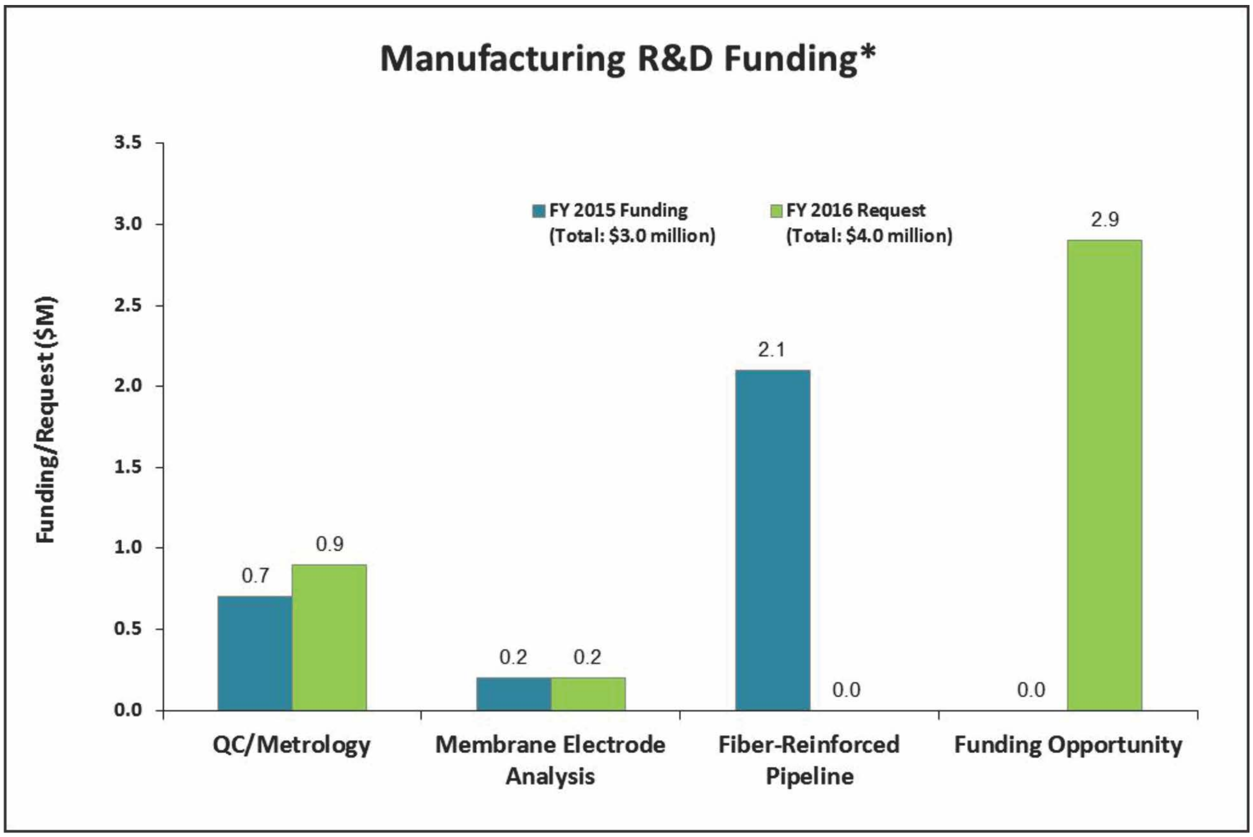
2015 — Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

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

The sub-program is addressing the broad problems and barriers facing the U.S. Department of Energy's Hydrogen and Fuel Cells Program (the Program), and these barriers are well matched to the needs of the industrial sector. According to reviewers, the objectives of the Manufacturing R&D sub-program were clearly presented and prior successes were described. Furthermore, reviewers stated that the sub-program is well managed and effective at addressing these barriers. The reviewers found that the sub-program has done a good job of engaging appropriate stakeholders and collaborating with them effectively. In fiscal year (FY) 2015, one manufacturing project, which addresses fuel cell stack in-line testing, was reviewed.

