# V.B.1 FC-PAD: Fuel Cell Performance and Durability Consortium

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Project End Date: September 30, 2021

## Overall Objectives

- Advance performance and durability of polymer electrolyte membrane fuel cells (PEMFCs) primarily at a pre-competitive level.
- Develop the knowledge base and optimize structures for more durable and high-performance PEMFC components.
- Improve high current density performance at low Pt loadings.
  - Loading: 0.125 mg Pt/cm$^2$ total
  - Performance @ 0.8 V: 300 mA/cm$^2$
  - Performance @ rated power: 1,000 mW/cm$^2$
- Improve component durability (e.g., membrane stabilization, self-healing, electrode-layer stabilization).
- Provide support to industrial and academic developers.
- Develop new diagnostics, characterization tools, and models.
- Each thrust area has a sub-set of objectives which lead to the overall performance and durability objectives.

## Fiscal Year (FY) 2017 Objectives

- Quantify cerium migration and diffusion within the membrane under both applied potential and applied current, including modeling of the migration.
- Demonstrate methods to stabilize cerium migration, improving membrane durability.
- Measure cation effects on membrane conductivity and water uptake.
- Measure effect of ionomer-cations on the oxygen reduction reaction (ORR).
- Establish database of Ce/ceria, carbon corrosion effects, and ionomer distribution observations as input data for model development.

## Technical Barriers

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

(A) Durability

(B) Cost

(C) Performance

## Technical Targets

This project develops membrane electrode assemblies (MEAs) that meet the targets in Table 1.

**TABLE 1.** Technical Targets: 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 $kPa_{abs}$) | m /cm$^2$ | 1,000 |

## FY 2017 Accomplishments

- Measured cerium migration in-plane, through-plane, and in in situ hydrogen pump mode.
- Analyzed cerium data to quantify migration and diffusion coefficients (at 100% relative humidity [RH]).
- Measured cation effect on conductivity and ORR in microelectrodes.
  - Measured reductions in microelectrode current due to cation content in ionomer.
- Identified Ce/carbon interactions as a likely cause for Ce stabilization in the catalyst layers.
- Measured a large improvement in membrane durability by incorporating Ce as CZO (cerium-zirconia) over similar concentrations of ion-exchange cerium.
- Measured perfluorinated sulfonic acid (PFSA) conductivity as a function of cation and water content.
  - Large/heavy cations → disrupt domains → lower uptake
  - Multi-valent cations → ionic crosslinks → restricted mobility
  - Conductivity *scales with water per charge*, not per poly(anion).
- Conducted a comparison study of perfluoroimide acid versus PFSA water uptake and conductivity.

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## INTRODUCTION

Although fuel cells are being deployed in cars with limited commercialization, they still fall short of the DOE targets for this technology, which are required for widespread consumer acceptance. The FC-PAD consortium was formed to advance performance and durability of PEMFCs at a pre-competitive level to further enable their commercialization. This consortium coordinates national laboratory activities related to fuel-cell performance and durability, provides technical expertise, and harmonizes activities with industrial developers. The consortium serves as a resource that amplifies the Office of Energy Efficiency and Renewable Energy impact by leveraging the core capabilities of several labs.

The major challenge to be addressed by this consortium is to develop the knowledge base and optimize structures for more durable, high-performing PEMFC component technologies, while simultaneously reducing cost. Current research is focused on achieving high performance and durability in low-Pt-loaded PEMFCs.

For FY 2017, FC-PAD is represented by three annual merit review presentations and annual progress reports:

- FC135 FC-PAD: Fuel Cell Performance and Durability Consortium (this report)
- FC136 FC-PAD: Components and Characterization (primary contact: Karren More)
- FC137 FC-PAD: Electrode Layers and Optimization (primary contact: Adam Weber)

FC-PAD is an integrated consortia of five national laboratories with a large number of contributing staff scientists, research technicians, post-docs, and students. For FY 2017, FC-PAD contributors were:

