
V.0 Fuel Cells Program Overview

INTRODUCTION

The Fuel Cells program supports research, development, and demonstration of fuel cell technologies for transportation applications, as well as stationary and early market applications, with a primary focus on reducing cost and improving durability. Efforts predominantly concentrate on research and development (R&D) of fuel cell stack components, as opposed to system balance-of-plant components, subsystems, and system integration. The program seeks a balanced, comprehensive approach to fuel cells for near-, mid-, and longer-term applications. The development of fuel cells for transportation applications is a primary focus due to the nation's goal of significantly reducing its energy and petroleum needs and the benefits inherent in fuel cell electric vehicles (FCEVs) (e.g., high efficiency, long driving range, zero emissions). Stationary applications include the development of fuel cells for distributed power generation, including combined heat and power (CHP) for residential and commercial applications. Existing early markets and near-term markets generating market traction for adoption of FCEVs include backup power, auxiliary power units, and specialty applications such as material handling equipment. The program's R&D portfolio is primarily focused on polymer electrolyte membrane (PEM) fuel cells, but also includes longer-term technologies, such as alkaline fuel cells and higher-temperature fuel cells like molten carbonate fuel cells for stationary applications.

The program's fuel cell tasks in the Fuel Cell Technologies Office *Multi-Year Research, Development, and Demonstration Plan*, updated in Fiscal Year (FY) 2016, are organized around the development of components, stacks, subsystems, and systems; supporting analysis; and testing, technical assessment, and characterization activities.

GOAL

The program's goal is to advance fuel cell technologies for transportation, stationary, and early market applications.

OBJECTIVES¹

The program's key objectives include:

- Developing a 65% peak-efficient, direct hydrogen fuel cell power system for transportation that can achieve 5,000-h durability (ultimate 8,000 h) and be mass produced at a cost of \$40/kW by 2020 (ultimate \$30/kW).
- Developing distributed generation and micro-CHP fuel cell systems (5 kW) operating on natural gas that achieve 45% electrical efficiency and 60,000-h durability at an equipment cost of \$1,500/kW by 2020.
- Developing medium-scale CHP systems (100 kW–3 MW) by 2020 that achieve 50% electrical efficiency, 90% CHP efficiency and 80,000-h durability at a cost of \$1,500/kW for operation on natural gas and \$2,100/kW when configured for operation on biogas.

FY 2016 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

Reducing cost and improving durability while maintaining performance continues to be the key challenge facing fuel cell technology R&D. For platinum group metal (PGM)-based catalysts, both a reduction in PGM loading and an increase in membrane electrode assembly (MEA) area power density are required to reduce material costs. Current state-of-the-art MEAs with very low cathode PGM loadings experience a higher-than-expected reduction in performance when operating at high power (e.g., near the rated power point), but FY 2016 saw continued progress towards addressing this performance loss. Commercial fuel cells are expected to use PGM-based catalysts in the near term; however, reaching cost competitiveness with conventional automobiles in the long term will require a transition from PGM-based catalysts to PGM-free catalysts. Advances in FY 2016 have brought PGM-free catalysts significantly closer to parity with conventional PGM-based catalysts. Major advances in FY 2016 were also made in development of durable, high-performance membranes that will allow fuel cells to operate for longer periods of time under harsh conditions.

¹Note: Targets and milestones were recently revised; therefore, individual project progress reports may reference prior targets.

One of the most important metrics used to guide the program's R&D efforts is the projected high-volume manufacturing cost for automotive fuel cells, which is tracked on an annual basis. The program is targeting a cost reduction to \$40/kW by 2020. Long-term competitiveness with alternative powertrains is expected to require further cost reduction to \$30/kW, which represents the program's ultimate cost target. This year, the preliminary cost projection for an 80-kW_{net} automotive PEM fuel cell system based on next-generation laboratory technology and operating on direct hydrogen is \$53/kW_{net} when manufactured at a volume of 500,000 units/year and \$59/kW_{net} when manufactured at 100,000 units/year. For comparison, the expected cost of automotive PEM fuel cell systems that are based on current technology and planned for commercialization in the 2016 time frame is approximately \$230/kW_{net} when manufactured at a volume of 1,000 units/year.

The 2016 cost estimate was based again this year on Argonne National Laboratory's (ANL's) projected stack performance for a real de-alloyed PtNi₃ catalyst (d-PtNi) from Johnson Matthey. The main changes from last year's analysis that materially impacted the cost included an improved cathode catalyst with a reduced Pt loading and increased power density, the use of more expensive bipolar plate stamping processes and equipment upon re-evaluation, and the incorporation of thinner gas diffusion layers. Taken together and with others, the changes made in 2016 result in almost no net change in system cost from 2015. Also of note in 2016 was the addition of an acid washing step to the catalyst coated membrane (CCM) preparation during the MEA fabrication process, a step incorporated based on research done at ANL as a means to prevent performance loss at low humidity levels. The results of the current year's cost analysis are compared to those of previous years in Figure 1.

