

V.B.2 FC-PAD: Components and Characterization

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Additional No-Cost Partners:

- Umicore – Sascha Toelle
- General Motors (GM) – Anu Konkanand
- EWii Fuel Cells – Madeleine Odgaard
- Ion Power – Steve Grot

Project Start Date: October 1, 2015

Project End Date: September 30, 2021

Overall Objectives

- Develop the knowledge base and optimize structures for more durable and high-performance polymer electrolyte membrane fuel cells (PEMFCs).
- Understand and elucidate specific structural and chemical factors and/or mechanisms that contribute to and control material constituent stability (e.g., electrocatalyst, catalyst support, ionomer, membrane) within electrode layers and membrane electrode assemblies (MEAs) during fuel cell operation.
- Define and measure specific degradation mechanisms through extensive characterization and diagnostics, such as electron microscopy, time-resolved on-line

inductively coupled plasma mass spectrometry (ICP-MS), Synchrotron-based X-ray methods, etc.

- Coordinate characterization efforts and methods with materials development (e.g., new state-of-the-art [SOA] materials) and accelerated stress testing (AST) activities.
- Develop and/or optimize novel techniques towards PEMFC materials characterization.

Fiscal Year (FY) 2017 Objectives

- Evaluate and quantify transition metal (TM) dissolution (e.g., Co) from a series of SOA PtCo catalysts (supplied by IRD Fuel Cells (now EWii Fuel Cells), Umicore, and GM) during ASTs.
- Optimize and integrate multiple characterization methods to fully understand and correlate TM and Pt dissolution behavior to describe observations following ASTs; these methods include analytical scanning transmission electron microscopy (STEM) at ORNL, time-resolved on-line ICP-MS at ANL, thin film characterization at LBNL, Synchrotron X-ray techniques performed using the Advanced Photon Source at ANL (e.g., X-ray nano computed tomography, wide-angle X-ray scattering (WAXS), and small-angle X-ray scattering, microelectrode studies, electrical impedance spectroscopy, and other diagnostic tools at LANL.
- Initiate support for industrial and academic FC-PAD partners awarded new projects as part of Funding Opportunity Announcement 1412.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4) of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- (A) Durability
- (B) Cost
- (C) Performance

Technical Targets

This project develops MEAs that incorporate SOA Pt-alloy catalysts that meet the technical targets summarized in Table 1.

TABLE 1. Technical Targets for MEAs for Transportation Applications

Characteristic	Units	2020 Targets
Cost	\$/kW _{net}	14
Durability with cycling	Hours	5,500
Start-up/shutdown durability	Cycles	5,000
Performance @ 0.8 V	mA/cm ²	300
Performance @ rated power (150 kPa _{abs})	mW/cm ²	1,000

FY 2017 Accomplishments

- Introduced new catalyst durability AST (30,000 cycles; 5s square wave (0.6–0.95 V) cycles) that is 5X faster than old catalyst durability AST (30,000 cycles; 15s triangle wave (0.6–1.0 V) cycles), that reduces test time from 133 h (old triangle wave) to ~50 h (new square wave).
- Time-resolved on-line ICP-MS measurements were developed and used to perform real time measurements of Pt and Co dissolution from PtCo alloy catalysts under cyclic potentials and to resolve anodic vs. cathodic dissolution by applying staircase potential cycling. In general, Co dissolution occurred at all potentials whereas Pt dissolution occurred above 0.9 V.
- Several SOA PtCo catalysts were provided to FC-PAD for extensive characterization after incorporation into cathode catalyst layers (CCLs) in MEAs, and were evaluated before and after catalyst durability ASTs as well as after testing under Fuel Cell Tech Team (FCTT) wet-dry drive cycle protocols (wet-portion only). A combination of three-dimensional electron tomography, high-resolution STEM-based imaging and energy dispersive X-ray spectroscopy, and WAXS were used to study catalyst degradation (e.g., coarsening) and compositional changes due to TM dissolution.
- The amount of Co loss from CCL into membrane during ASTs was quantified for each of the catalysts studied (GM, Umicore, and EWii) using STEM-based energy dispersive X-ray spectroscopy; it was shown that 50% of the Co initially present in the catalyst nanoparticles in the CCL dissolved into the ionomer and migrated/diffused from the CCL into the membrane during ASTs.



INTRODUCTION

The FC-PAD consortium was formed to advance performance and durability of PEMFCs at a pre-competitive level to meet DOE targets and further enable their commercialization. This will be accomplished by developing a comprehensive knowledge base regarding materials

durability and by using this knowledge to optimize structures for more durable and high-performance PEMFC components, while simultaneously reducing cost.

As part of the component and characterization effort, which coordinates activities across most of FC-PAD's thrust areas, we will actively study SOA materials provided by the fuel cell community, including novel electrocatalysts, catalyst supports, ionomers, and membranes. Materials will be fabricated into MEAs and examined/studied at the beginning-of-life (BoL) and after exposure to specific ASTs (end-of-life [EoL]) using a comprehensive suite of characterization and diagnostic tools, which are located at the different FC-PAD partner national laboratories (ANL, ORNL, LANL, National Renewable Energy Laboratory, LBNL). The staff expertise and unique capabilities available at the five national laboratories will also be incorporated in the research of the four new funding opportunity announcement projects with Vanderbilt University, GM, 3M, and United Technologies Research Center in the future.

APPROACH

The FC-PAD consortium is comprised of five national laboratories, with investigators at each lab having proven expertise in specific research areas developed during the course of prior DOE fuel cell projects related to durability, transport, and performance. The FC-PAD consortium combines expertise and cutting-edge capabilities into a single, highly coordinated effort that is broken down into six thrust areas (see the annual progress report for project FC135 [1] for additional details regarding FC-PAD organization). This report (summary for project FC136) highlights work that was coordinated primarily across five thrust areas: Thrust 1: Electrocatalysts and Supports; Thrust 2: Electrode Layers; Thrust 3: Ionomers; Thrust 4: Operando Evaluation; and Thrust 6: Component Characterization. The thrust areas and activities within FC-PAD are highly integrated and comprise three reports (FC135 [1], FC136, FC137 [2]), each of which incorporates many thrust areas, albeit with a different material/component focus.

