
- The approach is to develop and verify several diagnostic techniques that have the potential to be implemented in manufacturing lines. The potential cost savings for implementing any of the techniques is not addressed. An assessment of the minimum size defect that impacts performance needs to be determined. Testing with the segmented cell has shown that currently applied manufacturing tolerances of 2% of PTFE content are sufficient; a 4% difference did not affect cell performance. Similar analysis needs to be completed for the other diagnostics.
- The project's approach to the efforts are well thought out and planned and the effort is obtaining valuable direction from industry.

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

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

- NREL showed a web-line demonstration of optical and IR/DC diagnostics. The IR/RFT measurement appears to require significant work before it can be applied to a web-line.
- The progress on this project has been impressive to date. The detection level is excellent. This reviewer questioned what happens at higher speeds and what the maximum feed rate is, because there may be transient heat transfer issues.
- NREL has made excellent progress in systems for both coating quality and pin-hole detection.
- The results from this project so far are excellent. The optical and infrared diagnostics have been demonstrated at speeds and tolerances required for near-term component manufacturing. Significant progress has been made to improve the performance of the reactive flow-through technique. The initial segmented cell data are promising and should be helpful in determining the impact of defects both at the beginning of life and as the MEA ages.
- Reasonable progress is evident even with a budget reduction. The IR/DC diagnostic can be used to detect all scratches (up to 2 cm^2) and surface cuts (except those in the direction of motion) at line speeds up to 100 ft/min. In addition, invisible shorting defects were detected at speeds up to 30 ft/min. The IR/DC diagnostic appears to be the furthest along in development. An understanding of the detection limits needs to be developed and the minimum size defect that impacts performance needs to be established.
- Go/no-go decision metrics need to be established for the reactive flow technique, and the value of further work in the segmented cell needs better justification.
- NREL made good progress with the IR/DC diagnostic. Cuts and scratches in the direction of travel are problematic with this approach. Further characterization is needed for the IR/RFT approach to implement in-line.

Question 4: Collaboration and coordination with other institutions

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

- Materials from a number of sources have been used in the project.
- Because the presenter did not show any results from the LBNL modeling effort, it is hard to know how that effort is helping the project.
- The list of collaborators is impressive.
- It seems that NREL is tied in to many of the major players. This reviewer suggests that NREL also assess the potential impact on the assembly process and, at the other end, develop techniques to look at particle-size distribution for catalysts. The collaboration on this project appears to be very good, involving key players in both industry and academia.
- Industry collaborations are good, and industry input is used to guide the program in fruitful directions. It is not clear if the funding for specific partner studies is provided by the partners or if the results will be of benefit to the broader fuel cell community. The value that the funded partners bring to the project is not very clear.
- The project incorporates a number of useful collaborators from both industry and academia.

Question 5: Proposed future work

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

- Future work includes segmented cell studies, which are hard to justify in a manufacturing program. The PI stated that NREL will "perform aging studies to determine if failures develop at defect locations"; while the study may be interesting, it appears to be outside the "jurisdiction" of the Manufacturing sub-program.
- The proposed future work appears appropriate.
- The proposed future work appears to be focused in the right direction, but it lacks clarity. Additional details about other diagnostic techniques being considered would be helpful.
- The proposed future work plan lacks prioritization. It is unclear where limited resources can be best applied to achieve success for the most promising approaches. The work in the segmented cell needs much better justification before being carried forward.
- The project is incorporating further defect impact studies and cost-benefit analyses, which are essential for assessing the utility of various detection methods. Further detail regarding schedule and success metrics would be helpful.

Project strengths:

- The project's strength is seen in its accomplishments so far.
- The project's strength is its focus on developing diagnostics for high-speed manufacturing processes.
- NREL is making good progress in a number of defect detection and impact areas and is expanding into other fuel cell technologies (e.g., SOFCs).
- The project strengths include using commercially available hardware from other industries for this specific application, such as simple transient heat transfer techniques with high-speed thermal imaging. This reviewer expects that the feed speed will be limited by variability in the component thermal capacitance and thermal conductivity and that estimates of maximum feed speed might be possible by analyzing the acceptable variability of these properties as compared to the resolution limits of the IR camera response.
- This project has clearly demonstrated the viability of the in-line detection tools under commercial operating conditions. There has been excellent synergy between NREL and its industrial partners to develop methods to meet industry needs. The addition of the segmented cell technology may provide critical data about the impact of specific defects on the performance and durability of fuel cells.

Project weaknesses:

- It appears that the previously noted deficiencies have been resolved.
- The project's weakness is inherent in having an institution develop QC equipment for other companies while never being able to see the other companies' processes or be manufacturers themselves. Gap assessments are what is needed in judging technologies; for example, it is unclear if core-shell catalysts could ever be a manufacturable technology and, if so, at what cost.
- Although there has been great work done to demonstrate production speed, there has been no effort spent on examining production lengths. It is not clear if NREL could collect data on hundreds of meters of material and maintain accuracy and track defect locations effectively, or if there are other possible techniques that are already under consideration.
- Defects that do not cause an increase in temperature upon DC excitation will likely not be identifiable with this technique. The techniques have been developed and tested using induced defects. How these defects correlate with actual manufacturing defects is not clear.

Recommendations for additions/deletions to project scope:

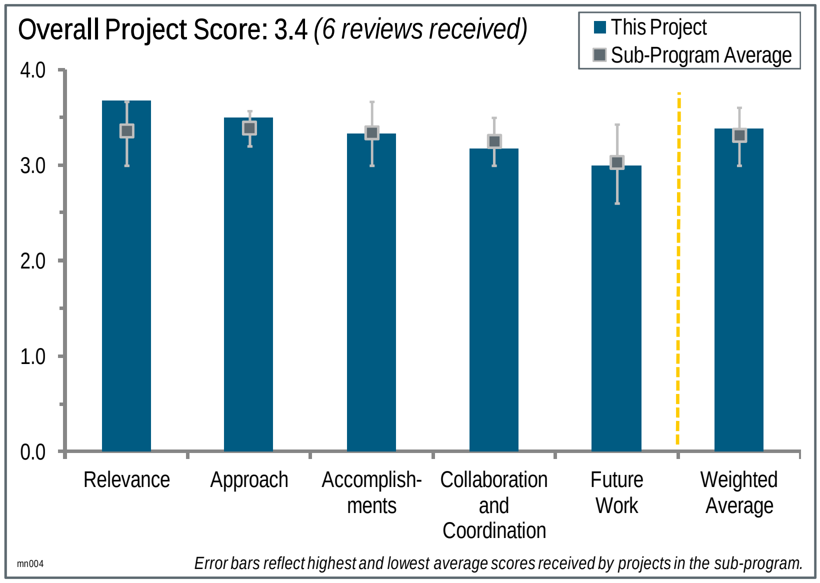
- This research should continue – it is nice work.
- Prioritize future work to account for the uncertainties in funding and to prepare to narrow the focus to the most promising approach.
- Segmented cell measurements can be a valuable tool for many purposes. However, for this project it seems to have limited applicability, as it could never be considered a manufacturing diagnostic. Aging studies using the

segmented cell should be deleted, because those studies are not part of a manufacturing study, and should be done under a durability program. This project should continue its development and feasibility assessments of in-line measurements for each of the components.