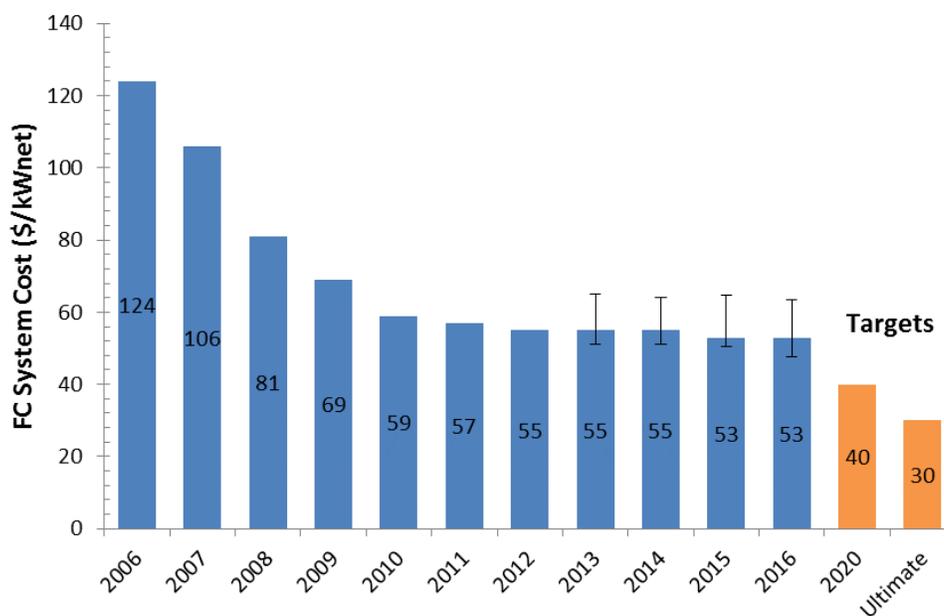


FIGURE 1. Modeled cost of an 80-kW_{net} PEM fuel cell (FC) system based on projection to high-volume manufacturing (500,000 units/year)

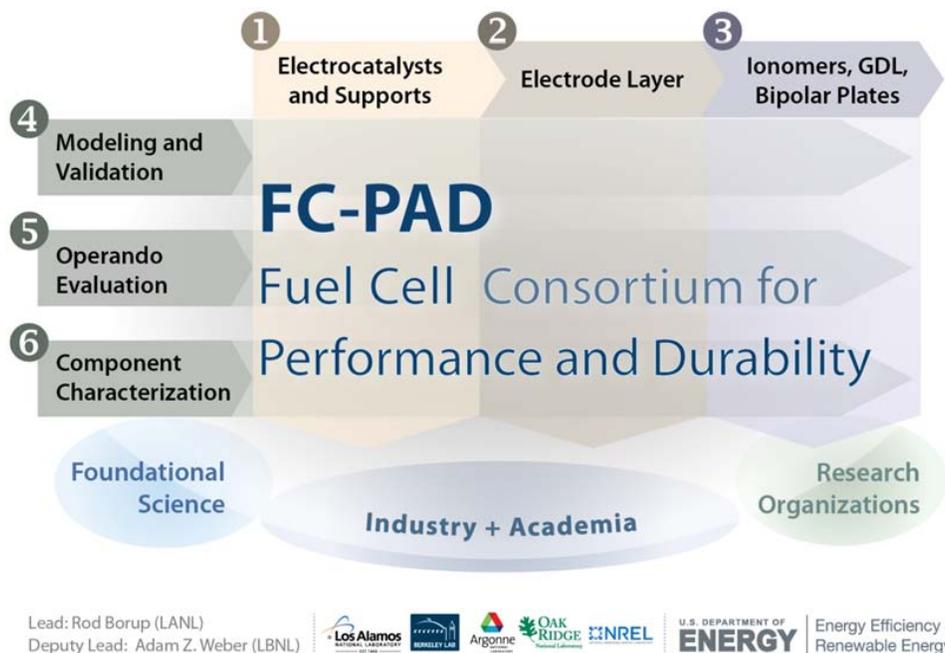
To enable vehicle commercialization, fuel cell systems must also meet the program's durability targets. These targets vary by application; for automotive systems, DOE has set a 2020 target of 5,000 h, and in 2016 increased its ultimate durability target to 8,000 h. This increase serves to more accurately represent the durability requirement in terms of miles driven (150,000 mi) for a larger range of drivers, specifically capturing requirements for people who drive at a lower average speed. Analysis in 2016 found that the current average lab-tested durability status is approximately 3,500 h.

Meanwhile, DOE independent validation of on-road FCEVs showed a more than four-fold increase in the maximum projected durability of fuel cell systems, increasing from 950 h in 2006 to over 4,100 h in 2016. Additionally, the maximum operating hours recorded for a single FCEV has remained at 5,600 h. For comparison, state-of-the-art maximum lab durability is projected to be over 12,000 h. The durability of fuel cell electric buses has

also been evaluated since 2000 in transit agency demonstrations and has continued to increase after having surpassed the 2016 interim 18,000 h target in 2015. The current bus maximum lifetime is over 23,000 h and was set by a bus that continues to operate.