- **Argonne National Laboratory:** Debbie Myers, Rajesh Ahluwalia, Nancy Kariuki, Dennis Papadias, C. Firat Cetinbas, J-K Peng, Xiaohua Wang;
- **Lawrence Berkeley National Laboratory:** Adam Weber, Ahmet Kusoglu, Kelsey Hatzell, Lalit Pant, Huai-Suen Shiau, Anna Freiburg, Meron Tesfaye, Anamika Chowdhury, Sarah Berlinger, Andrew Crothers, Grace Lau, Michael Tucker, Clayton Radke, Thomas Chan;
- **Los Alamos National Laboratory:** Rangachary Mukundan, Rod Borup, Natalia Macauley, Mahlon Wilson, Yu Seung Kim, Sarah Stariha, David Langlois, Roger Lujan, Siddharth Komini Babu, Andrew Baker, Joseph Dumont, Jacob Spendelow;
- **National Renewable Energy Laboratory:** Shyam Kocha, KC Neyerlin, Nihal Shah, Jason Zack, Jason Christ, Huyen Dinh, Guido Bender, Jocelyn Mackay, Lawrence Anderson;
- **Oak Ridge National Laboratory:** Karren More, David Cullen, Brian Sneed, Shawn Reeves.

## APPROACH

This consortium incorporates national laboratory investigators with proven experience (developed in prior projects) related to durability, transport, and performance, and combines them into one highly coordinated effort. The consortium formalizes already existing and effective collaborations among the national laboratories that have established leadership in PEMFC performance and durability research and development. Three thrust areas are related to components: (1) electrocatalysts and supports; (2) electrode layers; (3) ionomers, gas diffusion layers, bipolar plates, interfaces; three additional thrust areas are cross-cutting in nature; (4) modeling and validation; (5) operando evaluation–benchmarking, accelerated stress tests (ASTs), and contaminants; and (6) component characterization and diagnostics.

Four FC-PAD projects from DE-FOA-0001412 were announced by DOE during FY 2017. Those projects are led by 3M Company, General Motors, United Technologies Research Center, and Vanderbilt University. The core national lab team is working to support those four projects with an equal level of effort utilizing national lab capabilities. A national lab primary point of contact was assigned for each project, with a statement of work negotiated for FY 2017. National lab work for those projects is represented in those project reports.

## RESULTS

The results in this FC-PAD report are limited to our work related to membrane durability and understanding the membrane structure and performance.

Cerium is an additive used to improve the durability of fuel cell polymer electrolyte membranes (PEMs); however, migration of cerium (Ce) can be an issue. Cerium ions enhance the durability of PEM fuel cell components by rapidly and reversibly scavenging degrading radical species, which can be generated during operation. However, Ce migrates between the membrane and the catalyst layers (CLs). The migration of cerium is demonstrated in Figure 1, where a fresh MEA has a large concentration of cerium in the membrane (Figure 1a); however, after testing either by AST holding the cell at open circuit potential (Figure 1b) or operating the U.S. Drive Cycle Protocol (Figure 1c), little cerium remains in the membrane, with the majority residing in the catalyst layers, both anode (aCL) and cathode (cCL).

Hydrogen pump experiments were utilized in FY 2017 to understand the effects of potential gradients and proton/water flux on Ce migration. Figure 2 shows two-dimensional Ce maps during hydrogen pump experiments performed at 2 V and 100% RH for different amounts of charge transfer. The cerium concentration profiles show a progression of cerium migration to the counter electrode with time and charge transfer. After complete migration of the cerium, potential was removed and the corresponding time-dependent diffusion measured to define a cerium diffusion coefficient. With this cerium diffusion coefficient, a migration coefficient was modeled by the Nernst-Plank equation (Equation 1):

$$\frac{\delta c}{\delta t} + \text{V}. (-D\text{V}c - zu_m F c \text{V}\varphi_{ionic}) = 0 \qquad (1)$$

The coefficients determined and used in the modeling (solid lines) were:

- Diffusion Coefficient 0.686 [$\times 10^{-10}$ $m^2$ $s^{-1}$]
- Mobility 7.2±0.8 [$\times 10^{-15}$ s mol $kg^{-1}$]

To improve membrane durability to alleviate issues with migration, we have employed more effective radical scavengers in the cathode CL, nearest to the location of peroxide and reactive hydroxyl radical generation, based on CZO (cerium-zirconia) [1]. CZO addition to the cathode CL at a loading of 10 µg/$cm^2$ improved the durability of Nafion XL PEMs, which is demonstrated by reduced electrochemical gas crossover, open circuit voltage decay, and fluoride emission rates (shown in Figure 3) during PEM chemical stability ASTs. Additionally, this improvement in durability counteracts undesirable Ce migration due to ionomer degradation. The overall degradation rate, indicated by average fluoride emission rate (FER) over the test duration, also correlates well to the final Ce content in the PEM after ASTs. This result is consistent with our hypothesis that during aggressive ASTs, Ce movement from the PEM into the CLs is affected by degradation of the Ce-containing ionomer, itself. Therefore, employing a highly effective radical scavenger, such as CZO, dramatically mitigates PEM degradation, which negates the effects of Ce migration due to side chain scission. MEAs with improved chemical stability, which do not compromise cell performance, as shown here, directly address barriers of lifetime and cost which currently hinder PEM fuel cell commercialization.