- Devising a system to do inspection of GDLs would be most helpful in determining caliber; uniformity of hydrophobic coatings and microporous layer coatings could be next possible interest areas. Some modeling of potential airborne defects and clean room requirements versus defect count and subsequent yield reduction might be nice to share with industry and those wanting to determine ultimate MEA cost.
- It would be helpful to understand how the location of the defect influences performance in the segmented cell. It may also be helpful to consider different flow-field geometries for segmented cell analysis. Some effort should be spent to determine if any of these tools could also be used for measuring the uniformity of critical component properties. There may also be some benefit to demonstrating some of the more developed techniques on an actual commercial production line. A prioritized list of defect types and sizes from each supplier may be helpful for coordinating the segmented cell analysis.

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 5-layer membrane electrode assemblies (MEAs) that minimize stack conditioning. Goals will be achieved through modeling and experimenting with different configurations, including reinforced, 3-layer MEA layering, 5-layer heat and water management, and exploring a new 3-layer MEA process layering of cathode, reinforced membrane, and anode layers.

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

This project was rated **3.7** for its relevance to DOE objectives.

- W.L. Gore (Gore) works to develop high-volume manufacturing for 5-layer MEAs relevant to automotive volumes.
- High-volume MEA and fuel cell stack manufacturing processes are critical to fuel cell affordability. Developing a direct coating process for the catalyst addresses a major cost driver in MEA manufacturing. Reducing the number and cost of coating passes will directly result in lower-cost MEAs. Minimizing stack condition time addresses a major fuel cell stack cost driver.
- The Gore project fully addresses one of the major challenges facing fuel cell commercialization, namely, cost. The process being developed by Gore is consistent with achieving the DOE cost target of $9/kW MEA in 2017.
- This project can support several DOE fuel cell research and development goals, but it is also a project with some risk.
- The development of a direct-coating fabrication process is essential to enabling the needed cost reductions, thus this project is a perfect fit.
- Reducing the cost of MEA production is an important function. The improvement has to be measured in terms of cost savings to the overall cost of the MEA, which would include materials costs and manufacturing costs. This reviewer questioned what percent of improvement is anticipated.

Question 2: Approach to performing the work

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

- The elimination of backer materials, reduction of coating passes, minimization of solvents, and direct coating of membrane are all excellent approaches. It would be nice for more information to be shared, for example on slide 6, such as the environmental control required, and the line speed that is possible and has been demonstrated.
- The principal investigator (PI) has approached this work in a systematic, logical manner with appropriate go/no-go criteria at key milestones. The approach to reduce MEA costs and optimize durability by examining mechanical durability/power density trade-offs of the 3-layer construction is a very sound approach. Modeling of

mechanical stress and heat/water management (University of Delaware [UD] and University of Tennessee, Knoxville [UTK]) are both important aspects to achieving success in addressing cost and durability barriers.
- The approach to reducing MEA costs is to reduce the cost of intermediate backer materials, reduce the number and cost of coating passes, minimize solvent use, and reduce conditioning time. Gore has proposed and tested a number of innovations in the manufacture of MEAs that show promise for achieving the project goals. Testing at UTC Power will offer an unbiased evaluation of the success of this approach. The utility and added value of the two modeling efforts are rather unclear. Lifetime modeling of MEAs manufactured with the new process would be of value if it could take manufacturing defects into account.
- The approach combines the MEA low-cost backing fabrication method and modeling of the MEA and 5-layer structures to meet the project goals. These three efforts do have the potential to, in combination, develop a new process for low-cost, durable MEAs and 5-layer structures, as well as reduce stack conditioning time, but it seems that the risks of producing prototypes that meet all the goals are high, and the risk is not assessed.
- The approach nicely combines optimization through modeling with experimental validation versus reference targets.
- The approach is reasonable; it builds and expands the traditional manufacturing method. There was no discussion of scrap rates associated with the different forms of manufacturing.

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

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

- This project shows progress in the performance of direct-coated cathodes. However, there is little information about the process; thus, the only project that benefits from the developments is Gore.
- The cost model indicates that a 25% reduction in MEA cost is achievable and results support that estimate. This is primarily due to eliminating the use of backer material—for both membrane and electrode coating—and reducing scrap. Four sub-processes were eliminated in 3-layer roll-good finishing operations, which will favorably impact cost-reduction efforts. The mechanical modeling effort by UD appears to be of utility to Gore in understanding the impacts of potential manufacturing process changes. UTK work also appears to be of utility to Gore (5-layer heat and water management modeling).
- Progress has been good. Gore's state-of-the-art 10-µ membrane has been incorporated into the primary process path. The performance of the new MEAs surpasses that of their current commercial membrane. Gore developed a process waste map that identified areas for reducing waste in the manufacturing process. Most of the improvements have been realized in the past year. Gore was forced to find additional backer material suppliers when the current supplier discontinued the incumbent product line. The team identified two low-cost candidates and successfully coated the most promising backer in a 30-cm-wide, high-speed-capable, roll-to-roll coating and drying process.
- While the modeling is almost 100% complete and looks promising, the experimental validation is still incomplete. The addition of the 10-µ membrane from Gore is a valuable addition.
- Gore's progress was obviously hampered by the material supplier issue; however, the company appears to have identified and validated an appropriate substitute. Progress by Gore's partners, UD and UTK, appears significant. Extension of the project timeline was appropriate as there is too much invested not to see the outcome of the project.
- This project showed a high dependence on modeling to predict properties. It is not clear what all the parameters input into the model would be. This reviewer questioned if this is an empirical mode. The approach appears to be yielding proper results.

Question 4: Collaboration and coordination with other institutions

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

- The project shows the modeling by UD and UTK, but there is no evidence that any of this is actually being applied to anything. To date, there has not been any stack testing shown by UTC Power.
- Both UD's and UTK's collaboration with Gore is positive. Both of these institutions will benefit from working with an MEA original equipment manufacturer such as Gore. Based on some of the questions posed to the PI, it does not appear that the models being developed by UD and UTK will be generic enough to be of utility to other

MEA suppliers. Working with the National Renewable Energy Laboratory (NREL) on in-line quality control provides good collaboration and coordination of results. Using UTC Power for stack testing demonstrates good collaboration.

- Collaboration with the project partners is good; their roles are detailed. It appears that the two modeling efforts are nearly complete from the schedule presented. It is not clear if the models will have utility for the larger fuel cell community. They appear to be specific to Gore.
- It appears that the three partners collaborating to date (Gore, UD, and UTK) are collaborating well and their contributions are very complementary and necessary for success.
- Gore has developed good quality collaborations and the project builds on the results of the inputs for the partners.