Consortia

To simultaneously address performance and durability challenges, the program announced the creation of the Fuel Cell Performance and Durability (FC-PAD) Consortium in FY 2015. The consortium coordinates work under the thrust areas defined in Figure 2. There are three thrust areas related to components (electrocatalysts and supports; electrode layers; ionomers, gas diffusion layers, bipolar plates, interfaces) and three thrust areas that are cross-cutting in nature (modeling and validation; operando evaluation: benchmarking, accelerated stress tests, and contaminants; component characterization and diagnostics). This R&D consortium is led by a team of national laboratories and began operations in FY 2016. FC-PAD has met its FY 2016 milestones, including the development of new durability accelerated test protocols and the development of multiple electrode designs for optimizing high-current-density performance. The consortium is actively incorporating collaborators selected from the program's FY 2016 funding opportunity into its steering committee.



GDL – gas diffusion layer; LANL – Los Alamos National Laboratory; LBNL – Lawrence Berkeley National Laboratory

FIGURE 2. FC-PAD is structured across six components and cross-cutting thrusts

The program also established a second consortium in FY 2016, under the umbrella of DOE's Energy Materials Network, to address the materials problem of developing high-performance, low-cost, PGM-free catalysts for automotive fuel cells. Called ElectroCat (for Electrocatalysis consortium), the consortium aims to accelerate PGM-free catalyst and electrode development by coordinating relevant expertise and tools at the national labs to provide easy access to external researchers. Electrocat's capabilities consist of high-throughput combinatorial methodologies, computational tools, and PGM-free catalyst expertise. Several outreach events were carried out in FY 2016 to educate the broader research community about these capabilities and the general purpose of the consortium.

Examples of R&D advancements achieved in FY 2016 are described below, including major improvements in fuel cell catalysts, membranes, and MEAs.

Catalysts

Projects continued to make advances in low-PGM catalysts, and six new projects were initiated in FY 2016 on the topic of low-PGM catalysts and durable supports. Core-shell catalysts with platinum-monolayer shells have been established as alternatives to conventional platinum-alloy catalysts. In particular, researchers found that nitriding core components can facilitate the development of high-performance platinum-monolayer catalysts with low- or no-noble-metal cores. Nitriding NiPd alloy cores prior to depositing Pt monolayers to prepare PtPdNi/C core-shell catalysts results in a 50% reduction in Pd content as compared to previous Pt/Pd/C catalysts while enhancing overall stability and activity (Figure 3). This has the direct consequence of lowering the cost of these catalysts. At the same time, the formation of Ni nitride was found to stabilize Ni in the core. (Brookhaven National Laboratory)

Researchers have also developed a new in situ experimental technique including a rotating disk electrode (RDE) combined online with inductively coupled plasma mass spectrometry for the detection of ultra-low (parts per trillion) concentrations of metals including Pt, Au, Ni, Co, Fe, and others. This allows for detailed insight into foundational properties related to catalyst stability in an electrochemical environment. This setup has achieved extremely high sensitivity and was demonstrated in studying platinum dissolution from the extended single crystalline surfaces of Pt electrodes, as well as from commercially available carbon supported platinum. For Pt, the technique has allowed for the distinction between Pt dissolution and Pt particle detachment from the substrate. The technique can be used to study low-PGM and PGM-free catalyst durability and can serve as a valuable tool for researchers to use in optimizing catalyst structure and composition. (ANL)

A newly initiated project at General Motors focuses on the need to develop catalysts with high performance and durability at both low and high current densities. In order to develop low-PGM catalysts that meet these requirements, the effects of Pt surface area and local oxygen transport resistance on overall catalyst function were studied. Large performance losses at high current density were observed on low-Pt-content cathodes due to a higher flux of oxygen over a given Pt area, as seen in Figure 4 for PtCo alloys. The project highlights the importance of selection of a carbon support and electrolyte ionomer with favorable transport properties in the process of developing PtCo catalysts with improved dispersion and stability. As a starting point in demonstrating this, a 50 cm² General Motors MEA containing a PtCo alloy catalyst and a high-surface-area carbon support achieved a catalyst specific power of 6.9 kW/g_{PGM}. The MEA was tested at 150 kPa and at 94°C, meeting the Q/ΔT requirement imposed by DOE targets. When tested at a pressure of 250 kPa, the MEA achieved a specific power of 7.7 kW/g_{PGM}.

Electrolytes

Improved nanofiber-supported fuel cell membranes containing multi-acid side chain ionomers continued to progress in FY 2016. These membranes, which combine low equivalent weight (EW) perfluoro imide acid (PFIA) ionomers with new electrospun nanofiber supports and chemical stabilizing additives, meet DOE's area specific