A large effect of cations such as cerium is the reduction of water uptake and loss of conductivity. A series of cations

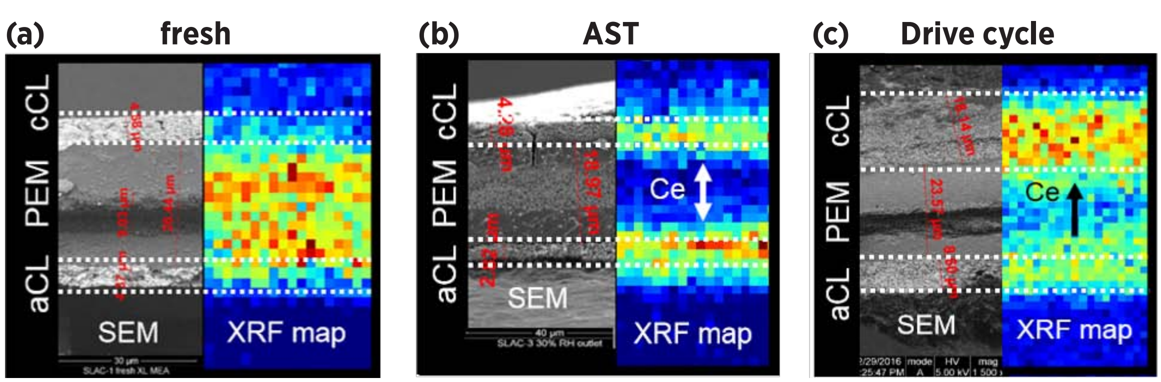
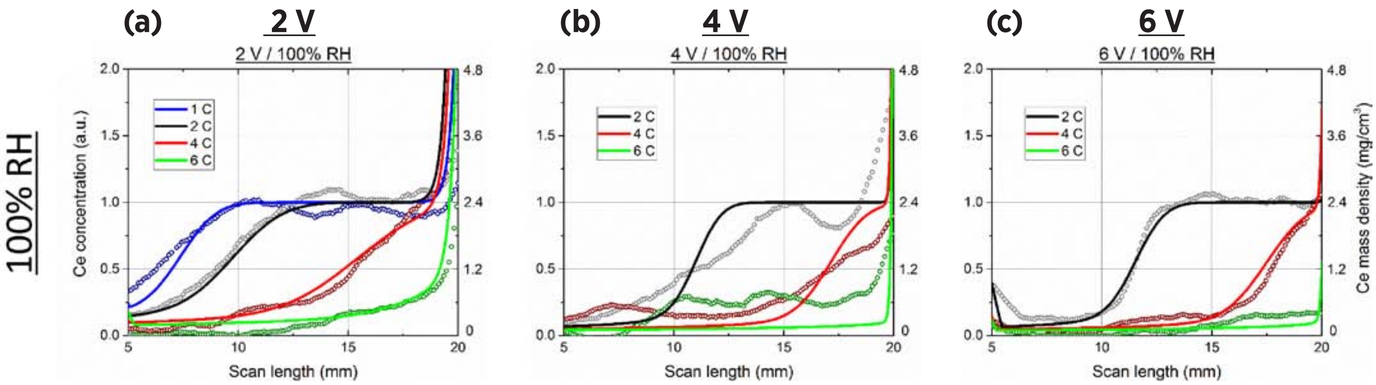



**FIGURE 1.** Cross-section images by scanning electron microscopy (SEM) and cerium mapping by X-ray fluorescence (XRF) of (a) fresh MEA, (b) an MEA after the membrane open circuit potential AST, and (c) an MEA after the U.S. Drive Cycle test




a.u. – arbitrary units

**FIGURE 2.** Cerium profiles by XRF measurement and modeled post hydrogen pump operation after 1 coulomb (blue), 2 coulombs (black), 4 coulombs (red), and 6 coulombs of charge transfer at (a) 2 V, (b) 4 V, and (c) 6 V at 100% RH