Question 5: Proposed future work

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

- Future work on the multilayer backer on a wide, high-speed, roll-to-roll is a good direction. There is a lack of integration of the other partners' work into the Gore work.
- Gore has executed this project in a logical and systematic manner with few disruptions caused by itself or its team. Gore describes a low-cost MEA scale-up process for its next step, which is a sign of a successful project to date. Future work discussion indicates a strong desire for Gore to implement the new processes proven in this effort on its production floor.
- The future work plan appears to be on track to reach the go/no-go decision point in August 2013, which is to achieve a high-volume cost of $9/kW. There is not much information presented on the break-in period and why it needs to be on the order of two hours. It is not clear if there is a path to eliminating the break-in period.
- The lion's share of the physical development remains for future work in the multiple steps involved in the low-cost MEA and gas diffusion media optimization and MEA conditioning (slides 19 and 20). The risks are likely high and their mitigation or alternatives are not evident in the future work statements.
- The program appears to be well structured and planned for the future.

Project strengths:

- Gore's developments look good for manufacturing.
- Elimination/reduction of backer material will realize significant cost savings in MEA production. Reduction in the number of coating passes will also reduce MEA costs. Durability of MEAs and stacks will be increased as a result of a better understanding of mechanical durability and power density trade-offs. UD and UTK are good partners for Gore in this effort, as are NREL and UTC Power (partners to a lesser degree). A 25% reduction of cost for a 3-layer MEA is impressive. The PI demonstrated strong leadership and focus throughout this effort and significant progress was achieved.
- The strength of the project remains Gore's experience and process knowledge.
- The strengths of this project are UD and UTK's modeling capability and Gore's ability to innovate in MEA processing and reinforced membranes.
- The relevance of the project makes it very important. The approach is well defined and the partners are appropriate. Incorporation of process control research, although not necessarily a defined project task but evident through collaboration with NREL, should increase the value of the final deliverables.
- The most important program strengths are the experience and database of Gore.

Project weaknesses:

- It is unclear how the UTK modeling effort relates to the rest of the project, and how this portion of the project is relevant to a manufacturing project. Similarly, the UD modeling does not seem to apply to a manufacturing project. At one point, the presenter mentioned a four-hour break-in as a target. That seems exceedingly long for transportation applications. The target should be substantially less than that.
- Results are not likely to have technology transfer beyond Gore.
- The project's weakness is its risk assessments.

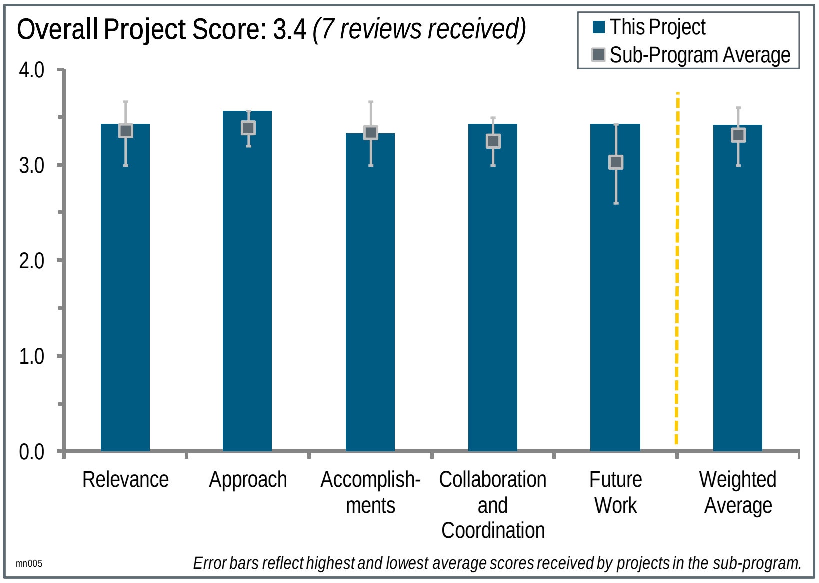
- The empirical results used in the modeling make the models dedicated to Gore and not beneficial to other MEA manufacturers.

Recommendations for additions/deletions to project scope:

- Apply the modeling effort to new materials and provide enough information so that other projects benefit by the knowledge produced by this project.
- Expand the model work to include other MEA manufacturers' databases.
- At the end of the project, Gore should project when these 3-layer MEAs will enter their product line.
- One reviewer felt this was a great project and had no recommendations.

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

Dan Walczyk; 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 (160°C–180°C) polymer electrolyte membrane (PEM) membrane electrode assemblies (MEAs) by: (1) significantly reducing MEA pressing cycle time through the development of novel, robust ultrasonic bonding processes for high-temperature (160°C–180°C) and low-temperature (<100°C) PEM MEAs; and (2) achieving greater manufacturing uniformity and performance through (a) an investigation into the causes of excessive variation in ultrasonically and thermally bonded high-temperature MEAs using more diagnostics applied during the entire fabrication and cell build process and (b) development of rapid, yet simple, quality control measurement techniques for use by industry.

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

This project was rated **3.4** for its relevance to DOE objectives.

- This work is right on target with what the DOE Manufacturing sub-program should be sponsoring.
- This project is important and addresses important aspects of increasing the production rate for MEAs.
- This project conforms to the overall objectives of the DOE Fuel Cell Technologies Program (FCT Program). If successful, this project could drop the bonding time of the electrodes by an order of magnitude while increasing the yield and reducing tooling costs.
- This project addresses high-volume manufacturing and quality control for the manufacture of phosphoric-acid imbibed polybenzimidazole-type MEAs.
- Automation is a key to cost reduction, as is adaptive manufacturing. This effort is relevant to DOE objectives. A cost model for scale production needs to accompany this work to ensure that a business case is demonstrated, and Rensselaer Polytechnic Institute (RPI) and its team ensured that a cost model and design guidelines are included. Ultrasonic sealing is a less energy-intensive and faster process that can give equal or better performance to thermal pressing. It is very relevant to DOE objectives to look at MEA manufacturing using ultrasonic sealing for both energy reduction and cost reduction purposes.
- Ultrasonic bonding for MEA fabrication has the potential to reduce MEA manufacturing costs. It is not yet certain if this will lead to the improvement of quality and performance.
- This project needs to prove the cost savings.

Question 2: Approach to performing the work

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

- The project has a well-thought-out plan, incorporating elements of experimental design, testing, and cost analyses.