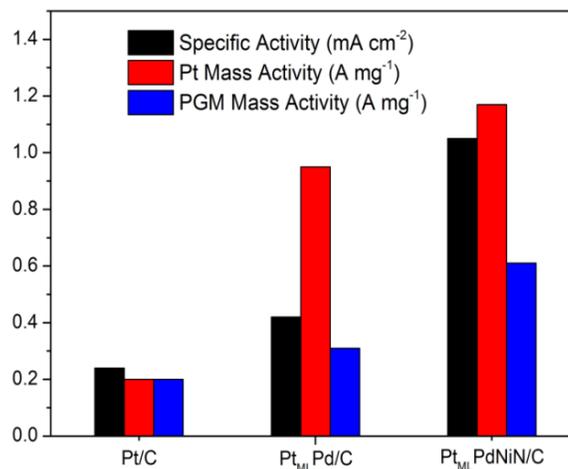


FIGURE 3. Specific activity, Pt mass activity, and PGM mass activity for commercial Pt/C, Pt_{ML}Pd/C, and Pt_{ML}PdNiN/C catalysts measured at 0.9 V

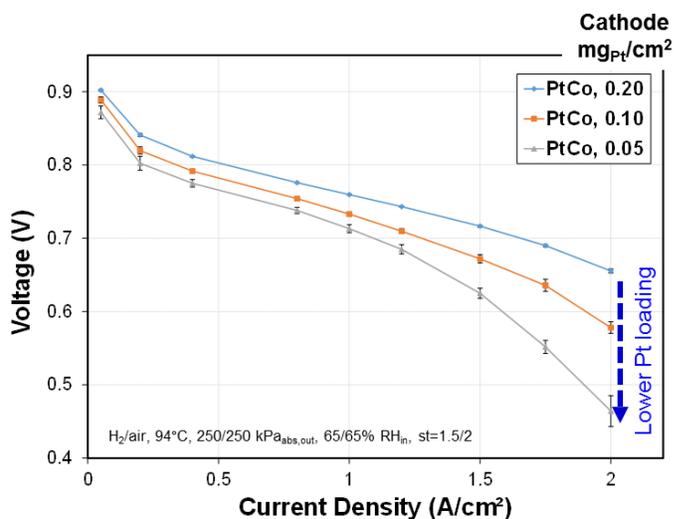


FIGURE 4. Fuel cell polarization curves of PtCo/C catalyst at different cathode Pt loadings showing large performance loss at high current density as Pt loading is reduced due to increasing flux of O₂ per a given Pt area

proton resistance targets at 80°C for all humidities and at 120°C for the highest specified humidity. Additionally, the membranes meet all mechanical and chemical durability targets laid out for membranes. Figure 5 shows the cell voltage and resistance for two PFIA-based membranes and a 725 EW-based perfluorosulfonic acid (PFSA) control with similar fiber and additive loading. The potential and resistance values are not very different between samples at high relative humidity (RH), but as the RH decreases, the resistance of the PFIA-based membranes remains low and, as a result, its performance at 1.5 A/cm² is as much as 100 mV higher than the control at the lowest RH tested (20%).

Polarization curves for the PFIA-based membranes and control under dry conditions (95°C, 50% inlet RH) are shown in Figure 6. Membranes based on PFIA ionomer have lower cell resistance and higher performance at all current densities, with up to 50 mV higher performance at 1.5 A/cm². (3M)

An improved electrolyte matrix for molten carbonate fuel cells with increased porosity and improved pore size distribution compared to a baseline matrix also continued to advance in FY 2016. The baseline matrix has already demonstrated over five years of field service in many commercial units. The improved porous ceramic matrix formulation demonstrated an increase of over 25% in mechanical strength compared to the baseline. A stable pore size, high phase stability (less than 3% phase transformation), low particle growth (over 3.5x reduction in coarsening), and over 80% reduction in gas crossover were also demonstrated during accelerated stress test (AST) conditions (Figure 7). The matrix achieved 5,000-h AST durability, demonstrating a projected 80,000-h stack durability. Attaining a stack durability of 80,000 h will reduce the number of stack replacements needed over the 20-year lifetime of the fuel cell to one, significantly lowering the cost of the system. This reduced life cycle cost of the fuel cell system will enable larger-scale deployment of molten carbonate fuel cells for distributed generation of electricity and hydrogen, CHP applications, and carbon capture from the exhaust of fossil fuel power plants and chemical processes. (FuelCell Energy)

Membrane Electrode Assembly Integration

Improved integration of fuel cell components based on nano-structured thin film (NSTF) catalysts into high-performance MEAs enabled a further increase in performance in FY 2016. High-performance, low-cost, and operationally robust MEAs were fabricated via continuous, scalable pilot processes and demonstrated a power output per gram of PGM at rated power of 6.8 kW/g_{PGM}. This is an increase from the 2.8 kW/g_{PGM} measured in FY 2008 and the 6.5 kW/g_{PGM} measured in FY 2015 and was observed under conditions that satisfy the DOE heat rejection ($Q/\Delta T$) target (see Figure 8). The MEA included a platinum nanoparticle-based cathode interlayer to improve its robustness and tolerance to non-ideal operating conditions. The NSTF-based MEA developed in FY 2016 had an