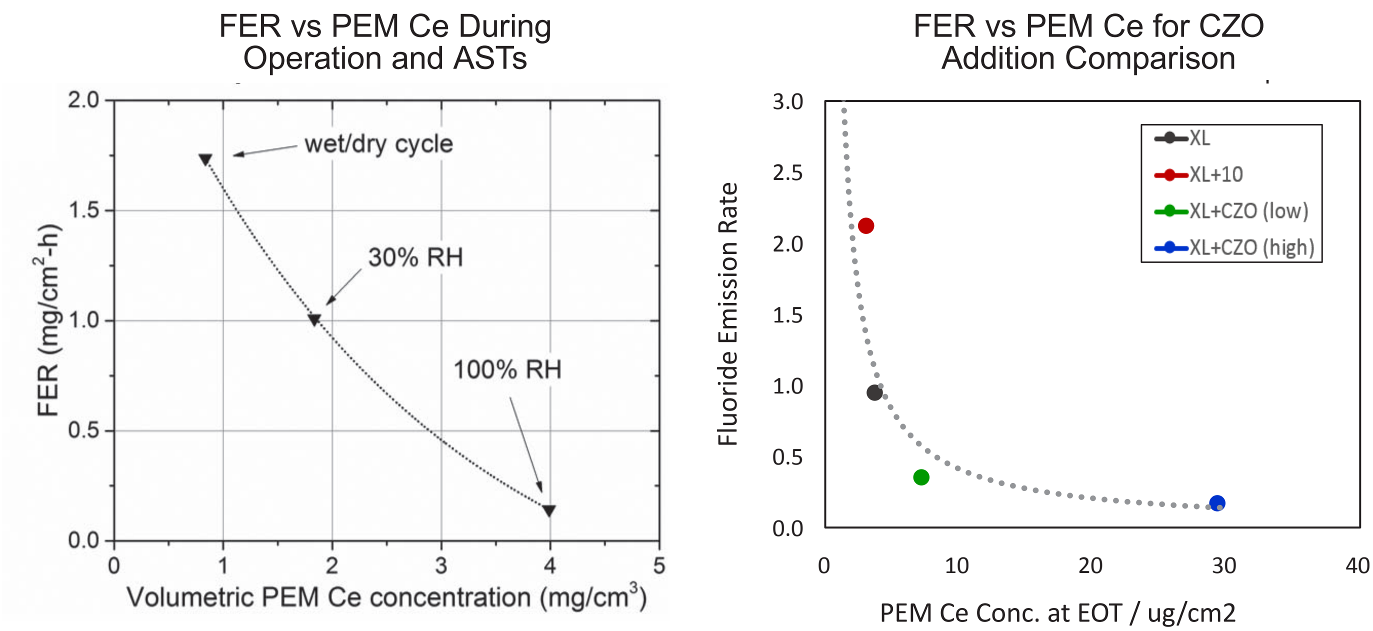



**FIGURE 3.** Relationship between fluoride emission rate and the residual amount of Ce in the PEM after ASTs at EOT (end of test)

was examined to correlate the membrane conductivity to cation concentration and water content. The membrane conductivity versus water content is shown in Figure 4 for this series of cations. From this, we can determine that conductivity *scales with water per charge*, not per poly(anion). Overall, the cationic-interaction-dependent properties are strongly affected by hydration/RH to which the system is exposed, with the effect of the different cations being:

Large/heavy cations → disrupt domains → lower uptake

Multi-valent cations → ionic crosslinks → restricted mobility

Interestingly, cerium has an exceptionally high conductivity, higher than it expected from similar sized or valance cations. This is a fortuitous result as cerium is a cation of choice for radical scavenging, and these properties may limit deleterious effects of the cation on membrane and ionomer conductivity.

## CONCLUSIONS AND UPCOMING ACTIVITIES

Significant progress is reported in this report related to understanding cerium migration in membranes and its potential effects on durability. Migration and diffusion coefficients were quantified at 50% and 100% RH. CZO is shown to enhance the membrane durability much better than adding cerium cations. Work also demonstrates advances in