Manufacturing R&D Funding:

Funding for the Manufacturing R&D sub-program was $3 million for FY 2015, and $4 million was requested for FY 2016. FY 2015 funding includes a continuation of existing Manufacturing R&D sub-program projects for quality control (QC)/metrology and membrane electrode analysis, as well as fiber-reinforced pipeline projects from the FY 2015 funding opportunity. The FY 2016 request-level funding will continue existing Manufacturing R&D sub-program projects for QC/metrology and membrane electrode analysis, as well as provide funding for new projects through a competitive funding opportunity announcement, subject to appropriations.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

Majority of Reviewer Comments and Recommendations:

One Manufacturing R&D project was reviewed, earning a score of 3.4. Reviewers judged the project to be highly relevant to Program activities and to feature an excellent technical approach. They noted that project progress and accomplishments are very good. The project team was judged to be strong; participation and contributions from industry partners were identified as useful and coordinated.

Fuel Cell Membrane Electrode Assembly (MEA) Manufacturing: One project was reviewed in the area of fuel cell MEA manufacturing, receiving a score of 3.4. Reviewers noted that the project's approach is very good and that its collaboration with industry and other partners has been, and continues to be, very good. Reviewers also noted that the National Renewable Energy Laboratory (NREL) has made significant progress this year in further developing the reactive impinging flow technique and demonstrating the technique on a continuously running web-line. The reviewers encouraged NREL to conduct a greater number of trials to get statistically meaningful results for each approach, as well as to improve its focus on correlating defect size (as detected in a web-line) with fuel cell performance.

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

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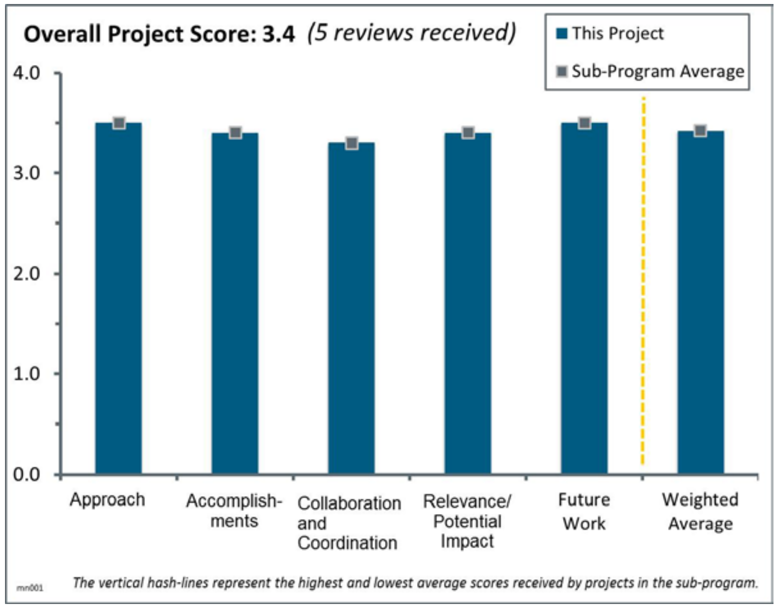

Brief Summary of Project:

The objectives of this project are to (1) understand quality control needs from industry partners and forums, (2) develop diagnostics using modeling to guide development and in-situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Question 1: Approach to performing the work