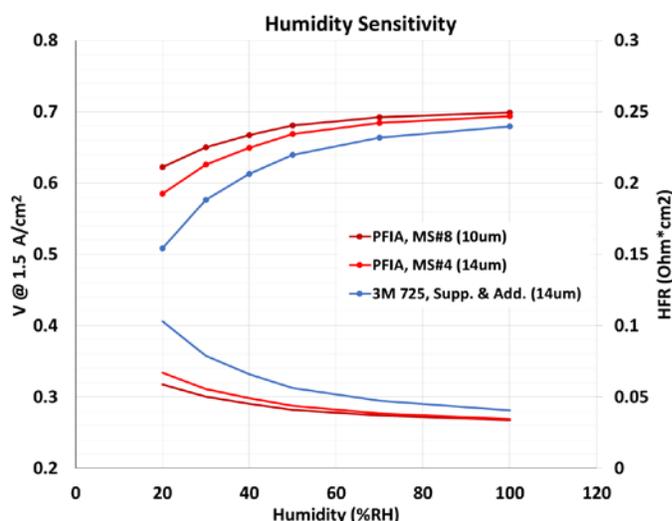
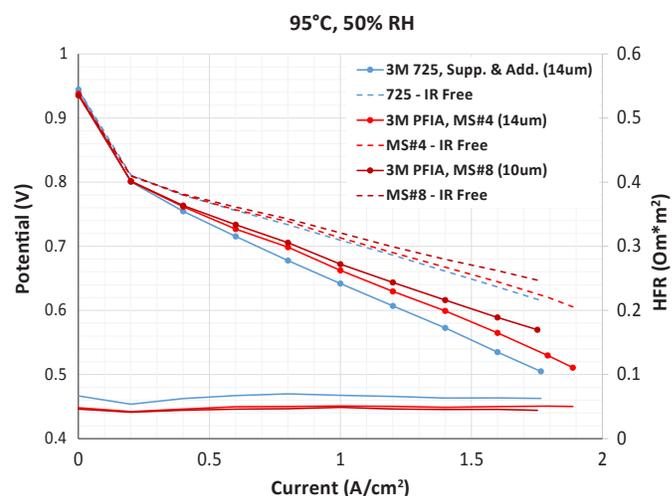
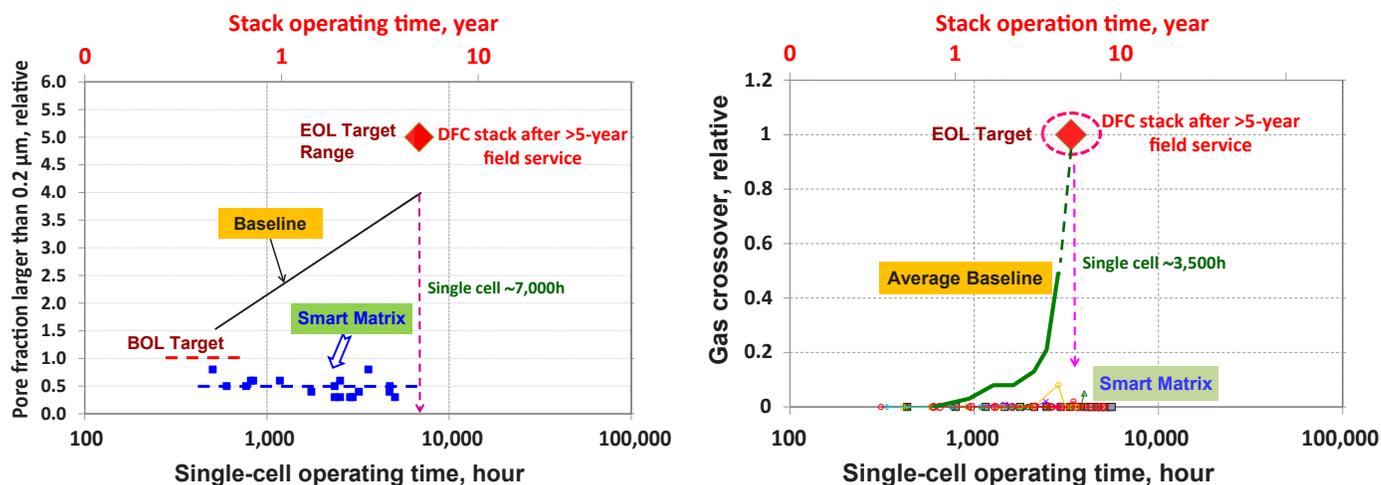


FIGURE 5. Voltage and high frequency resistance (HFR) for PFIA based membranes (red lines) and a PFSA control (blue lines), as a function of humidity at 1.5 A/cm²



IR – internal resistance

FIGURE 6. Polarization curves at 95°C and 50% inlet humidity for PFIA-based membranes (red lines) and a PFSA control (blue lines). Voltage versus current density data are shown by lines with symbols, HFR is shown with solid lines, and HFR corrected data are shown with dashed lines.



BOL – beginning of life; EOL – end of life; DFC – direct fuel cell.