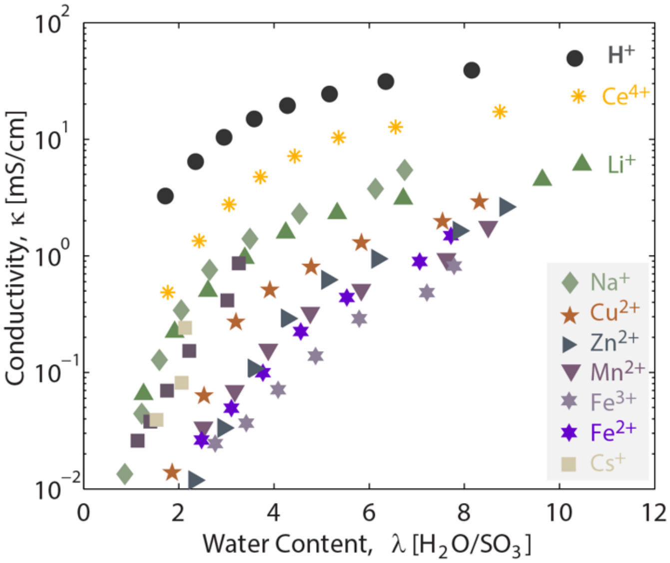



**FIGURE 4.** Membrane conductivity versus water content for a series of cations

modeling of membrane structures and detailing water uptake with various cationic species.

As a consortium, the future work planned is broad, but concentrates on developing the foundational science understanding of the MEA components:

- MEA/catalyst layer structure
  - Binary interactions that govern structure in an ink (polymer/solvent, Pt/C and solvent, Pt/C and ionomer, etc.).
  - Effect of interactions on catalyst layer morphology.
    - Microporosity, ionomer/carbon, and ionomer/Pt structure.
  - Catalyst layer restructuring during conditioning.
  - Cation effect on CL and ionomer structure (Ce, Co, Ni, etc.).
- Micro-continuum model for domain-scale physics
  - Nanoscale interactions: electrostatics, solvation, finite size, image charge, dispersion forces.
  - Effect of elected cations relevant to leaching, for thin film ionomers.
  - Isolation of nanoscale and mesoscale resistances.
- Durability: low catalyst loading and catalyst type effect
  - Comparative $H_2O_2$ and radical formation at lower loadings ($2e^-$ versus $4e^-$).
  - Ionomer degradation in catalyst layer; ionomer degradation versus structural change.
  - Local conditions effects on performance and durability (e.g., dissolution).
  - Alloy-type/support/ionomer effect on catalyst layer durability.

Specifically related to this report, future work related to membrane durability includes:

- Membrane, membrane additives, and cation effects
  - In situ fuel cell operation with measurement of Ce concentration profiles.
  - Surface analysis of Ce/C catalyst supports to identify Ce bonding/stabilization.
  - Correlation or demonstration of no correlation of $R_{CL}$ with Ce ionomer concentrations.
  - Better stabilization of Ce in localized areas of the membrane (CZO, Ce stabilized within fibers or capsules).
  - 2D (or 3D) modeling of the cation migration.
  - Model prediction of durability with Ce content and migration.

## SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

- Ahmet Kusoglu received the Supramaniam Srinivasan, Early Career Award from the Energy Technology Division of the Electrochemical Society.
- Ahmet Kusoglu received a Toyota Young Investigator Award from the Electrochemical Society.
- Andrew Baker received the Bill Baron Fellowship in recognition of his contributions related to the renewable energy field from the University of Delaware.
- Rangachary (Mukund) Mukundan has been selected as a 2017 recipient as a fellow of the Electrochemical Society.

## REFERENCES

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## FY 2017 PUBLICATIONS/PRESENTATIONS

**1.** Publications and presentations listed here represent the three FC-PAD annual merit review presentations and annual progress reports: FC135 (V.B.1), FC136 (V.B.2), and FC137 (V.B.3).

## Publications Relevant to FC-PAD from Consortium Members

**1.** Iryna V. Zenyuk, Prodip K. Das, and Adam 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). doi: 10.1149/2.1161607jes.

**2.** Ahmet Kusoglu, Thomas J. Dursch, and Adam Z. Weber, 'Nanostructure/Swelling Relationships of Bulk and Thin-Film PFSA Ionomers,' *Advanced Functional Materials*, 26, 4961–4975 (2016). doi: 10.1002/adfm.201600861.

**3.** Shouwen Shi, Adam Z. Weber, and Ahmet Kusoglu, 'Structure/property relationship of Nafion XL composite membranes,' *Journal of Membrane Science*, 516, 123–134 (2016). doi: 10.1016/j.memsci.2016.06.004.

**4.** Iryna Zenyuk, Dilworth Y. Parkinson, Liam G. Connolly, and Adam Z. Weber, 'Gas-Diffusion-Layer Structural Properties under Compression via X-Ray Tomography,' *Journal of Power Sources*, 328, 364–376 (2016). doi: 10.1016/j.jpowsour.2016.08.020.