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

- The project is investigating in-line detection of membrane electrode assembly (MEA) manufacturing defects. The approach is appropriate and should be the path followed. The techniques of reactive impinging flow (RIF) with IR thermal imaging appear to be appropriate for on-line detection. Modeling has been initiated to determine the impacts of defects and to determine the defect resolution needed for the on-line equipment. Experiments with segmented cells are planned to help validate the model. The modeling will be key to determining a correlation between defect size and impact on performance and/or durability. It is not clear that a two-dimensional (2D) model will be sufficient for some of the defects (i.e., it is not clear how a 2D model will appropriately differentiate between scratches and a bare spot). From the work presented, it seems that the second and third steps in the approach are coming before the first step (i.e., developing techniques for defect detection before knowing what the requirements for defect detection are). It is not clear that the resolution needed for defect detection is known or that the correlation between defect size or type and performance is known. Perhaps this is commercially sensitive information and the National Renewable Energy Laboratory (NREL) has this information and cannot disclose it, but that information is critical to the success of this project.
- It is very timely that the U.S. Department of Energy (DOE) is addressing quality control issues in fuel cell manufacturing. This task, development of useful tools to access quality control, has to be done just once, if done well. The result offers high return on investment because many manufacturers can build collectively on these results rather than individually reinventing them. The NREL activities impress, and there were some novel approaches. There remains some uncertainty. For example, the hardware shown was required rolled goods, and assumes that, for example, one can acquire a "roll" of membrane. Clearly the membrane vendor has responsibility to provide in-specification products, and thus there will be various stages of quality control, probably beginning with the chemicals needed for membrane synthesis. There has been no suggestion yet of sensible ways to distribute the various quality control measurement tasks. There was also no appreciation that the manufacturing procedures might result in the creation of failures, say, the introduction of the ink might result in membrane degradation, etc. Therefore, the early and interesting NREL quality measurement technologies are just the beginning—but a good, solid beginning.
- The approach includes stakeholder input, technical development, and (more recently) validation. This is very good. It would be nice to see a thrust toward gauge repeatability and reproducibility. An effort to run large lengths or areas of materials for each of the inspection methods with "normal" materials is needed to demonstrate the robustness of the measurement methods and to determine the rates of false positives, false negatives, repeatability, etc.

- The approach is very good and is broad-based and covers a number of defects that can appear in different manufacturing processes for MEAs and gas diffusion electrodes (GDEs) using a role-to-role technique.
- Incorporating industry input, modeling, and validation testing, this effort's approach is well designed to evaluate various quality control techniques.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The RIF method was improved by utilizing laser-drilled holes in the gas knife. Modeling suggests that by using a GDE backing, the resolution can be improved further. Optical reflectance detection of defects was demonstrated at 10 fpm, and algorithms for automated detection were developed. The algorithm development is key to implementing this at industrial speeds. Results are needed from a statistical validation of the algorithm with percentage of defects missed and percentage of false positives detected. It is still not clear what detection limits are needed for quality assurance and what the correlations between defect size and frequency and performance are. Modeling of the impact of defects has been continuing. It is not clear what the sizes of the defects being modeled are, and validation of the model has not been completed.
- NREL has made good technical progress in measurement technology, and good progress is assembling a quality project team. The modeling results, to date, seem modest. Perhaps that is the necessary gate for beginning the modeling tasks. The thermal data technique, "hot spot," seems highly useful and novel. It makes sense to commence with simple tasks, finding "holes," etc. Measurement of spatial mechanical properties will be the necessary eventual focus. Certainly, because a wide variety of PEM fuel cell systems are now in the global marketplace, there are many parallel "quality control" activities underway. It would have been interesting to have NREL investigate those competing measurement techniques and prepare a document that describes what is known as the 2015 state of the art (SOA) for fuel cell component quality control. The interactions with "industry" were not described well enough to make any conclusions about "worth." Even so, clearly there is necessity to develop quality tools for the control of fuel cell manufactured products. Importantly, it is equally important to use such quality control (QC) tools on any system that will be utilized for durability testing—it is important to understand fully what is being tested and not to expend resources to evaluate fuel cell systems that come assembled using poorly defined, non-reproducible components.
- Scale-up of the IR/RIF gas knife was a good accomplishment, with further improvements identified and modeled. Modeling of defect sensitivity is an important contribution.
- Good progress has been made for the IR/reactive flow-through (RFT) technique in an open environment with very high moving rates of 30 fpm.
- The project is aligned with DOE's goals for fuel cell commercialization.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- Collaborations between Lawrence Berkeley National Laboratory's (LBNL's) modeling efforts and NREL appear to be working well. More input from General Motors, Ion Power, and W.L. Gore on the correlation between defects and performance would improve the project immensely (especially information that can be shared publicly).
- The project is well coordinated and has excellent cooperation with relevant industrial partners and institutes.
- The project has a good mix of industrial, national laboratory, and academic collaborators providing valuable contributions.
- More collaboration is always nice. However, it seems that the project has been able to maintain a healthy and continuous rotation of partners.
- Collaboration is complicated in that it involves teaming with many industrial partners with significant differences in market position and in technological competence. In some ways, fuel cell manufacturing