FIGURE 7. Left: Pore fraction larger than 0.2 μm over a 5,000-h AST. Right: Gas crossover over a 5,000-h AST. Both metrics meet the end-of-life target, demonstrating a projected 80,000-h stack durability.

operational range similar to that of the FY 2015 Best Of Class (BOC) NSTF-based MEA but yielded higher cell performance at cell temperatures between 40°C and 80°C. Further work is still required to meet performance, durability, and robustness targets simultaneously. (3M)

Investigations were carried out to find methods for realizing the oxygen reduction reaction (ORR) mass activity benefits of advanced Pt-based cathode electrocatalysts in both MEAs and stacks operating at high current densities, on air and at low PGM loading (≤ 0.1 mgPt/cm² on the cathode and < 0.025 mgPt/cm² on the anode). These efforts resulted in improved MEA performance, as well as an increased understanding into the aspects of MEA preparation that affect the performance of de-alloyed PtNi catalysts at high current density, particularly at low RH. In FY 2016, the performance of dealloyed-PtNi₃ (d-PtNi) based catalysts was increased at high current density by (1) decreasing the initial Ni content of the d-PtNi/C catalyst; (2) using an organic solvent in the catalyst-ionomer ink; (3) increasing the ionomer-to-catalyst ratio from 0.8 to 1.0; (4) using an intermediate EW ionomer, 850 EW; and (5) acid-washing the catalyst-coated membrane after fabrication (see Figure 9). The d-PtNi MEAs achieved 1,259 mA/cm² at 0.675 V, with a total cell loading of 0.1107 mg_{Pt}/cm² and under differential conditions, and achieved 6.6 kW/g_{PGM} at rated power in a 50 cm² MEA tested under conditions meeting the Q/ΔT target (90°C, 40% RH, and 150 kPa). The d-PtNi catalysts exceed the mass activity and electrochemically active surface area durability targets after being subjected to the catalyst AST (<40% loss after 30,000 cycles between 0.6 V and 1.0 V at 50 mV/s) and the high current density durability target (<30 mV at 1.5 A/cm²) when limiting the upper potential limit of the AST to 0.925 V. (ANL)

PEM fuel cell MEA integration studies will be further pursued in FY 2017 primarily under FC-PAD.

Alkaline Membrane Fuel Cells

An alkaline membrane fuel cell (AMFC) workshop was held in FY 2016 to assess the current status of and the R&D needs for AMFC technology. There have been substantial advances in AMFC technology since the previous workshop held in 2011. Alkaline membranes stabilized through cationic group and polymer backbone modifications

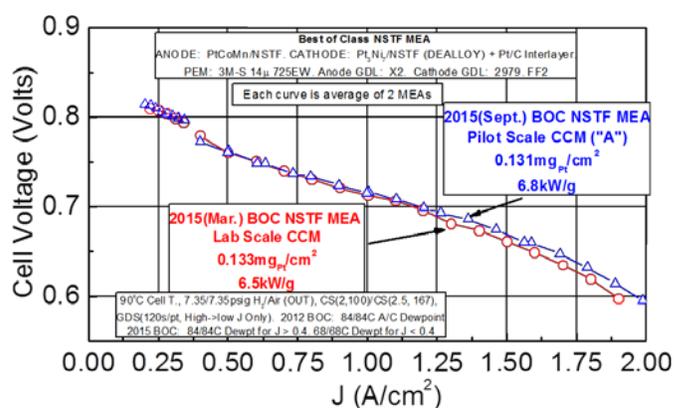


FIGURE 8. Improved MEAs produce 6.8 kW/g_{PGM} under conditions that satisfy DOE's Q/ΔT target

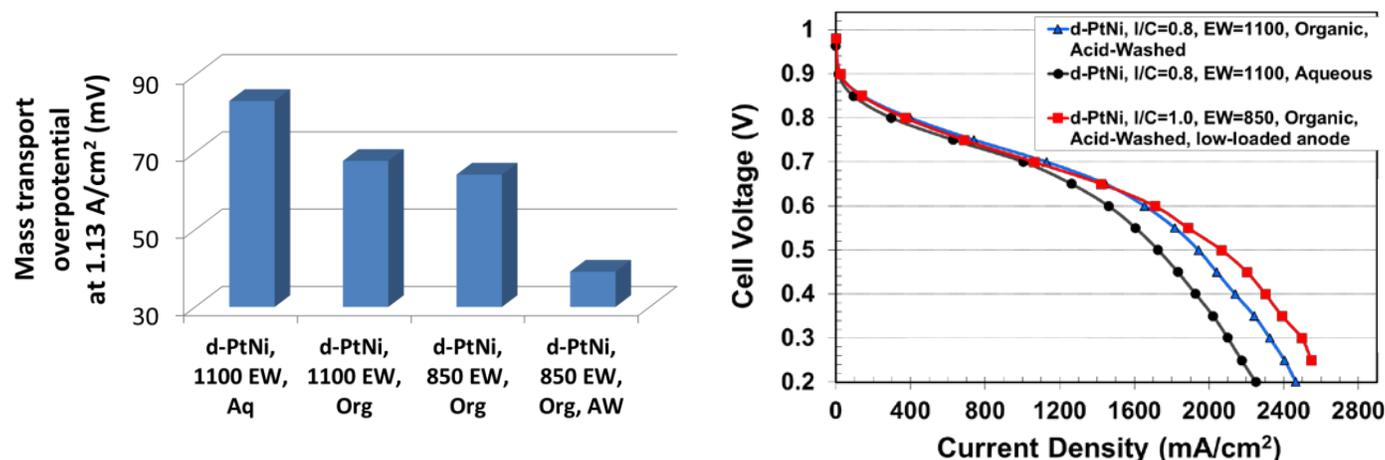


FIGURE 9. Left: MEA performance for d-PtNi MEAs with varying EW ionomer, catalyst-ionomer ink solvent, and post-fabrication procedures, showing the improvement in performance with intermediate EW ionomer, ionomer to catalyst ratio (I/C) = 1.0, organic solvent, and acid-washing of CCM. Right: Effect of organic versus aqueous solvent, lower EW ionomer, and acid-washing of CCM (AW) on polarization curve mass transport voltage losses at 1.13 A/cm² in d-PtNi MEAs.