**5.** Shouwen Shi, Adam Z. Weber, and Ahmet Kusoglu, 'Structure-Transport Relationship of Perfluorosulfonic-Acid Membranes in Different Cationic Forms,' *Electrochimica Acta*, 220, 517–528 (2016). doi: 10.1016/j.electacta.2016.10.096.

**6.** Iryna Zenyuk, Adrien Lamibrac, Jens Eller, Dilworth Parkinson, Federica Marone, Felix Büchi, and Adam 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). doi: 10.1021/acs.jpcc.6b10658.

**7.** Ahmet Kusoglu and Adam Z. Weber, 'New Insights into Perfluorinated Sulfonic-Acid (PFSA) Ionomers,' *Chemical Reviews*, 117 (3), 987–1104 (2017). doi: 10.1021/acs.chemrev.6b00159.

**8.** Franz B. Spingler, Adam Phillips, Tobias Schuler, Michael C. Tucker, Adam Z. Weber, 'Investigating Fuel-Cell Transport Limitations using Hydrogen Limiting Current,' *International Journal of Hydrogen Energy* (2017). doi: 10.1016/j.ijhydene.2017.01.036.

**9.** S. Shukla, S. Bhattacharjee, A.Z. Weber, 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). doi: 10.1149/2.0961706jes.

**10.** Lalit M. Pant and Adam Z. Weber, 'Modeling Transport in PEFC Cathode Agglomerates with Double Trap Kinetics,' *Journal of the Electrochemical Society*, 164 (11), E3081–E3091 (2017). doi: 10.1149/2.0081711jes.

**11.** Anna T.S. Freiberg, Michael C. Tucker, and Adam Z. Weber, 'Polarization Loss Correction Derived from Hydrogen Local-Resistance Measurement in Low Pt-Loaded Polymer-Electrolyte Fuel Cells,' *Electrochemical Communications* (2017). doi: 10.1016/j.elecom.2017.04.008.

**12.** N. Macauley, R. Mukundan, D.A. Langlois, K.C. Neyerlin, S.S. Kocha, K.L. More, Madeleine Odgaard, and Rod L. Borup, 'Durability of PtCo/C Cathode Catalyst Layers Subjected to Accelerated Stress Testing,' *ECS Transactions*, 75 (14), 281–287.

**13.** A.M. Baker, R. Mukundan, D. Spernjak, S.G. Advani, A.K. Prasad, and R.L. Borup, 'Cerium Migration in Polymer Electrolyte Membranes,' *ECS Transactions*, 75 (14), 707–714.

**14.** 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).

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**16.** C. Firat Cetinbas, Rajesh K. Ahluwalia, Nancy Kariuki, Vincent De Andrade, Dash Fongalland, Linda Smith, Jonathan Sharman, Paulo Ferreira, Somaye Rasouli, and Deborah 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).

**17.** Andrew M. Baker, Rangachary Mukundan, Dusan Spernjak, Elizabeth J. Judge, Suresh G. Advani, Ajay K. Prasad, and Rod L. Borup, 'Cerium migration during PEM fuel cell accelerated stress testing,' *Journal of The Electrochemical Society*, 163 (9), F1023–F1031.

**18.** 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,' submitted to *ACS Catalysis* (under review).

**19.** Natalia Macauley, Joseph Fairweather, Rangachary Mukundan, D.D. Papadias, Dusan Spernjak, David Langlois, R. Ahluwalia, Karren More, and Rodney L. Borup, 'Accelerated testing of carbon corrosion in PEM fuel cells,' submitted.

**20.** Natalia Macauley, Roger W. Lujan, Dusan Spernjak, Daniel S. Hussey, David L. Jacobson, Karren More, Rodney L. Borup, and Rangachary Mukundan, 'Durability of Polymer Electrolyte Membrane Fuel Cells Operated at Subfreezing Temperatures,' *J. Electrochem. Soc.*, 163 (13), F1317–F1329 (2016).

## 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, August 2016.

**2.** A. Kusoglu, "New Insights into PFSA Ionomers: From Membranes to Thin Films," 3M Company, February 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," ECS Meeting, 2016.

**5.** T. Schuler, M.C. Tucker, and A.Z. Weber, "Gas-Transport Resistances in Fuel-Cell Catalyst Layers," ECS Meeting, 2016.

**6.** Adam Z. Weber, Lalit Pant, Tobias Schuler, Haui-Suen Shiau, Anna Freiberg, Michael C. Tucker, Anamika Chowdhury, K.C. Neyerlin, Shyam Kocha, and Iryna Zenyuk, "Elucidating and Understanding Transport Phenomena in Polymer-Electrolyte Fuel Cells," CARISMA, Newcastle upon Tyne, United Kingdom, April 2017.