today already involves "assembly," the collection of various parts from a number of parts suppliers, and then using manufacturing steps that result in the desired hardware. The quality of the final step, component engineering to assemble a fuel cell system, is necessarily limited by the quality of the various components used to get that result. It makes sense to collaborate with various component suppliers and understand the challenges and opportunities they face as they strive to improve their products. It is important that cost implications of future, probably tighter, values become understood. An example might be that more rigorous specification of uniform membrane thickness might be doable, but only for higher cost, and the irregular membrane might perform well enough, etc. It seems that NREL needs to create some ongoing "sensitivity" study that explores such issues. A beginning step would be to acquire a number of starting components and evaluate them to understand the existing variations in current components. Such a study, of course, must necessarily include all system components, not only those that reside in the stack. It would be good to add quality manufacturing firms as part of this QC effort, as that makes sense.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- DOE has invested significant funds in fuel cell technology—indeed, planting "seeds" that have sprouted into a huge global enterprise. The challenge now is to include U.S. manufacturers in these emerging markets. This activity seems pivotal—and essential for success in that direction. However, the NREL effort to date is just one small advance in what needs to be a large, continuing activity. Although today the emphasis is on "voltage degradation" or "low RH performance," the necessary emphasis needs to be long-term performance and durability of fuel cell systems. In most published studies, the observed fact is that the balance-of-plant components turn out to be responsible for about 75% of fuel cell system failures. Moreover, at times "stack failures" are also the result of balance-of-plant failures, e.g., a sensor in the thermal management system fails, and the resulting out-of-control temperatures ruin the active fuel cell components. Therefore, this NREL activity is an essential, timely first step. However, in the absence of a far larger scope that works to understand the fuel cell system, this effort cannot have much impact. In summary, the project is highly relevant and clearly necessary, but not sufficient.
- Maintaining relevance in manufacturing issues is particularly challenging, as it requires a great deal of industry disclosure. Considering this challenge, the project seems to have made great efforts to maintain engagement with industry. Perhaps there are innovative approaches to encourage further openness and participation from other industry stakeholders. Relevance could be improved if it were possible to pool statistical data from a larger group of industry partners (very challenging). It would be great to compile a Pareto of defects by frequency, or weighted ratings of frequency, severity, and detectability (failure mode and effects analysis [FMEA]). Perhaps it would be possible to confidentially gather and pool data (not opinions) to ensure program relevance. This would be very valuable.
- The project is targeting the main challenges of quality control in fuel cell manufacturing. Identifying the impacts of the imaged defects on fuel cell operation is an excellent approach to verify that the defects will influence the local and overall performance.
- The project is relevant to DOE goals and has potential to have a significant impact on fuel cell cost by increasing yield and reducing waste.
- A number of Program goals are being addressed by this effort, and it is enabling the transition of QC technologies toward industrial adoption.

Question 5: Proposed future work

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

- The project has clearly responded to past reviewer comments. The efforts to link defects to performance are not easy tasks. Perhaps leveraging results of similar efforts in the literature would help in efficiently gathering more data. The continuous nature of the program is a positive, as it allows the project team to shape future efforts based on feedback.