- This project has a strong creative approach. RPI is a national leader in developing a unique manufacturing methodology for fuel cell systems.
- Comparing different bonding technologies and understanding the structure differences could be valuable to different types of electrode manufacturing. Just from a time restriction, the project should concentrate on ultrasonic bonding, not thermal bonding.
- The technical approach follows a logical and systematic path with go/no-gos placed at appropriate program milestones. Ultrasonic sealing was not only applied to high-temperature PEM MEAs, but also low-temperature MEAs, where much of the PEM manufacturing currently exists. The principal investigator's (PI's) problem statement spoke about the mismatch between variances in MEA components and only a standard MEA manufacturing process—and the need to better understand their interrelationship. There does not appear to have been a lot of work in this area, as it is mostly consumed with the ultrasonic sealing novel process. This effort has a well-designed experimental approach. Teaming with BASF is a real plus because it maximizes the opportunity for technology transfer. Having Ballard on the team is also a plus. The royalty-free license for the RPI work allows for further dissemination to other MEA manufacturers.
- The detailed program approach appears to be sound and well thought out. Scale up to a commercial-size platform and use in a field application when both thermally and ultrasonically bonded MEAs are operating in the same stack and are being exposed to the exact same semi-controlled field conditions seems to be missing from the plan.

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

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

- Progress has been great and the potential savings are outstanding.
- Voltammetry does not seem like a reasonable manufacturing quality control test. It is unclear why the different processing methods would affect the platinum particle size.
- There is limited use of diagnostics that give a good indication of how the manufacturing process works. Scanning electron microscopy cross-sections, radiography, or X-ray tomography could all add value to this project.
- The project accomplished what it set out to do: demonstrate the viability of ultrasonic sealing of MEAs compared to existing thermal processes.
- RPI saw little value in continuing with adaptive process controls; the company took the initiative to contact DOE and request that the remaining effort be solely focused on ultrasonic sealing.
- The business case via cost model will inform industry adopters of this technology and help them make an informed decision. A design guide for ultrasonic testing is an important "leave behind" that RPI is undertaking.
- Significant energy reduction, cycle time, and sealing time reductions were demonstrated compared to conventional process.
- The progress reported, including the quality assurance checks, is impressive. It is not clear if there is work to resolve the cause of the performance difference between the thermally bonded and ultrasonically bonded MEAs. It was also unclear if a hydrogen (H_2) pump wasvrun on both types of MEAs and a new calibration curve generated, which would bridge the performance gap.
- There has been reasonable progress in testing and validating ultrasonically bonded MEAs. Further work is required to resolve influences due to bipolar plates in testing, as well as characterization of mass transport performance deficiencies. Cost results should be expressed relative to total MEA and/or stack cost. Cost analyses for lower production volumes would be nice to see.
- RPI has improved the rate of production by 15-fold. The researchers are conducting analyses to prove production without defects, i.e., quality control. They are testing stacks to prove their system performance. They are also looking at low-temperature PEM MEAs; the approach there was good, but low-temperature MEA are not optimized for ultrasonic bonding. This work is demonstrating a cost reduction for ultrasonic sealing.
- This reviewer wondered the rate is when the system is scaled up.

Question 4: Collaboration and coordination with other institutions

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

- The collaboration appears to be appropriate for this type of project.

- Participation and contribution from industry partners has been useful and coordinated.
- This project has proper representation from all possible players, which is a nice balance.
- This project has a good collaboration team that covers the breadth of high-temperature to low-temperature PEM fuel cells and is working with a quality control group.
- There is good collaboration between BASF and RPI. It is unclear what the National Renewable Energy Laboratory (NREL) and Ballard have provided.
- The royalty-free license will maximize collaboration and coordination with other MEA original equipment manufacturers.
- The RPI Center for Automation Technologies and Systems program has a short but strong history of technology transfer, including the nanotechnology and integrated circuit manufacturing areas.
- Other collaborators such as NREL, UltraCell, Ballard, PMD Manufacturing, and Arizona State University make information dissemination more likely.
- Coordinating with DOE on the need to focus remaining resources more on ultrasonic testing was positive.
- It was not clear how much the results address BASF-only processes and whether or not they might be transferrable to other MEA suppliers, especially for low-temperature PEM fuel cells.

Question 5: Proposed future work

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

- The proposed follow-on work is appropriate. A little more specification on the steps would have been nice.
- Future work efforts are appropriate and will hopefully address some anomalies that have arisen in validation testing.
- The use of diagnostics and thermal characterization could be valuable in understanding the manufacturing differences. This project should concentrate more on this aspect rather than the 10-cell stack testing. Diagnostics during the MEA build process could also be valuable.
- More testing is critical to informing both the cost model and the design guidelines. RPI will address the issue with larger MEA (140 cm^2) problems before this project is over.
- Design guidelines for ultrasonic testing will be very valuable for further demonstration of this technology by other entities, as well as the BASF production facility.
- The path forward seems logical, but the project is 85% complete and with only four months remaining, it may be tight to fit everything in. If additional funding was needed and could be provided to ensure completion, then this reviewer recommends that DOE continue support. This is especially important because the low-temperature application looks promising, but further research needs to be done to investigate and potentially develop a plan to mitigate, if possible, the performance degradation at higher current densities.
- W.L. Gore needs to predict the production rate and number of production lines required to make a 40 MW fuel cell power station.

Project strengths:

- The strengths are the knowledge and dedication of the project members.
- The effort is well designed and executed, and it is generally making good progress.
- The project has been well coordinated and executed, and all partners are actively engaged. The accomplishments have been outstanding and the payback potential appears huge.
- This project has improved its approach to bonding of MEAs. The methodology appears specific to membrane fuel cell systems.
- The project's strength is its design of the experiments in making a sound comparison between thermal and ultrasonic testing. The project also has a good team established to include RPI as lead, BASF (the MEA manufacturer), Ballard (the stack manufacturer), UltraCell (the system manufacturer), and NREL.
- The project team did not try to do too many things and just focused on a comprehensive evaluation of ultrasonic sealing versus thermal sealing and producing comprehensive results.
- RPI demonstrated agility in seeking to reduce the adaptive process controls thrust and to increase the ultrasonic thrust.

Project weaknesses:

- The performance of these MEAs is low; much lower than typical H_2 MEAs. To be competitive with other types of MEAs supported in the FCT Program, the electrode layer cost must be significantly lower; however, it is the opposite. It is unclear why, at this point in time with this technology, this work is addressing the high-volume manufacturing of these MEAs, as opposed to increasing the performance and reducing the electrode cost so that they are cost competitive. The performance of the low-temperature MEAs is well below the standard MEAs that are commercially available. There are many other presentations at the DOE Hydrogen and Fuel Cells Program Annual Merit Review, for example. This performance needs to be brought to competitive standards before the manufacturing technique optimization can be considered valuable.
- This project is somewhat limited in scope. For example, commenting on reducing from 30 seconds to 3 seconds part of the MEA manufacturing process, the PI states that the “dominance of heat treatment may diminish the importance of the ultrasonic method.”
- No major weaknesses, with the possible exception of the suggested future work, were noted. The perceived weaknesses can be easily corrected by the project members.
- Cost impacts need to be expressed at a level higher than the specific process.
- The project’s weakness is that, compared to phosphoric acid fuel cells (PAFCs), the MEA production rate would yield the same data, because PAFCs are not based on membrane design.