have now been demonstrated. However, implementation of these membranes in MEAs and subsequent characterization of their stability and performance under realistic fuel cell operating conditions is still needed. Also, ionomers which are specific to the different operating environments of the anode and cathode need development. While improved PGM-free hydrogen oxidation reaction and ORR catalytic activity has been demonstrated, at least at the RDE level, performance in MEAs still needs significant improvement. Finally, additional efforts are required to address AMFC-specific water management issues as well as CO₂ tolerance and mitigation.

Standardized protocols and metrics for AMFCs were also discussed. Existing performance and durability protocols for PEM fuel cells may be used as a solid starting point for assessing alkaline fuel cells, but longer term ones specific to AMFCs may be required. The workshop report and presentations can be found on <http://energy.gov/eere/fuelcells/downloads/2016-alkaline-membrane-fuel-cell-workshop>.

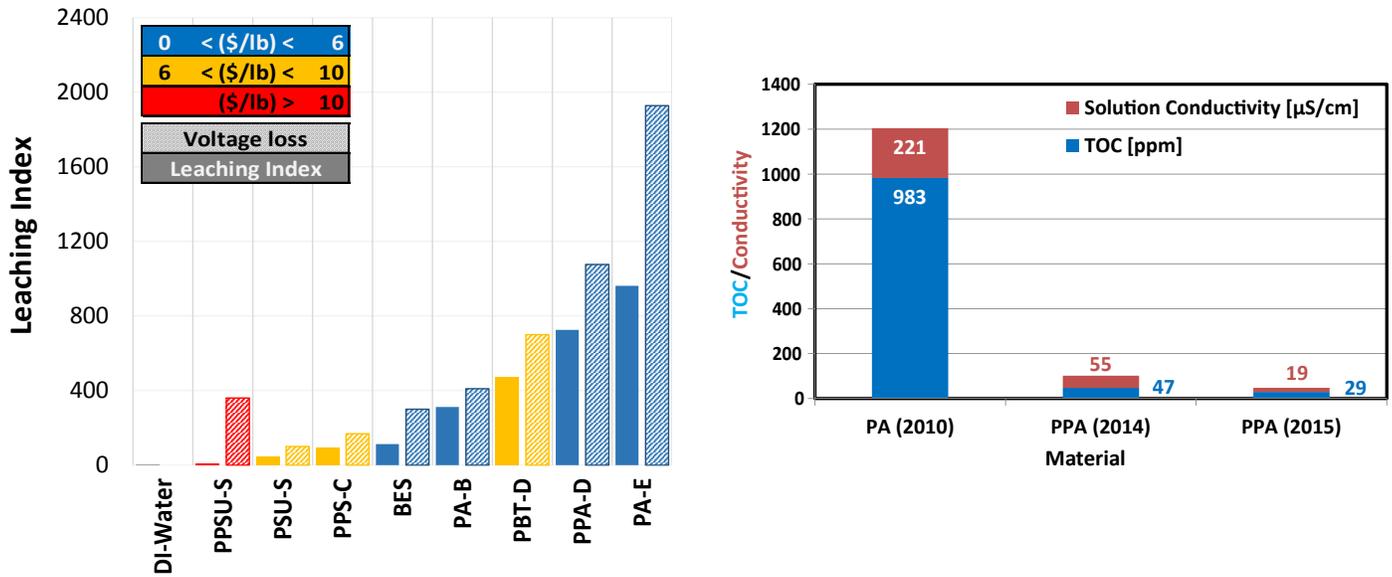
Characterization and Analysis

In FY 2016, microstructural and microchemical studies continued to provide insight into materials comprising MEAs, offering valuable information on the stability and durability of specific components during operation. Studies were primarily focused on three-dimensional (3D) electron tomography of electrocatalysts, supports, and fully intact catalyst layers. A 3D reconstruction providing visualization of ionomer dispersions in “real” catalyst layers and correlation with porosity is shown in Figure 10. An additional advantage of 3D tomography, especially when utilized to analyze a fully intact catalyst layer, is that it provides more direct quantitative information regarding the size characteristics of the individual constituents than traditional two-dimensional images do. (Oak Ridge National Laboratory)



FIGURE 10. 3D imaging of ionomer dispersions in catalyst layers. Individual F maps were acquired from slices and stacked to create a 3D rendering of the ionomer distribution.