**7.** Adam Z. Weber, Tobias Schuler, Franz Spingler, Anna Freiberg, Michael C. Tucker, Anamika Chowdhury, K.C. Neyerlin, and Ahmet Kusoglu, "Ionomer-Associated Transport Resistances in Fuel Cell Electrodes," 21st International Conference on Solid State Ionics, Padua, Italy, June 2017.

**8.** Andrew R. Crothers, Shouwen Shi, Peter Dudenas, Ahmet Kusoglu, and Adam Z. Weber, "Structure-Transport Relationships of Perfluorinated-Sulfonic-Acid Membrane Interfaces," Polymer-Electrolyte Fuel Cell Components, Asilomar, 2017.

**9.** Andrew R. Crothers, Clayton Radker, and Adam 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.** Pablo A. García-Salaberri, Jeff T. Gostick, Gisuk Hwang, Marcos Vera, Iryna Zenyuk, and Adam 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.** Andrew Shum, Liam Connolly, Kelsey B. Hatzell, Xianghui Xiao, Dilworth Y. Parkinson, Odne Burheim, Adam Z. Weber, and Iryna 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, 2016.

**12.** Adam Z. Weber, "Understanding Transport in Polymer-Electrolyte-Fuel-Cell Ionomers," Mechanical Engineering Seminar, UC Merced, 2016.

**13.** Ahmet Kusoglu, "Ion-Conductive Polymer for Energy Conversion Devices," Mechanical Engineering Department Seminar, UC Berkeley, February 2017.

**14.** Ahmet Kusoglu, "Structural Characterization of Ionomers using X-rays," Advanced Light Source, Chemical Sciences Seminar Series, Berkeley Lab, Berkeley, CA, July 2016.

**15.** Ahmet Kusoglu, "New Insights into PFSA Ionomers," National Renewable Energy Lab, Golden, CO, 2017.

**16.** A. Kusoglu, S. Shi, and A. Weber, "Impact of Cation Form on Structure/Function Relationships of Perflurosulfonic Acid Ionomers," APS Meeting, New Orleans, LA, March 2017.

**17.** A. Kusoglu, S. Shi, and A. Weber, "Impact of Equivalent Weight and Side-Chain on Structure/Functionality of PFSA Ionomers," ECS Meeting, Hawaii, 2016.

**18.** Iryna V. Zenyuk, Adrien Lamibrac, Jens Eller, Felix N. Büchi, and Adam Z. Weber, "Understanding Evaporation in Fuel-Cell Gas-Diffusion Layers with X-ray Computed Tomography," Interpore, 2016.

**19.** Meron Tesfaye, Bryan D. McCloskey, and Adam. Z. Weber, "Gas Permeation Study in Thin and Ultra-thin Ionomer Films," ECS Fall Meeting, Hawaii, 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," Fall ECS Meeting, Hawaii, 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," Fall ECS Meeting, Hawaii, 2016.

**22.** Kelsey Hatzell, Ahmet Kusoglu, Pete Dudenas, Nancy Kariuki, Deborah Myers, and Adam Weber, "Indirect and direct observation of ionomer colloidal systems with applications to membrane electrode assemblies for energy conversion systems," Fall ECS Meeting, Hawaii, 2016.

**23.** Anna Freiberg, Tobias Schuler, Franz Spingler, Michael C. Tucker, and Adam Z. Weber, "Determination and Origin of Local Resistances in PEFC Catalyst Layers," ISE Annual Meeting, Hague, Netherlands, 2016.

**24.** Andrew Shum, Kelsey B. Hatzell, Liam Connely, Odne Burheim, Dilworth Y. Parkinson, Adam Z. Weber, and Iryna V. Zenyuk, "Understanding Phase-Change-Induced Flow in PEFCs Through *In-situ* X-ray Computed Tomography," ISE Annual Meeting, Hague, Netherlands, 2016.

**25.** A. Kusoglu, "Morphology of PFSA ionomers and thin films," 21st International Conference on Solid State Ionics, Padua, Italy, June 2017.

**26.** R.L. Borup (Invited), "Material Degradation in PEM Fuel Cell Electrodes," 231st ECS Meeting, May 2017.

**27.** R.L. Borup (Invited), "The FC-PAD Consortium: Advancing Fuel Cell Performance and Durability," 231st ECS Meeting, May 2017.