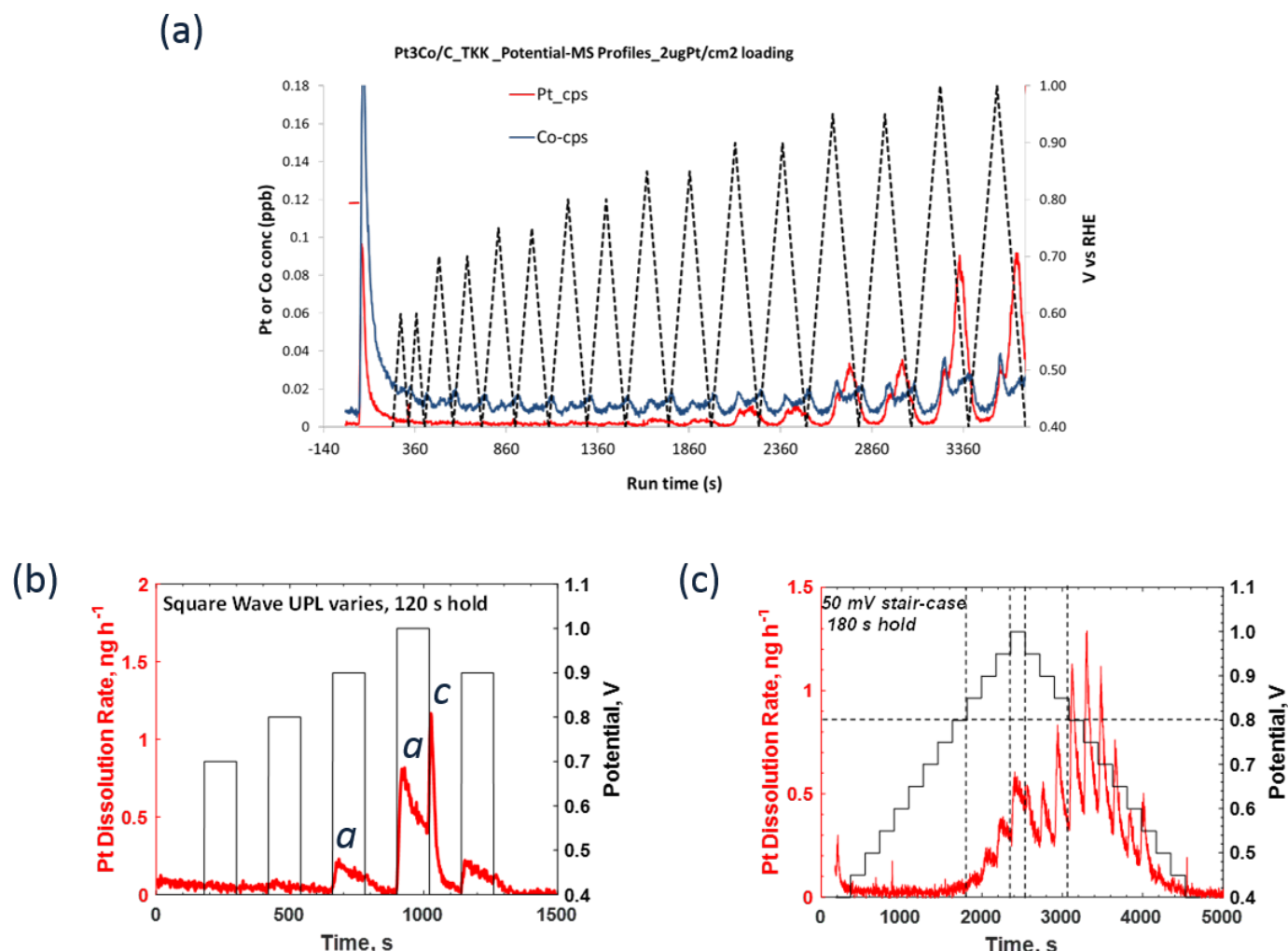
This report focuses on the evaluation of several SOA PtCo electrocatalysts incorporated into the CCL of MEAs, which were studied at BoL and EoL to elucidate the mechanisms of Co and Pt dissolution and subsequent effect on performance loss. Multiple characterization tools (involving most of the thrust areas and unique tools available at the national laboratories) were used to interrogate the stability of several highly active PtCo alloy catalysts, and to understand the degradation issues specific to morphology and chemistry of these alloy catalysts. New tools were optimized (e.g., time-resolved on-line ICP-MS and micro-electrodes) and successfully used by FC-PAD researchers, and will be available for use by the new FC-PAD funding opportunity announcement partners.

RESULTS

A major focus of FC-PAD is understanding CCL degradation, most notable CCLs incorporating Pt-alloy catalysts, and the impact of the catalyst composition, physicochemical properties, and cell operating conditions on catalyst degradation. ANL developed a system for studying the real-time dissolution rates of TM alloying elements and Pt under cyclic potentials using ICP-MS coupled with a thin-layer, flow electrochemical cell. For the initial studies reported here, two types of PtCo catalysts, TKK (TEC36-E52 Pt₃Co) and Umicore (Elyst Pt30 0670 Pt₃Co), were deposited as a catalyst + ionomer thin film on a glassy carbon electrode. The time delay between generation of the dissolved species in the film and detection at the ICP-MS was calibrated using

Au nanoparticles. Initial results were demonstrated using triangle-wave stair-case potential cycling between 0.4–1.0 V (black dashed line in Figure 1a) using the TKK catalyst. The plot in Figure 1a clearly shows the correlation between potential and dissolution, indicating that Co dissolution occurred at all potentials (blue line) and that there were distinct peaks for anodic and cathodic dissolution of Pt (red line) at potentials greater than 0.9 V.