System material-derived contamination of the fuel cell has also been studied and has led to a public dataset of materials providing leaching indices, identities and quantities of contaminants, and recommended testing procedures to assess contamination. These materials include structural plastics, hoses, lubricants, adhesives, and seals (Figure 11). Researchers correlated a high “leaching index” to MEA degradation and lower material cost. Based on these findings, the project identified a cleaner polyphthalamide (PPA) structural material that resulted in no significant



DI – deionized; PPSU – polyphenylsulphone; PSU – phenylsulphone; PPS – polyphenylene sulfide; BES – Bakelite epoxy-based structural material from Sumitomo; PA – polyamide; PBT – polybutylene terephthalate; BPS – bisphenol S.

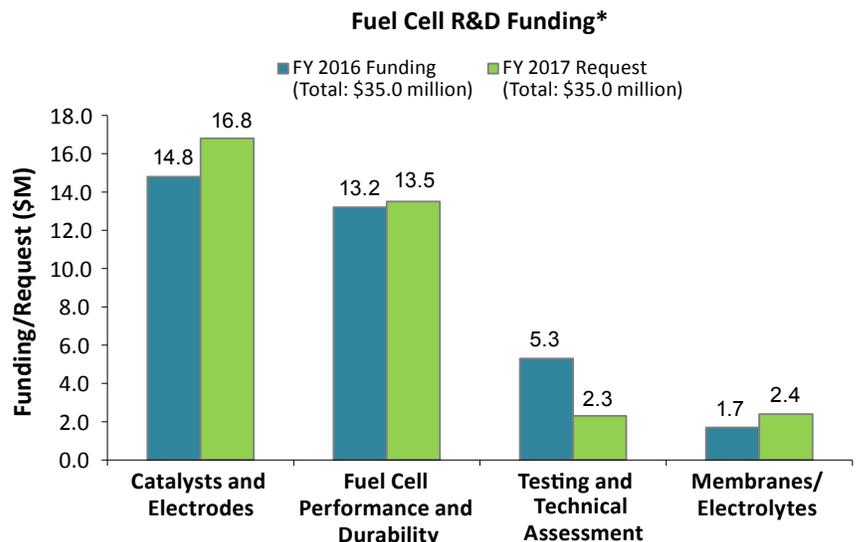
FIGURE 11. Left: Leaching index for various materials increased with decreasing material cost. Right: 25x improvement in combined total organic carbon (TOC) and solution conductivity for a cleaner PPA (2015) material.

increase in material cost yet afforded higher performance. The publicly available balance-of-plant material screening data tool and extensive database have had approximately 1,400 site visits since May 2013 (see http://www.nrel.gov/hydrogen/system_contaminants_data/). (National Renewable Energy Laboratory, General Motors)

BUDGET

The President’s FY 2017 budget request calls for \$35 million for the Fuel Cells program, which is equal to the FY 2016 appropriation.

Figure 12 shows the budget breakdown by R&D area for the FY 2016 appropriation and the FY 2017 budget request. The program continues to focus on reducing costs and improving performance and durability with an emphasis on fuel cell stack components. New projects were initiated in FY 2016 for R&D on advanced catalysts and supports and on alkaline membrane fuel cells. Additionally, new industry/university-led projects targeting the advancement of fuel cell performance and durability were selected in FY 2016 and will be incorporated into FC-PAD. FY 2016 also saw the launch of ElectroCat as part of the Energy Materials Network to expedite the development



*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.

FIGURE 12. Budget breakdown for FY 2016 through FY 2017

of PGM-free catalysts and electrodes. In FY 2017, the program plans to issue an ElectroCat funding opportunity announcement for awards to be selected and funded in FY 2017.

FY 2017 PLANS

As part of its Tech-to-Market activities in FY 2016, DOE's Fuel Cell Technologies Office developed an approach coined the L'Innovator (for "lab innovator") to accelerate the commercialization of innovative hydrogen and fuel cell technologies developed at national labs and enable a robust domestic industry and supply base in the emerging area of hydrogen and fuel cells. The approach involves bundling intellectual property from various labs to offer the most promising hydrogen/fuel cell technologies to prospective manufacturers with the ability to attract investors. In FY 2017, the Fuel Cells program will support an initial pilot intellectual property bundle: LANL's MEA technology will be optimized to integrate core-shell catalyst technology developed at Brookhaven National Laboratory. National Renewable Energy Laboratory will be involved in developing and applying roll-to-roll processing methods to demonstrate manufacturability.

In FY 2017, the Fuel Cells program will continue R&D efforts on fuel cells and fuel cell systems for diverse applications that employ a variety of technologies (including PEM and alkaline membrane fuel cells) and a range of fuels (including hydrogen, natural gas, and liquid fuels). Support will continue for R&D that addresses critical issues with membranes and electrolytes, catalysts, electrodes, and component integration at the cell level, with an emphasis on cost reduction and durability improvement. The program's consortia will continue accelerating innovation both within the national laboratories and in the greater research community. Ongoing support of modeling will guide component R&D, benchmarking complete systems before they are built and enabling exploration of alternate system components and configurations.

Dimitrios Papageorgopoulos
Fuel Cells Program Manager
Fuel Cell Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585-0121
Phone: (202) 586-5463
Email: Dimitrios.Papageorgopoulos@ee.doe.gov