Recommendations for additions/deletions to project scope:

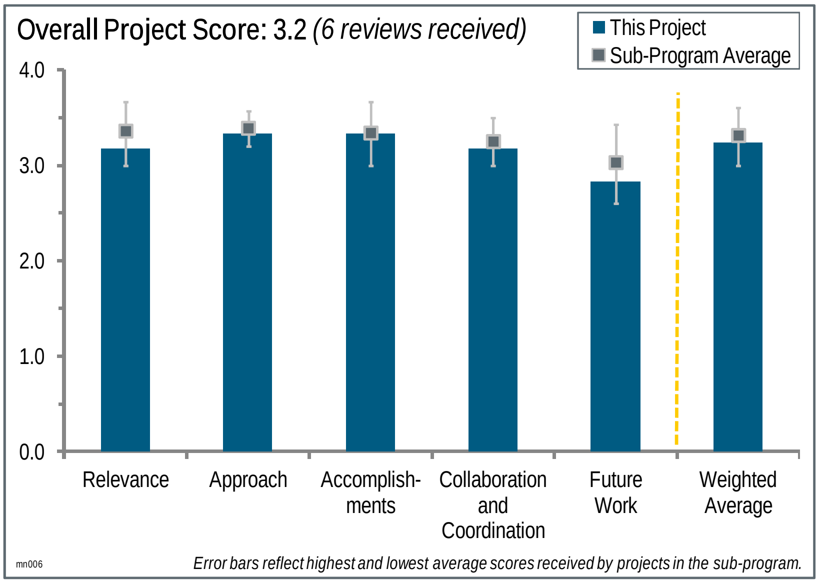
- This reviewer suggests publishing the costing data referred to by the presenter.
- The project is the cart-before-the-horse; these MEAs are not close to being competitive with Nafion®-based MEAs, thus until the performance/cost is improved, improving the manufacturing of these MEAs will show limited benefit to the FCT Program.
- The DOE Hydrogen and Fuel Cells Program should be funding improved MEA designs with reduced electrode loadings before it funds improved manufacturing of the technology.
- Only a small portion of this project deals with low-temperature MEAs. That portion should become the main emphasis of the project.
- Thermal bonding of MEAs taking 30 seconds should be eliminated from the project.

Project # MN-006: Metrology for Fuel Cell Manufacturing

Eric Stanfield; National Institute of Standards and Technology

Brief Summary of Project:

The objectives of this project are to: (1) identify and evaluate the capability and uncertainty of commercially available non-contact, high-speed scanning technologies for applicability to bipolar plate manufacturing process control, and (2) develop, demonstrate, and optimize the system's ability to measure thickness and variation-in-thickness, which can then be used to assess stack parallelism.



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

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

- The non-contact dimension sensor and the scatterometry measurement systems can be very important in reducing manufacturing costs and enabling improved quality for both bipolar separators and catalyzed membrane electrode assemblies (MEAs).
- The goal of this project is to provide bipolar plate manufacturers and designers with the data necessary to make informed tolerance decisions to enable reduction of fabrication costs. This clearly is relevant to DOE objectives. Additionally, the fact that the National Institute of Standards and Technology (NIST) has adjusted the objective based on future industry input supports the relevance and the ongoing efforts to support industry. The fact that Ballard, FuelCell Energy, and UTC Power are interested in these technologies further validates its relevance.
- The objective of one of the projects is to provide bipolar plate manufacturers with a high-speed, automated approach for process control dimensional inspection. The other project is focused on an automated high-throughput process inspection of platinum (Pt) loading. Both topics are very relevant to DOE's efforts to bring fuel cell technology one step closer to widespread adoption by lowering the cost of manufacturing through better process control.
- Both aspects of this project do not adequately characterize how advances made in the effort could support reaching DOE objectives.
- The methodology fits well into establishing quality control (QC) data. The project does not appear to be applied to an existing bipolar plate manufacturing process, so it is not clear if this will or can be applied to continuous production technology.

Question 2: Approach to performing the work

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

- It is difficult to identify a better prepared and higher skilled awardee than NIST to execute this project.
- The approach to generating this database 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, NIST will quantify the performance effects, if any, and correlate these results into required dimensional fabrication tolerance levels. This is a sound engineering approach.

- The approach with bipolar plates (P2 project) is to identify suitable non-contact measurement technologies with 12–50 µ resolution and demonstrate the ability to measure plate thickness to enable overall fuel cell stack parallelism to be assessed during manufacture. Having the capability for a high-speed measurement system will be important eventually for high-volume manufacture; this capability is not currently available commercially. It is not so critical now, when fuel cells are manufactured at low rates.
- The objective of the P3 subproject is to evaluate the optical scatterfield metrology tool's sensitivity to Pt and Pt alloy catalyst loading and various defects such as pinholes that can be characterized by other methods such as x-ray fluorescence and scanning electron microscopy. Successful development would provide MEA manufacturers with an automated, high-throughput technique for determining Pt loading with greater sensitivity (0.01 mg/cm^2) than currently available.
- The approach is simple in that it includes the steps that are typically necessary to alter or design new optical metrology methods that, in this project, overcome barriers in MEA and separator surface measurement speed and accuracy. NIST still needs to manage large sets of raw two-dimensional data and to develop routines for analysis.
- The non-contact plate sensor approach is adequate for validating the sensor technology. It is not clear how a validated technology improves stack cost or performance. The approach for the optical scatterfield portion of the project is not adequately explained. This reviewer is left to try to infer it from the accomplishments.
- This project's approach to obtaining measurements is outstanding; however, the approach to integrate with existing manufacturing production line is poor.

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

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

- NIST delivered another year of outstanding progress and accomplishments. This reviewer had high expectations for NIST and felt that they delivered at that level of expectation.
- The accomplishments for the P2 project are reasonable, given the small amount of funding. NIST demonstrated a dual opposed-probe configuration to measure thickness and variation in thickness with less than 10 µ accuracy. Error in measurement is currently being evaluated.
- The optical properties of Perylene from 3M were determined to provide model parameters that enable a realistic scattering model for the 3M nanostructured thin film (NSTF) catalyst coated membrane (CCM) to be developed. Preliminary simulations for quantifying the effect of roughness on CCM scatterfield measurements were completed, but conclusions are still being determined. The optical design of a large aperture system prototype for fuel cell Pt loading measurements was completed.
- The opposed probe for plate thickness and profiling builds on the earlier accomplishments of the single-sided probe, and progresses toward a complete high-speed dimension metrology system for bipolar plates.
- The plate thickness measurement effort is showing useful results. It is not clear how important calibration (both initial and continuing) is relative to producing consistent measurements. More detail regarding the utility of the approach with increasing line speeds would be helpful.
- The scatterfield metrology effort shows lots of results, but it is not yet clear how the results will lead to improved QC and reduced component cost. It is also not clear how scatterfield metrology can be transitioned to an industrial environment.
- The accomplishments are very good. NIST has demonstrated the performance of the QC method and has developed the interest of industry. Good progress is being made in the measurement of electrode surfaces using ellipsometry.
- The accomplishments to date are appropriate for the effort. The results appear to be outstanding.