It was determined from the initial triangle-wave experiment (Figure 1a) that improved resolution of anodic and cathodic dissolution could be achieved using square-wave potential cycling (Figure 1b); this protocol also more closely matched the new square-wave catalyst durability AST. Pt will dissolve via several anodic reactions below 0.9 V (e.g., $\text{Pt} = \text{Pt}^{2+} + 2\text{e}^-$), which is evidenced in the stepping



RHE – reference hydrogen electrode

FIGURE 1. (a) Initial triangle-wave stair-case potential cycling between 0.4–1.0 V (dashed line) for TKK Pt₃Co catalyst indicates that Co dissolution occurred at all potentials (blue line) and distinct anodic and cathodic dissolution of Pt at potentials greater than 0.9 V (red line). (b) Square-wave stair-case potential cycling between 0.4–1.0 V shows anodic Pt dissolution below 0.9 V (labeled a) and cathodic Pt dissolution above 0.9 V (labeled c). (c) 50 mV stair-case potential cycles with a UPL of 1.0 V shows that the Pt dissolution rate during cathodic steps is ~3X higher than during anodic steps.

up of the potential from 0.4 V to 0.9 V, labeled *a* in Figure 1b. Higher oxides of Pt will dissolve by multiple cathodic reactions above 0.9 V, as evidenced by the appearance of a large dissolution peak when the potential is stepped down, labeled *c* in Figure 1b. Thus, during square-wave stair-case potential cycling, the anodic peaks increase in magnitude as the potential is stepped up and the cathodic peak is highest during step down from 0.9 V to 0.85 V. For 50 mV stair-case potential cycles with an upper potential limit (UPL) of 1.0 V (Figure 1c), the Pt dissolution rate during cathodic steps is $\sim 3X$ higher than during anodic steps, indicating the formation and dissolution of Pt oxides. The anodic peaks are higher at higher potentials and both anodic and cathodic Pt dissolution rates increase at higher potential steps.

Unlike observations for Pt, Co is unstable and dissolves at all potentials above 0.4 V (Figure 1a). As shown in Figure 2a, a break-in protocol of ~ 1 h conditioning using a 0.4–1.0 V square-wave cycling is required to reach a constant Co dissolution rate. Figure 2b is higher resolution of the square-wave stair-case potential cycling showing that the Co dissolution rate is nearly constant for potentials stepping up to 0.8 V, with prominent anodic peaks above 0.8 V (labeled *a* in Figure 2b) and the highest cathodic peak at the potential step down from 0.8 V to 0.6 V (labeled *c* in Figure 2b). The Co dissolution rate slows during potential holds, suggesting that Co may form oxides. The cathodic dissolution peaks suggest possible coordination of formed Co-oxides with Pt-oxides. Unlike Pt dissolution, the Co dissolution rates during anodic and cathodic steps are comparable.

While multiple PtCo catalysts have been evaluated by the FC-PAD team, this report will focus on the GM SOA PtCo catalyst incorporated into the CCL of an MEA (catalyst loading $0.1 \text{ mg}_{\text{Pt}}/\text{cm}^2$ and electrochemically active surface area [ECSA] of $43 \text{ m}^2_{\text{Pt}}/\text{g}_{\text{Pt}}$; MEA prepared with a DuPont

XL-100 membrane and Pt supported on high surface area carbon [HSAC] anode), which had a BoL PtCo average particle size of 4.5 nm and a Pt:Co composition of 85:15 in the bulk CCL. This MEA was subjected to several AST protocols to evaluate alloy catalyst durability; the old triangle-wave (30,000 [0.6–1.0 V] cycles) AST, the new square-wave (30,000 [0.6–0.95 V] cycles) AST, and the wet-portion of the FCTT drive cycle protocol for 1,200 h (the most aggressive test). Results for the final alloy particle size distributions (PSD) determined by STEM imaging in the CCL after each test are compared to the BoL PSD in Figure 3a, where the resulting particle sizes are labeled according to the specific test (5.0 nm for triangle-wave AST, 5.1 nm for square-wave AST, and 7.4 nm for 1,200 h wet-drive cycle test). More significant is the accompanying change in the individual catalyst nanoparticle compositions shown in Figure 3b as determined from STEM-based energy dispersive X-ray spectroscopy, which exhibit a very distinct particle size vs. composition profile that degrades with the different tests. It is noted that the smaller particles are consistently Pt-rich, whereas the larger particles are Co-rich for the BoL condition, with the average composition in the CCL of 1,000s of particles of 85Pt:15Co. This trend is exacerbated after the various testing protocols (EoL), with the smallest nanoparticles losing nearly all their Co through dissolution, with several of the larger particles showing very high Co levels (note results for most aggressive test, FCTT wet-drive cycle test). This size vs. composition relationship should not be ignored for SOA alloy catalysts; it was observed for all the PtCo catalysts analyzed by FC-PAD to date, and is especially prominent for catalysts exhibiting a wide PSD. After both the square-wave and triangle wave catalyst durability ASTs, the bulk CCL composition changed from 85Pt:15Co at BoL to 90Pt:10Co at EoL, representing a significant loss of Co out of the catalyst nanoparticles into the XL-100 membrane. More

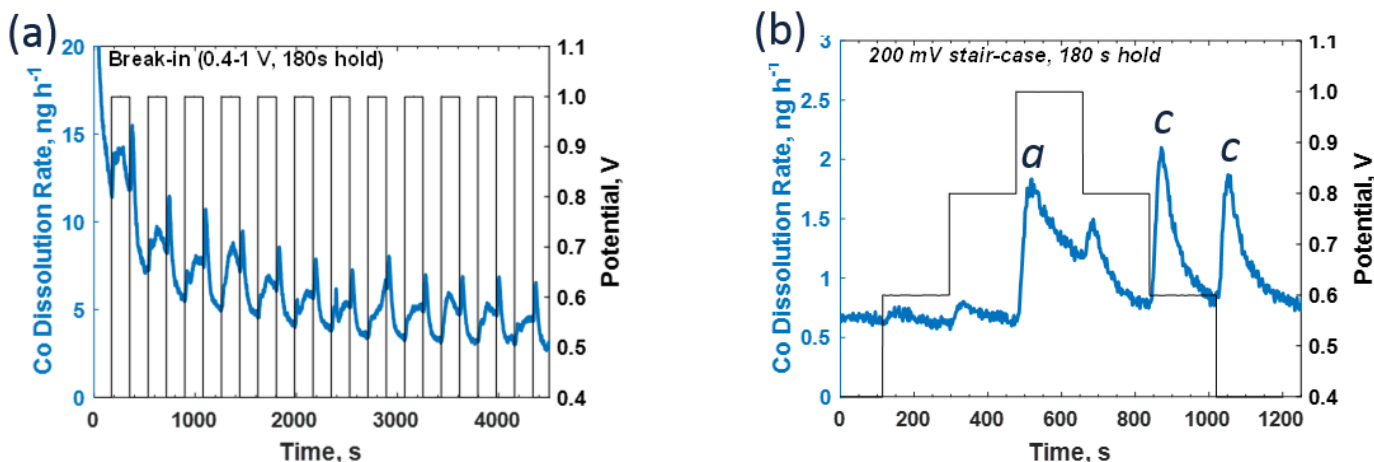


FIGURE 2. (a) Break-in protocol of ~ 1 h conditioning using a 0.4–1.0 V square-wave cycling is required to reach a constant Co dissolution rate. (b) High resolution square-wave stair-case potential cycling between 0.4–1.0 V shows Co dissolution rate is constant for potential stepping up to 0.8 V with anodic peaks above 0.8 V (labeled *a*) and the highest cathodic peak (labeled *c*) at the potential step down from 0.8 V to 0.6 V.