- Every task of the proposed future work is good and important, especially the study of impacts of the relevant defects on fuel cell performance and failure onset.
- The proposed future work to predict the performance effects of defects is very important to this work. The correlation between "defects" and performance is needed to make sure time is not wasted improving resolution beyond what is needed or looking for blemishes that have no impact on performance or durability.
- Future work has been planned appropriately, most importantly the effects of defects.
- The challenge remains: there are many quality control concerns in fuel cell system manufacturing. Clearly this NREL project provides value, and the proposed future work will expand that worth. A robust stack is a sensible goal, and NREL should move into tasks that address stack engineering, the art of making MEAs into useful machines. A robust fuel cell system is the necessary goal. It makes sense to purchase commercial stacks and, as possible, explore the existing SOA in manufacturing quality control in hardware already in the global marketplace. NREL seems well established for making such measurements. One needs to understand the starting point, where we are today. (This could be accomplished without revealing the manufacturer, but the results would serve well as a benchmark of the 2015 fuel cell technology.) There need to be considerable new efforts in the optimization of the "system" and in the evolution of a fuel cell stack that results in a robust and reliable product.

Project strengths:

- The project team has clearly responded to past comments with real actions in a timely manner. The work is in many ways thorough, particularly with the incorporation of performance response and modeling. The project has overcome challenges of industry collaboration on a sensitive topic.
- This project is well designed and well executed and follows methodical approaches to quality control technology development.
- The project team has done excellent research and has good cooperation with industrial partners.
- Certainly the skills, abilities, and experience of the NREL staff and the DOE-sponsored existing quality facilities at NREL are strong project attributes. The timing of the project is, perhaps, a little late. However, the team is clearly well focused and is making significant progress.
- A project strength is NREL's experience in MEA fabrication and manufacturing and analytical capabilities.

Project weaknesses:

- There seems little indication that fuel cell quality control measurement technology is a global challenge and that others may be well ahead of the United States and its national laboratories in this area. There are operational fuel cell trade organizations around the world. The one in British Columbia (teamed with a world-class automotive OEM, the ones built around Japan's Ministry of International Trade and Industry, the three in the United States come to mind. It seems necessary to associate with this existing global community and to acquire data about what particular measurements provide the highest value for quality control in manufacturing. This focus on global market issues would strengthen the project.
- Manufacturing quality control involves statistical significance. These QC techniques would be further validated by continuing to run project systems with larger samples. Donation, purchase, etc. of "known" good material for testing would be very good. The project could determine how much the background noise varies, how environmental perturbations impact performance, and whether certain electrode compositions are better or worse for each approach.
- The correlation between defect type, size, frequency, and performance/durability is lacking. This information is critical to ensure effort is directed toward appropriate techniques and not wasted looking for or detecting blemishes that have no impact. More input from industry in this area would be invaluable.

Recommendations for additions/deletions to project scope:

- This project needs to be expanded to cover the entire inventory of parts in fuel cell systems. The emphasis on the fuel cell components is a fine, appropriate place to begin. However, as in a chain in which one bad link is all it takes for failure, one needs to understand durability from a system perspective. The proper project scope needs expansion to this system level. Indeed, one suspects that the largest, early opportunity for U.S. manufacturers will be in components such as blowers, valves, hydrogen pumps, gaskets, etc., and learning the art of manufacturing acceptable mechanical components seems critical. There are some component "standards" in place. Such a project might involve the U.S. Departments of Commerce and, perhaps, U.S. Department of Defense and "trade associations." DOE needs to participate in building a well-defined set of manufacturing guidelines that serve as metrics for those involved in fuel cell component manufacture.

- The project should add a high run aspect to determine the statistical performance of each approach. The program could be duplicated to include other volume components, such as plates.
- The researchers should try to apply the diagnostic tools on MEA components also catalyst coated membranes (CCMs) and GDEs for PEM water electrolysis.