Question 4: Collaboration and coordination with other institutions

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

- Collaborations with a number of plate manufacturers are leading project P2 in fruitful directions. W.L. Gore (Gore) and 3M are interested collaborators on the P3 project and provide samples of material sets for development of the scatterfield technology. Discussions are underway with a leading semiconductor toolmaker for future collaborations to prototype the scatterometry tool. NIST is collaborating with Los Alamos National

Laboratory (LANL) to provide an optical technique capable of nanoscale materials characterization based on scatterfield technology.
- This project demonstrates an interaction with LANL, 3M, and Gore, but this reviewer is unsure of the degree or quality of interaction or contribution. Certainly the future work with industrial collaborators' membranes and MEAs is important. Working with Treadstone on the metal plate metrology will provide a realistic basis with industry for the bipolar plate manufacturing.
- The plate thickness measurement effort collaboration seems to largely consist of samples provided by a few companies. While there are a few current collaborators for the scatterfield metrology effort, others are tentative or even speculative (proposed work participants).
- NIST has identified companies with interest and companies that they are submitting proposals with, but they have not directly applied the technology to an existing production or pilot plant production facility.
- The collaboration and coordination is appropriate and appears to be growing.
- This work displays extensive collaboration with industry leaders in materials.

Question 5: Proposed future work

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

- According to the schedule, the project is nearly complete. It is not clear just how far the two projects can proceed with the available funding. Proving the usefulness of these techniques in actual practice will likely require additional resources. The research team should consider partnering with the National Renewable Energy Laboratory.
- The main project will be bringing the opposed probe thickness and profile device to a practical reality by optimizing its accuracy. This builds on the progress made on the single probe system.
- The sub-project future work plan can progress to building a prototype set of instruments for MEA and membrane measurements of surface and catalyzation. This may be a large increment from the current project status and difficult to achieve. If achieved, however, it will result in a valuable tool set for manufacturing metrology.
- Future work efforts identified are appropriate for further validation of the technologies. It does not appear that there is enough time or budget remaining to complete the identified future work. The work is lacking any assessment of the usefulness relative to quality improvements or cost reductions.
- The proposed improvements and understanding of the QC technology are very good to outstanding. However, it is a concern that the two techniques discussed have not been integrated with a fabrication line.
- One reviewer felt that the proposed new work appears appropriate.

Project strengths:

- The highly qualified and experienced team at NIST is successfully collaborating with numerous organizations to prove the viability of the two approaches. It provides manufacturers with established processes and procedures for determining measurement standards.
- The researchers are very competent and have a strong knowledge base.
- The project's strength is its analytical approach.

Project weaknesses:

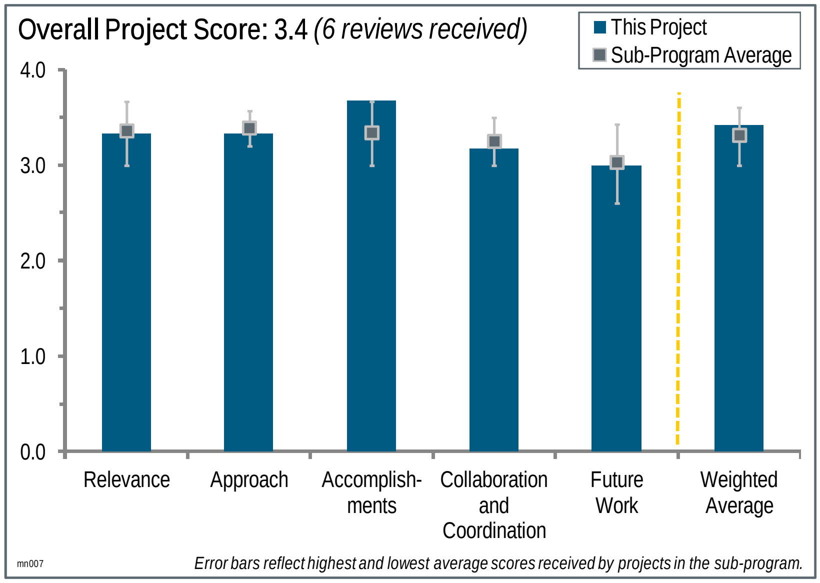
- A rigorous comparison of techniques in commercial practice with those being developed by NIST is missing. This comparison could provide stronger justification for developing these measurement techniques and for determining the impact on manufacturing cost savings if they are successfully implemented in practice.
- This project remains too focused on things one could do and not focused on whether one should do them.
- A stronger partnership with a fabricator is needed.

Recommendations for additions/deletions to project scope:

- Continue the excellent work.

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), especially for 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 obtain a threefold throughput increase on full width and length cloth, and to expand efforts on non-woven paper.

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

This project was rated **3.3** for its relevance to DOE objectives.

- This project is an integral contributor to the success and viability of high-temperature polymer electrolyte membrane (PEM) technology.
- This project focuses on reducing the fabrication costs of GDEs for high-temperature PEM applications, which is relevant to the DOE objectives in the manufacturing session.
- The project's objectives are well rounded and directly support the Fuel Cell Technologies (FCT) Program and its objectives related to membrane electrode assembly (MEA) cost reduction and quality improvement.
- Cost reduction is critical and relevant to the development of this technology. This reviewer questions what portion of the cost is platinum (Pt) and if it is more important to reduce this cost.
- This project clearly meets the DOE objectives for lower-cost, higher-performing components.
- BASF works to improve manufacturing and quality of GDEs for CHP.

Question 2: Approach to performing the work

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

- One reviewere felt that GDEs have a limited role in the FCT Program, with few developers working on them, and few developers working on polybenzimidazole (PBI)/phosphoric acid.
- The in-line QC/in-line Pt measurements are good advances.
- The overall approach of this project is solid, focusing on increasing throughput by improving line speed and reducing the required number of coating passes.
- The work approach incorporates aspects of modeling, experimental design, and testing in a clearly described work flow with decision points.
- The approach is given in very broad terms -- a stronger discussion with more details would have been preferred. If a catalyst cannot be directly applied to the membrane, then attachment to the gas diffusion layer (GDL) approach is logical. It is not clear why BASF needs a microporous layer (MPL) and how a three-dimensional catalyst layer would be connected to the electrolyte. This needs further discussion.
- The approach is well thought out and methodical. This is as expected, based on the principal investigator.

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

This project was rated **3.7** for its accomplishments and progress.