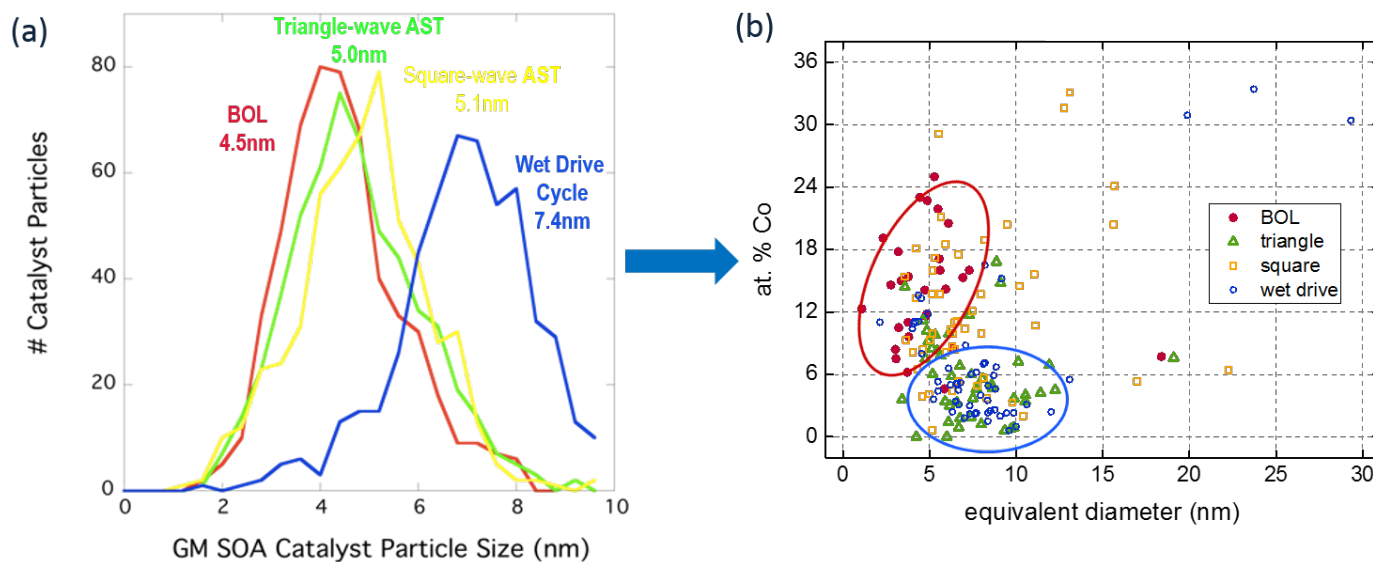


FIGURE 3. (a) GM PtCo catalyst PSDs comparing BoL (red) and EoL conditions (triangle-wave AST, green; square-wave AST, yellow; wet-drive cycle, blue). (b) Particle size vs. composition scatter plot for GM PtCo catalysts in BoL (red) and EoL conditions (triangle-wave AST, green; square-wave AST, yellow; wet-drive cycle, blue).

significantly, after the FCTT wet-drive cycle test for 1,200 h, the composition of the CCL further degraded to 95Pt:5Co, representing a Co loss of greater than 50% out of the CCL and into the XL-100 membrane.

WAXS data collected from the GM CCL at BoL and the three EoL conditions are summarized in Figure 4a. The PSDs determined by small-angle X-ray scattering are consistent with the STEM-based measurements of PSDs for the GM catalyst. The WAXS data is certainly more informative than simple PSDs since these data provide the average change in the (111) *d*-spacing as a function of testing protocol. Interestingly, as the GM PtCo catalyst is subjected to more aggressive testing (compare GM BoL to GM square-wave EoL and GM wet-drive EoL), the (111) *d*-spacing values become larger indicating that as more Co is lost (dissolves/leaches) out of the catalyst nanoparticles, the PtCo electrocatalysts become more “Pt-like.”

Figure 4b shows polarization curves comparing all the PtCo catalysts evaluated by FC-PAD to date (SOA GM, Umicore, EWii catalysts) with Pt-only (ECSA vs. number of potential cycles); each of these PtCo catalysts are supported on HSAC and exhibit differences in initial particle size, morphology, and composition. While the initial characteristics of the various PtCo catalysts are different, it is interesting to note that after square-wave catalyst durability AST, the EoL ECSAs converge to the same value after 30,000 0.6–0.95 V cycles, matching the EoL ECSA of Pt-only catalysts.

CONCLUSIONS AND UPCOMING ACTIVITIES

Work conducted during the previous year has been highly focused on understanding the durability and performance of Pt-alloy catalysts. The FC-PAD team evaluated a series of SOA PtCo catalysts from various sources (GM, Umicore, EWii) in terms of size, composition, and morphology using microscopy, ICP-MS, and X-ray scattering methods, in the BoL and EoL (following several different ASTs) conditions. The Co leaching during AST was quantified, and it was determined that regardless of the starting structure and composition, all the alloy catalysts behaved similarly in terms of compositionally stability, e.g., all catalysts lost greater than 50% of the Co, which resulted in the electrocatalysts becoming more Pt-like and Co migration into the membrane.