- This project has demonstrated a decrease in manufacturing time and identified various problems with catalyst inks that have been solved to increase the manufacturing rate.
- This project provides potential for substantive cost savings in labor and Pt loading.
- There was a significant amount of progress in this project compared to last year. A fourfold increase in throughput rate, an order of magnitude reduction in defects, and a fivefold reduction in variation of Pt loading are very impressive accomplishments. There was a 75% cost reduction attributed to reducing labor hours, which is a significant achievement for this project as well.
- BASF has achieved appreciable increases in process capacity while maintaining performance. The labor savings identified were significant but should be characterized as a function of stack cost.
- BASF has shown an improvement in throughput. The production rates should reflect these improvements. It is unclear what the cost benefit for this improvement is and why the team needs an MPL for a non-woven material. This reviewer also wondered if the MPL is carbon or graphite.
- The progress and accomplishments are impressive. The learnings to date, if only applied to older processes, would still warrant the expenditures.

Question 4: Collaboration and coordination with other institutions

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

- The collaborations and coordination with other investigators are limited, as should be expected based on the proprietary nature of some of the initial processes being evolved.
- ClearEdge Power and the National Renewable Energy Laboratory (NREL) are strong additions, and it appears that there is a good amount of collaboration on this project.
- The two collaborators appear to be reasonably engaged and coordinated.
- This project is working with two good organizations: NREL and ClearEdge Power.
- BASF is providing GDEs to NREL for their project. ClearEdge Power is validating the materials.

Question 5: Proposed future work

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

- Work on the non-woven back is a step in a positive direction, and woven materials are not being considered by most original equipment manufacturers.
- Developing a one/two pass application process will be the most likely candidate for commercialization.
- The future work appears appropriate, as far as it goes. It would be hoped that the new materials would be subjected to field trials and benchmarked against current product lines for performance and durability.
- The proposed future work appears solid, but is not well defined. It is unclear what is considered “production level”; what the plan is for achieving two or fewer passes for both anode and cathode GDEs; what risks are involved with these targets; and how these risks are being addressed.
- One task remains and the future work is adequately defined. Further detail regarding schedule would be helpful.
- It is not clear if a 30% reduction in material and labor is a significant number. This sounds like a good objective, but it needs some justification.

Project strengths:

- There has been very significant progress made in increasing throughput and reducing fabrication costs in this project. Additional improvements in quality should help further reduce the total cost of the GDE.
- The strengths are the knowledge, technical capabilities, and dedication of the project members.
- This is a well-conceived and -executed project that is exceeding its objectives.
- The project’s strength is its very experienced group.

Project weaknesses:

- The project has limited applicability for other programs and manufacturers. There are few developers of PBI/phosphoric acid fuel cells and few developers using GDE technology. Thus, this project is mostly only applicable to one company.
- The path forward lacks clarity and there is no reference to how close the throughput rate is to being ready for commercial production. Additional information about the cost savings due to improved product uniformity would also be helpful in assessing this project.
- It is not clear if the team fully understands the impact of carbon corrosion on their electrodes. Manufacturing may be improved, but the stability of the system may not be improved.

Recommendations for additions/deletions to project scope:

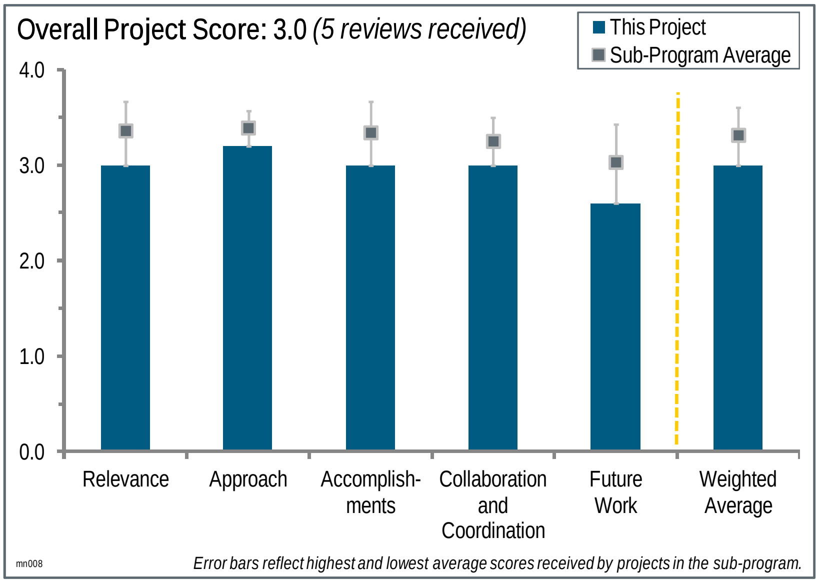
- The project seems to be on the right track and does not require any major changes to the overall scope. It may be helpful to have more clearly defined goals for the next portion of the project, however.
- The project should require durability testing of the new catalyst layers.
- Continue the good work.

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 objective of this project is to manufacture Type IV hydrogen (H_2) storage pressure vessels utilizing a new hybrid process with the following features: (1) optimized elements of advanced fiber placement (AFP) and commercial filament winding (FW) and (2) improved understanding of polymer liner H_2 degradation. The project will develop a manufacturing process with lower composite material usage, lower cost fiber, and higher manufacturing efficiency.



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

This project was rated **3.0** for its relevance to DOE objectives.

- Quantum is developing new hybrid Type IV H_2 storage tanks, which require less carbon fiber (CF) than conventional filament wound pressure vessels. The work is relevant to DOE's goal of reducing the cost of onboard H_2 storage systems. The project aims to improve understanding of the compatibility of H_2 with Type IV high-density polyethylene (HDPE) liner through testing in a 4,000 psi H_2 environment (tests done by Pacific Northwest National Laboratory [PNNL]).
- This continuing project addresses improved design and manufacturing methods for high-pressure compressed H_2 gas storage vessels. While proposed modifications are predicted to give an approximate 22% reduction in the baseline tank weight for Type IV tanks, any cost savings seem to be minimal (approximately 5%, at best) and there is virtually no positive impact on volumetric capacities of these vessels. This effort is to include characterization of the polymer liners with high-pressure H_2 gas, including permeation and degradation effects.
- This project addresses the key issues of cost and weight of H_2 pressure vessel storage for vehicles. This can add leverage to high-pressure storage as an early enabler to fuel cell electric vehicle penetration.
- Developing innovative manufacturing techniques for forming tanks will be very useful for improving H_2 storage systems. Fibers with windings, lower-cost materials, and higher manufacturing efficiency are all important. However, because it appears that most of the cost savings comes from fiber cost reductions, it is unclear if the rest of the effort is worth all the expense for the rest of the project.
- The research goals as pursued directly address DOE Hydrogen and Fuel Cells Program goals. However, while the work performed is excellent and meets the objectives stated in the presentation, it did not specifically target issues with conformal vessels. However, this reviewer believes the work as performed should come before more advanced studies on conformal vessels.