Future work will continue to focus on alloy catalyst durability, with a specific emphasis on assessing catalysts with different morphologies and compositions (for example, core-shell catalysts and ordered structures). The FC-PAD team will continue to develop, optimize, and apply unique methods towards understanding alloy cathode catalyst durability and performance. The work will be highly focused on fundamental dissolution studies of selected alloy catalysts; for example, particle size and morphological effects. These data, in combination with microscopy and X-ray scattering, will provide input for catalyst (and catalyst layer) degradation models. In addition, the FC-PAD team will improve methods to interrogate ionomer thin films (layers) within the electrodes to further our understanding of dissolution effects on ionomer transport properties, which will be coordinated

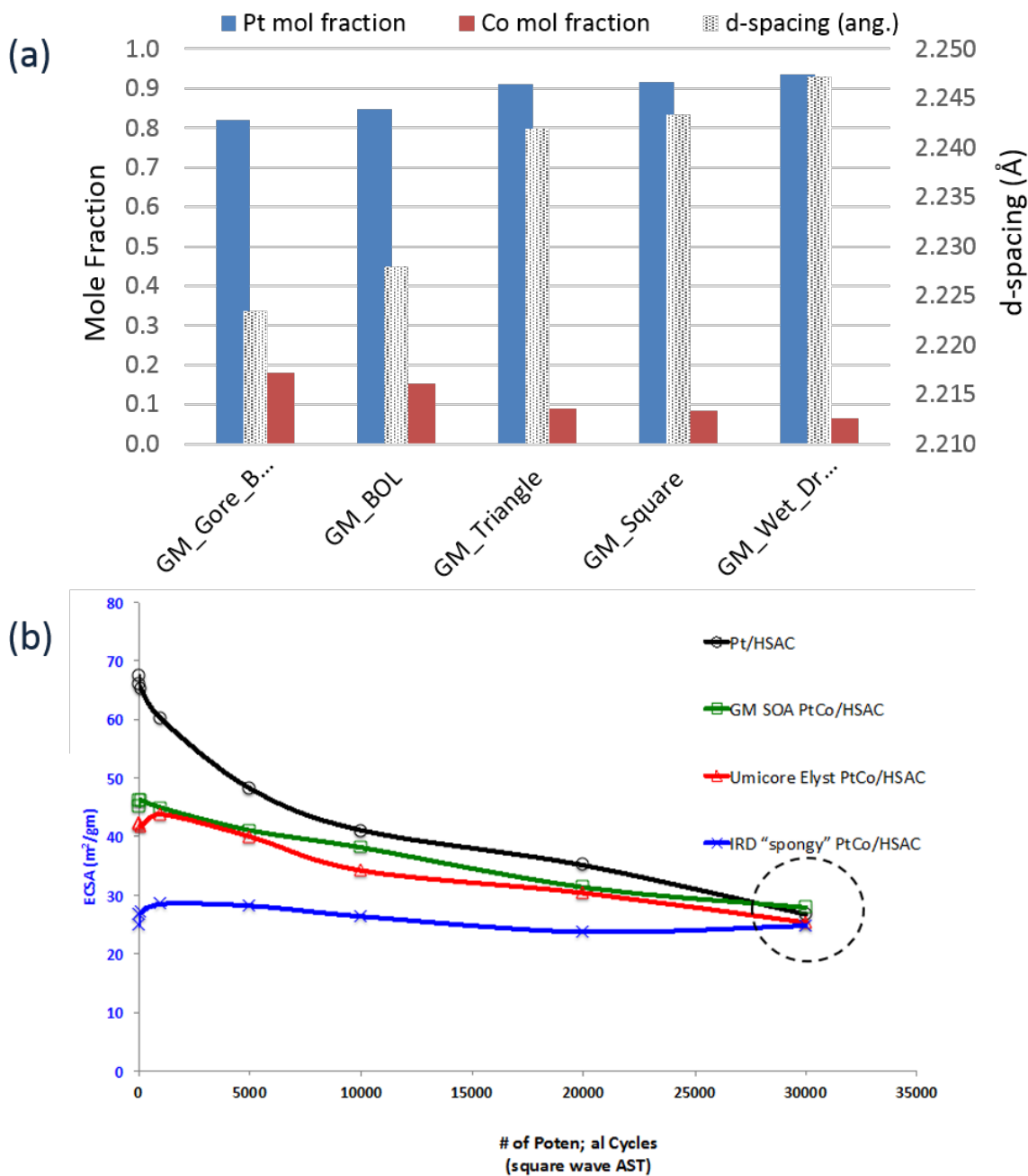


FIGURE 4. (a) WAXS data comparing PtCo catalysts for BoL and EoL conditions showing that PtCo catalysts become more Pt-like with more aggressive testing. (b) Polarization curves comparing all PtCo catalysts evaluated by FC-PAD team showing that regardless of initial nanoparticle size, morphology, and ECSA, after square-wave AST (30,000 [0.6–0.95 V] cycles) the EoL ECSAs converge to values consistent with Pt-only catalyst.

with model studies of ionomer thin films. These fundamental studies will be coupled with refinement of ASTs to study specific materials components within catalyst layers, most notably related to catalyst and ionomer stability towards improving performance and durability.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Ahmet Kusoglu received the Supramaniam Srinivasan Early Career Award from the Energy Technology Division of the Electrochemical Society.
2. Ahmet Kusoglu received a Toyota Young Investigator Award from Electrochemical Society (ECS).

3. Andrew Baker received the Bill Baron Fellowship in recognition of his contributions related to the renewable energy field from the University of Delaware.
4. Rangachary (Mukund) Mukundan was named a 2017 Fellow of the Electrochemical Society.
5. Karren More was named ORNL's "Mentor of Early Career Researchers," November 2016.

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1. R. Borup, A. Baker, A. Kusoglu, Rangachary Mukundan, J. Dumont, D. Langlois, A. Weber, R. Ahluwalia, D. Myers, S. Kocha, K. More. *FC-PAD: Fuel Cell Performance and Durability Consortium*. U.S. DOE Annual Progress Report 2017.
2. A. Weber, A. Kusoglu, T. Schuler, S. Berlinger, L. Pant, A. Freiberg, M. Tesfaye, R. Mukundan, S. Babu, N. Macauley, J. Spendelaw, M. Wilson, R. Borup, K. More, B. Sneed, S. Kocha, K.C. Neyerlin, D. Myers, F. Cetinbas, R. Ahluwalia. *FC-PAD: Electrode Layers and Optimization*. U.S. DOE Annual Progress Report 2017.

FY 2017 PUBLICATIONS/PRESENTATIONS

The list below includes all publications and presentations relevant to FC-PAD from consortium members representing the three FC-PAD annual merit presentations and reports: FC135 (V.B.1), FC136 (V.B.2), and FC137 (V.B.3).