Question 2: Approach to performing the work

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

- The hybrid AFP/FW scheme reduces total CF usage by as much as 22% as compared to FP alone. Additional incremental cost reduction is achieved by using lower-cost fiber on the outer layers of the AFP/FW tank. While the combined 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 the DOE cost target. The cost reduction is not in direct proportion to

reduction in CF usage because of the higher cost associated with AFP manufacturing. In situ testing is carried out at PNNL to characterize H_2 compatibility with the HDPE liner.
- This project displays a well-organized, mixed approach to relevant challenges for H_2 storage.
- The Quantum/Boeing team would reduce the cost of Type IV tanks by optimizing CF placement and the winding process to minimize the amount of expensive high-strength CF, while maintaining strength to pass performance requirements. PNNL was to characterize candidate polymer liner materials for H_2 compatibility better, but it was not clear whether improved options would be found.
- The approach is clever and straightforward. While the elements of the approach are excellent, an argument should be provided that makes it clear that more testing to improve statistics is not needed.
- Most of the effort is focused on developing techniques to integrate less expensive fibers with hybrid tanks. The efforts are appropriate.

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

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

- In collaboration with Boeing, this project has built and tested several additional vessels to validate the hybrid AFP/FW design for Type IV pressure vessels. In addition to burst tests, cycling tests were conducted (vessels 8 to 11 were presented at the DOE Hydrogen and Fuel Cells Program Annual Merit Review, but not included in the submitted slides).
- Improvement was made to reduce marcelling and wrinkling in end dome plies and reduce peak stress at the AFP/FW interface.
- PNNL tested the compatibility of polymer liners with H_2 at 4,000 psi. Initial sample results showed a decrease in liner modulus under high H_2 pressure.
- Issues with analysis software for designing tank configurations led to tanks rupturing at pressures just below the requirement level when CF contents were decreased. The project team has not yet demonstrated a prototype type vessel that would pass pressure tests. Boeing implemented IR heating during the fiber wrapping process that produced improved vessels, although not all problems with wrinkling of fibers were addressed or resolved. It looks like more processing refinements are still needed. Only limited data were obtained at PNNL on the H_2 compatibility of HDPE polymer liner materials, and it looks as though this effort has been de-scoped from the project.
- The reduced marcelling and reduced CF use, combined with IR heating, all contribute toward DOE cost and weight goals. The cycle and burst testing helped in indicating realistic progress, but this is initial testing.
- A lot of work has been performed with hybrid vessel integration with lower-cost fibers, testing, modeling, and process development, which points to meeting the goals.

Question 4: Collaboration and coordination with other institutions

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

- It appears that interactions between Quantum and Boeing have led to modest improvements in the quality of the wrapped fibers and tank walls, although the vessels still do not satisfy safety requirements. Efforts were made to adapt manufacturing processing with designs. It is not clear how PNNL’s work on polymer liners correlated with the other team members, and there does not seem to have been other significant roles played by PNNL.
- This project displays great collaboration with Boeing and PNNL, which leverages the capabilities of each partner.
- All three organizations mesh well in this project. This project displays good collaboration and coordination, playing on the team’s strengths.
- This project has strong collaboration with Boeing and PNNL.
- The team consists of industry players whose strengths appear complementary.

Question 5: Proposed future work

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

- The project is ending in March 2013, and the proposed future work is proper to wrap up this project. Testing to national standards is a prerequisite to meeting U.S. Department of Transportation and Society of Automotive Engineers standards. Cyclic tests to collect fatigue data for T700 CF will be a valuable addition to the database for use by modelers as well as tank manufacturers.
- A complete cost analysis of the hybrid vessel designs is within the scope of this project.
- The next step seems to be improving the finite element computer modeling to yield better designs needing less CF to meet mechanical requirements that will be checked by pressure and burst testing. The project is unlikely to improve either mass or volume properties substantially, and even an approximate 20%–25% reduction in costs will not allow these Type IV tanks to meet the cost targets. Significant cost saving can only come from using very inexpensive and high-strength alternative materials that are outside of the current scope of this project.
- Continued production of vessels with a hybrid of carbon and lower-cost fibers, followed by cycle and burst testing, is a major element in the future plans and is critical. The continued, incremental manufacturing improvements in things such as tensioner controls will also help in cost reductions.
- The proposed future work to upgrade in-house computer models and to design and build vessels with baseline and low-cost fibers on hybrid is reasonable.
- Elements of the proposed work are good. However, the comment about increasing the statistical sample should be considered.

Project strengths:

- The project's strengths are (1) its substantial experience in Type IV tanks and CF winding, (2) the fact that the company is one of leading manufacturers of Type IV tanks for commercial application, and (3) leveraging advanced proprietary technology from Boeing to advance the project goal.
- A coordinated effort between commercial Type IV storage vessel manufacturers and an aerospace technology company with expertise in CF manufacturing offers the possibility for developing less-expensive compressed gas H_2 storage systems.
- The effort is using a lot of existing capabilities to optimize H_2 storage tanks with lower-cost fibers. It appears the project should be able to meet the goals.
- The project's strengths are that it is well organized, makes continuous progress, and has a complementary team of partners.
- The concept that the approach addresses is an excellent one.

Project weaknesses:

- This reviewer wonders whether sufficient test articles were fielded to provide an adequate number of samples to achieve statistical significance. Vessel burst test results were compared to modeling and a limited number of vessels whose construction was not identical. Construction was changed during testing in an attempt to address an apparent weakness. This sort of approach suggests that there is a risk of not establishing a good baseline. During the question and answer period, several questions touched on this issue, but the presenter was confident that the modeling was sufficiently accurate to back the experimental results. However, it should be noted that in one case a need was felt to improve the model.
- Even though the team may be able to optimize fabrication processing using their stated approach, it cannot overcome the cost issues with conventional high-strength CF. Any improvement in manufacturing will still have only limited benefits. There was no follow through on the polymer line characterizations or alternative materials being assessed.
- It would be more interesting to see such large efforts be used to identify potential routes that could substantially improve tanks and reduce costs associated with tank design and manufacturing, rather than relying on decreasing fiber costs as the main way to decrease costs.
- While a 10% cost reduction is welcoming, it is unlikely that more significant cost reduction (30%–50%) can be achieved with the hybrid designs and utilization of lower-cost fiber for outer layers.

Recommendations for additions/deletions to project scope:

- Quantum should document and show more clearly the rupture regions of pressure-tested tanks, determine whether failures are due to design inadequacies or manufacturing issues, and clarify whether there will be any additional assessments of the polymer liner materials.
- Consider conducting a modeling effort that considers, among other things, the diffusivity, solubility, and permeability of H_2 in polymers to guide efforts on polymer liners.
- The project should focus on designs and processes that could substantially reduce costs.
- All the data collected during the life of this project should be published or made available to DOE.