Publications Relevant to FC-PAD from Consortium Members

1. I.V. Zenyuk, P.K. Das, and A.Z. Weber, "Understanding Impacts of Catalyst-Layer Thickness on Fuel-Cell Performance via Mathematical Modeling," *Journal of the Electrochemical Society* **163**[7] F691–F703 (2016).
2. A. Kusoglu, T.J. Dursch, and A.Z. Weber, "Nanostructure/Swelling Relationships of Bulk and Thin-Film PFSA Ionomers," *Advanced Functional Materials* **26** 4961–4975 (2016).
3. S. Shi, A.Z. Weber, and A. Kusoglu, "Structure/property Relationship of Nafion XL Composite Membranes," *Journal of Membrane Science* **516** 123–134 (2016).
4. I. Zenyuk, D.Y. Parkinson, L.G. Connolly, and A.Z. Weber, "Gas-Diffusion-Layer Structural Properties under Compression via X-Ray Tomography," *Journal of Power Sources* **328** 364–376 (2016).
5. S. Shi, A.Z. Weber, and A. Kusoglu, "Structure-Transport Relationship of Perfluorosulfonic-Acid Membranes in Different Cationic Forms," *Electrochimica Acta* **220** 517–528 (2016).
6. I. Zenyuk, A. Lamibrac, J. Eller, D. Parkinson, F. Marone, F. Büchi, and A.Z. Weber, "Investigating Evaporation in Gas Diffusion Layers for Fuel Cells with X-ray Computed Tomography," *Journal of Physical Chemistry C* **120**[50] 28701–28711 (2016).
7. N. Macauley, R. Mukundan, D.A. Langlois, K.C. Neyerlin, S.S. Kocha, K.L. More, M. Odgaard, and R.L. Borup, "Durability of PtCo/C Cathode Catalyst Layers Subjected to Accelerated Stress Testing," *ECS Transactions* **75**[14] 281–287 (2016).
8. A.M. Baker, R. Mukundan, D. Spornjak, S.G. Advani, A.K. Prasad, and R.L. Borup, "Cerium Migration in Polymer Electrolyte Membranes," *ECS Transactions* **75**[14] 707–714 (2016).
9. K. Shinozaki, Y. Morimoto, B.S. Pivovar, and S.S. Kocha, "Suppression of Oxygen Reduction Reaction Activity on Pt-based Electrocatalysts from Ionomer Incorporation," *Journal of Power Sources* **325** 745–751 (2016).
10. K. Shinozaki, Y. Morimoto, B.S. Pivovar, and S.S. Kocha, "Re-examination of the Pt Particle Size Effect on the Oxygen Reduction Reaction for Ultrathin Uniform Pt/C Catalyst Layers without Influence from Nafion," *Electrochimica Acta* **213** 783–790 (2016).
11. N. Macauley, R.W. Lujan, D. Spornjak, D.S. Hussey, D.L. Jacobson, K.L. More, R.L. Borup, and R. Mukundan, "Durability of Polymer Electrolyte Membrane Fuel Cells Operated at Subfreezing Temperatures," *Journal of The Electrochemical Society* **163**[13] F1317–F1329 (2016).
12. A.M. Baker, R. Mukundan, D. Spornjak, E.J. Judge, S.G. Advani, A.K. Prasad, and R.L. Borup, "Cerium Migration during PEM Fuel Cell Accelerated Stress Testing," *Journal of The Electrochemical Society* **163**[9] F1023–F1031 (2016).
13. C.F. Cetinbas, R.K. Ahluwalia, N. Kariuki, V. De Andrade, D. Fongalland, L. Smith, J. Sharman, P. Ferreira, S. Rasouli, and D.J. Myers, "Hybrid Approach Combining Multiple Characterization Techniques and Simulations for Microstructural Analysis of Proton Exchange Membrane Fuel Cell Electrodes," *Journal of Power Sources* **344** 62–73 (2017).
14. A. Kusoglu and Adam Z. Weber, "New Insights into Perfluorinated Sulfonic-Acid (PFSA) Ionomers," *Chemical Reviews* **117**[3] 987–1104 (2017).
15. S. Shukla, S. Bhattacharjee, A.Z. Weber, and M. Secanell, "Experimental and Theoretical Analysis of Ink Dispersion Stability for Polymer Electrolyte Fuel Cell Applications," *Journal of the Electrochemical Society* **164**[6] F600–F609 (2017).
16. L.M. Pant and A.Z. Weber, "Modeling Transport in PEFC Cathode Agglomerates with Double Trap Kinetics," *Journal of the Electrochemical Society* **164**[11] E3081–E3091 (2017).
17. F.B. Spingler, A. Phillips, T. Schuler, M.C. Tucker, and A.Z. Weber, "Investigating Fuel-Cell Transport Limitations using Hydrogen Limiting Current," *International Journal of Hydrogen Energy* **42**[19] 13960–13969 (2017).
18. A.T.S. Freiberg, M.C. Tucker, and A.Z. Weber, "Polarization Loss Correction Derived from Hydrogen Local-Resistance Measurement in Low Pt-Loaded Polymer-Electrolyte Fuel Cells," *Electrochemistry Communications* **79** 14–17 (2017).
19. B.T. Sneed, D.A. Cullen, K.S. Reeves, O.E. Dyck, D.A. Langlois, R. Mukundan, R.L. Borup, and K.L. More "3D Analysis of Fuel Cell Electrocatalyst Degradation on Alternate Carbon Supports," accepted for publication in *ACS Applied Materials & Interfaces*.

Presentations Relevant to FC-PAD from Consortium Members

1. A. Kusoglu, "State of Understanding of PFSA Ionomers and Thin Films," Gordon Research Conference (GRC) Fuel Cells, Easton, MA (2016).

2. A. Kusoglu, "New Insights into PFSA Ionomers: From Membranes to Thin Films," 3M Company, Minneapolis, MN (2017).
3. A.Z. Weber (Keynote), "Multiscale Modeling of Polymer-Electrolyte-Fuel-Cell Components," Meeting Abstracts, MA2016-01 (2016) 2211.
4. A. Shum, K.B. Hatzell, L.G. Connolly, O.S. Burheim, D.Y. Parkinson, A.Z. Weber, and I.V. Zenyuk, "Exploring Phase-Change-Induced Flow in Fuel Cells through X-Ray Computed Tomography," PRiME 2016 - 230th ECS Meeting, Honolulu, HI (2016).
5. T. Schuler, M.C. Tucker, and A.Z. Weber, "Gas-Transport Resistances in Fuel-Cell Catalyst Layers," PRiME 2016 - 230th ECS Meeting, Honolulu, HI (2016).
6. A.Z. Weber, L. Pant, T. Schuler, H. Shiau, A. Freiberg, M.C. Tucker, A. Chowdhury, K.C. Neyerlin, S. Kocha, and I. Zenyuk, "Elucidating and Understanding Transport Phenomena in Polymer-Electrolyte Fuel Cells," CARISMA, Newcastle upon Tyne, UK (2017).
7. A.Z. Weber (Invited), T. Schuler, F. Spingler, A. Freiberg, M.C. Tucker, A. Chowdhury, K.C. Neyerlin, and A. Kusoglu, "Ionomer-Associated Transport Resistances in Fuel Cell Electrodes," 21st International Conference on Solid State Ionics, Padua, Italy (2017).
8. A.R. Crothers, S. Shi, P. Dudenas, A. Kusoglu, and A.Z. Weber, "Structure-Transport Relationships of Perfluorinated-Sulfonic-Acid Membrane Interfaces," Polymer-Electrolyte Fuel Cell Components, Asilomar, CA (2017).
9. A.R. Crothers, C. Radker, and A.Z. Weber, "Elucidating Multiscale, Multiphysics Coupled Transport Phenomena in Polymer-Electrolyte Membranes Structure-Transport Relationships of Perfluorinated-Sulfonic-Acid Membrane Interfaces," Coupled Problems, Rhodes, Greece (2017).
10. P.A. García-Salaberri, J.T. Gostick, G.Hwang, M. Vera, I. Zenyuk, and A.Z. Weber, "Multiphysics, Multiphase and Multiscale Modeling of Polymer Electrolyte Fuel Cells: With a Focus on the Gas Diffusion Layers," Coupled Problems, Rhodes, Greece (2017).
11. A. Shum, L. Connolly, K.B. Hatzell, X. Xiao, D.Y. Parkinson, O. Burheim, A.Z. Weber, and I.V. Zenyuk, "In-Situ Examination of Phase-Change-Induced Flow in Gas Diffusion Layers and Water Distribution in Microporous Layers using X-Ray Computed Tomography," MRS Fall Meeting, Boston, MA (2016).
12. A.Z. Weber (Invited), "Understanding Transport in Polymer-Electrolyte-Fuel-Cell Ionomers," Mechanical Engineering Seminar, UC Merced, CA (2016).
13. A. Kusoglu (Invited), "Ion-Conductive Polymer for Energy Conversion Devices," Mechanical Engineering Department Seminar, UC Berkeley, CA (2017).
14. A. Kusoglu, "Structural Characterization of Ionomers using X-rays," Advanced Light Source, Chemical Sciences Seminar Series, LBNL, Berkeley, CA (2016).
15. A. Kusoglu, "New Insights into PFSA Ionomers," National Renewable Energy Laboratory, Golden, CO (2017).
16. A. Kusoglu, S. Shi, and A.Z. Weber, "Impact of Cation Form on Structure/Function Relationships of Perfluorosulfonic Acid Ionomers," APS Meeting, New Orleans, LA (2017).
17. A. Kusoglu, S. Shi, and A.Z. Weber, "Impact of Equivalent Weight and Side-Chain on Structure/Functionality of PFSA Ionomers," PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
18. I.V. Zenyuk, A. Lamibrac, J. Eller, F.N. Büchi, and A.Z. Weber, "Understanding Evaporation in Fuel-Cell Gas-Diffusion Layers with X-ray Computed Tomography," 8th International Conference on Porous Media, Cincinnati, OH (2016).
19. M. Tesfaye, B.D. McCloskey, and A.Z. Weber, "Gas Permeation Study in Thin and Ultra-thin Ionomer Films," PRiME 2016 – 230th ECS Fall Meeting, Honolulu, HI (2016).
20. A.R. Crothers, S. Shi, C.J. Radke, and A.Z. Weber, "Decoupling the Influences of Molecular- and Mesoscales on Macroscopic Transport Properties in Perfluorosulfonic-acid Membranes," PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
21. I.A. Cordova, C. Wang, A.Z. Weber, R.A. Segalman, M.A. Brady, and G.M. Su, "Operando Resonant Soft X-Ray Scattering As a Spatio-Chemical Characterization Technique for Electrochemistry," PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
22. K. Hatzell, A. Kusoglu, P. Dudenas, N. Kariuki, D. Myers, and A. Weber, "Indirect and Direct Observation of Ionomer Colloidal Systems with Applications to Membrane Electrode Assemblies for Energy Conversion Systems," PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
23. A. Freiberg, T. Schuler, F. Spingler, M.C. Tucker, and A.Z. Weber, "Determination and Origin of Local Resistances in PEFC Catalyst Layers," ISE Annual Meeting, Hague, The Netherlands (2016).
24. A. Shum, K.B. Hatzell, L. Connolly, O. Burheim, D.Y. Parkinson, A.Z. Weber, and I.V. Zenyuk, "Understanding Phase-Change-Induced Flow in PEFCs Through In-situ X-ray Computed Tomography," ISE Annual Meeting, Hague, The Netherlands (2016).
25. A. Kusoglu, "Morphology of PFSA Ionomers and Thin Films," 21st International Conference on Solid State Ionics, Padua, Italy (2017).
26. R.L. Borup (Invited), "Material Degradation in PEM Fuel Cell Electrodes," 231st ECS Meeting, New Orleans, LA (2017).
27. R.L. Borup (Invited), "The FC-PAD Consortium: Advancing Fuel Cell Performance and Durability," 231st ECS Meeting, New Orleans, LA (2017).
28. R.L. Borup (Invited), R. Mukundan, A. Baker, D. Spornjak, D. Langlois, S. Stariha, N. Macauley, K. More, S. Kocha, A.Z. Weber, D. Myers, and R. Ahluwalia, "Material Degradation in PEM Fuel Cell Electrodes," CARISMA, Newcastle upon Tyne, United Kingdom (2017).
29. R.L. Borup (Invited), A.Z. Weber, D. Myers, S. Kocha, R. Ahluwalia, R. Mukundan, and K. More, "The FC-PAD Consortium: Material Degradation in PEM Fuel Cell Electrodes," EMN Meeting on Fuel Cells 2017, Prague, Czech Republic (2017).

- 30.** R.L. Borup (Invited), A.M. Baker, R. Mukundan, D. Spornjak, E.J. Judge, S.G. Advani, and A.K. Prasad, “Membrane Degradation in PEM Fuel Cells: Antioxidant Migration and Recoverable Degradation Losses,” 21st International Conference on Solid State Ionics, Padua, Italy (2017).
- 31.** D. Myers (Invited), “Structural Characterization of Polymer Electrolyte Fuel Cell Cathode Catalyst Layers,” NCNR/LENS Workshop, National Institute of Science and Technology (2016).
- 32.** F. Cetinbas, R. Ahluwalia, N. Kariuki, K. More, D. Cullen, B. Sneed, R. Winarski, J. Ilavsky, V. De Andrade, and D. Myers, “Structural Characterization and Transport Modeling of Pt and Pt Alloy Polymer Electrolyte Fuel Cell Cathode Catalyst Layers,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 33.** R.L. Borup (Invited), “FC-PAD: PEM Fuel Cell Durability,” Workshop on Recent Advances in PEMFCs, CEA, Grenoble, France (2016).
- 34.** S.S. Kocha, “Investigation of the Performance of PtCo/C Cathode Catalyst Layers for ORR Activity and Rated Power for Automotive PEMFCs,” PRIME 2016 – 230th ECS Meeting Honolulu, HI (2016).
- 35.** K.C. Neyerlin (Invited), “Low Pt Resistances,” DOE Transport Modeling and Durability Working Group, Lawrence Berkeley National Laboratory, Berkeley, CA (2016).
- 36.** K.C. Neyerlin (Invited), “Examinations of Kinetic and Transport Losses in Low Pt Electrodes,” DOE Catalysis Working Group, Argonne National Laboratory, Argonne, IL (2016).
- 37.** K.C. Neyerlin (Invited), “Examinations of Kinetic and Transport Losses in Low Pt Electrodes,” GRC on Fuel Cells, Easton, MA (2016).
- 38.** R. Borup, “On Track for a Clean, Hydrogen-powered Future,” Santa Fe, NM (2016).
- 39.** R. Borup, “Forget Jetpacks. Where are our Hydrogen-powered Cars?” The Huffington Post (2016).
- 40.** R. Borup, Video: Science in 60–A Clean, Renewable Power Source, LANL, Los Alamos, NM (2016).
- 41.** N. Macauley, R.L. Borup, R. Mukundan, M.S. Wilson, D. Spornjak, K.C. Neyerlin, S.S. Kocha, and S. Grot, “Performance of Stratified Fuel Cell Catalyst Layers,” 231st ECS Meeting, New Orleans, LA (2017).
- 42.** D. Spornjak (Invited), R.L. Borup, D.S. Hussey, P. Zelenay, and R. Mukundan, “Imaging Fuel Cell Components: From Flow Field Channels to Catalyst Layers,” 231st ECS Meeting, New Orleans, LA (2017).
- 43.** D.A. Cullen (Invited), B.T. Sneed, and K.L. More, “Fuel Cell Electrode Optimization through Multi-Scale Analytical Microscopy,” Microscopy & Microanalysis 2016, Columbus, OH (2016).
- 44.** D.A. Cullen, B.T. Sneed, and K.L. More, “Fuel Cell Electrode Optimization through Multi-Scale Analytical Microscopy,” GRC on Fuel Cells, Easton, MA (2016).
- 45.** K.L. More (Invited Plenary), “Correlating Structure and Chemistry of PEM Fuel Cell Materials with Performance and Durability using Advanced Microscopy Methods,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 46.** K.L. More (Invited), “Correlating Structure and Chemistry of PEM Fuel Cell Materials with Performance and Durability using Advanced Microscopy Methods,” University of Illinois – Chicago, Departmental Seminar, Chicago, IL (2016).
- 47.** B.T. Sneed, D.A. Cullen, K.S. Reeves, and K.L. More, “3D STEM Analysis of Ionomer Dispersion and Pore Structures within PEM Fuel Cell Catalyst Layers,” MRS Fall Meeting, Boston, MA (2016).
- 48.** B.T. Sneed, D.A. Cullen, K.S. Reeves, and K.L. More, “Structural and Chemical Study of the Stability of Pt-Based Fuel Cell Electrocatalysts in 3D via Electron Tomography,” Pacific Rim Symposium on Surfaces, Coatings, and Interfaces (PAC-SURF), Kohala Coast, HI (2016).
- 49.** K.L. More (Invited), B.T. Sneed, and D.A. Cullen, “Understanding Fuel Cell Materials Degradation Through the Use of Advanced Microscopy Methods,” 231st ECS Meeting, New Orleans, LA (2017).
- 50.** K.L. More (Invited), B.T. Sneed, and D.A. Cullen, “Critical interfaces in PEM Fuel Cells: Understanding Behavior through Advanced Microscopy Studies,” 21st International Conference on Solid State Ionics, Padua, Italy (2017).
- 51.** R. Mukundan, D. Spornjak, D. Hussey, D. Jacobson, and R.L. Borup, “Applications of High Resolution Neutron Imaging to Polymer Electrolyte Fuel Cells,” 253rd ACS National Meeting, San Francisco, CA (2017).
- 52.** R. Mukundan, D.A. Langlois, K.C. Neyerlin, S.S. Kocha, K.L. More, M. Odgaard, and R.L. Borup, “Durability of PtCo/C Cathode Catalyst Layers Subjected to Accelerated Stress Testing,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 53.** R.L. Borup, R. Mukundan, D. Spornjak, D.A. Langlois, N. Macauley, and Y.S. Kim, “Recoverable Degradation Losses in PEM Fuel Cells,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 54.** A.M. Baker, D. Spornjak, E.J. Judge, S.G. Advani, and A.K. Prasad, “Cerium Migration in PEM Fuel Cells,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 55.** D.S. Hussey, J.M. LaManna, D.L. Jacobson, S.W. Lee, J. Kim, B. Khaykovich, M.V. Gubarev, D. Spornjak, R. Mukundan, and R.L. Borup, “Neutron Imaging of the MEA Water Content of PEMFCs in Operando,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).
- 56.** J.S. Spendelow, L. Castanheira, G. Hinds, T. Rockward, D.A. Langlois, R. Mukundan, and R.L. Borup, “Measurement of Local Electrode Potentials in an Operating PEMFC Exposed to Contaminants,” PRiME 2016 – 230th ECS Meeting, Honolulu, HI (2016).