**28.** R.L. Borup (Invited), R. Mukundan, T. Rockward, M. Brady, J. Thomson, D. Papadias, et al., "(Metal) Bipolar Plate Testing," DOE Bipolar Plate Workshop, Detroit, February 2018.

**29.** R.L. Borup (Invited), Rangachary Mukundan, Andrew Baker, Dusan Spernjak, David Langlois, Sarah Stariha, Natalia Macauley, Karren More, Shyam Kocha, Adam Z. Weber, Debbie Myers and R. Ahluwalia, "Material Degradation in PEM Fuel Cell Electrodes," CARISMA, Newcastle upon Tyne, United Kingdom, April 2017.

**30.** R.L. Borup (Invited), Adam Z. Weber, Deborah Myers, Shyam Kocha, Rajesh Ahluwalia, Rangachary Mukundan, and Karren More, "The FC-PAD Consortium: Material Degradation in PEM Fuel Cell Electrodes," EMN Meeting on Fuel Cells 2017, Prague, Czech Republic, June 2017.

**31.** R.L. Borup (Invited), A.M. Baker, R. Mukundan, D. Spernjak, 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, June 2017.

**32.** D. Myers (Invited), "Structural Characterization of Polymer Electrolyte Fuel Cell Cathode Catalyst Layers," NCNR/LENS Workshop, National Institute of Science and Technology, September 29, 2016.

**33.** Firat Cetinbas, Rajesh Ahluwalia, Nancy Kariuki, Karren More, David Cullen, Brian Sneed, Robert Winarski, Jan Ilavsky, Vincent De Andrade, and Debbie Myers, "Structural

Characterization and Transport Modeling of Pt and Pt Alloy Polymer Electrolyte Fuel Cell Cathode Catalyst Layers," PRIME 2016, Electrochemical Society Meeting, October 5, 2016.

**34.** N.N. Kariuki, D.J. Myers, D. Fongalland, A. Martinez, and J. Sharman, "Microstructure Analysis of Polymer Electrolyte Membrane Fuel Cell Catalyst-Ionomer Inks and Cathode Catalyst Layers by Small Angle X-ray Scattering," 229th Electrochemical Society Meeting, San Diego, California, June 1, 2016.

**35.** R.L. Borup (Invited), "FC-PAD: PEM Fuel Cell Durability," Workshop on Recent Advances in PEMFC, CEA, Grenoble, France, September 2016.

**36.** K.C. Neyerlin, Jason W. Zack, Natalia Macauley, Rangachary Mukundan, Rod L. Borup, Karren L. More, and Shyam S. Kocha, "Investigation of the Performance of PtCo/C Cathode Catalyst Layers for ORR Activity and Rated Power for Automotive PEMFCs," In *Meeting Abstracts*, no. 38, pp. 2488–2488. The Electrochemical Society, 2016.

**37.** K.C. Neyerlin, Jason M. Christ, Jason W. Zack, Wenbin Gu, Swami Kumaraguru, Anusorn Kongkanand, and Shyam S. Kocha, "New Insights from Electrochemical Diagnostics Pertaining to the High Current Density Performance of Pt-Based Catalysts," In *Meeting Abstracts*, no. 38, pp. 2492–2492. The Electrochemical Society, 2016.

**38.** Shyam Kocha, "Investigation of the Performance of PtCo/C Cathode Catalyst Layers for ORR Activity and Rated Power for Automotive PEMFCs," In *PRiME 2016/230th ECS Meeting (October 2–7, 2016).* The Electrochemical Society, 2016.

**39.** K.C. Neyerlin (Invited Talk), "Low Pt Resistances," DOE Transport Modeling and Durability Working Group, Lawrence Berkeley National Lab, May 11–12, 2016.

**40.** K.C. Neyerlin (Invited Talk), "Examinations of Kinetic and Transport Losses in Low Pt Electrodes," DOE Catalysis Working Group, Argonne National Lab, July 27, 2016.

**41.** K.C. Neyerlin (Invited Talk), "Examinations of Kinetic and Transport Losses in Low Pt Electrodes," Gordon Research Conference on Fuel Cells, Stonehill College, Easton, MA, August 7–12, 2016.

**42.** Rod Borup, "On track for a clean, hydrogen-powered future," Santa Fe New Mexican, October 9, 2016.

**43.** Rod Borup, "Forget jetpacks. Where are our hydrogen-powered cars?" The Huffington Post, December 13, 2016.

**44.** R. Borup, Video: Science in 60–A Clean, Renewable Power Source, Los Alamos National Laboratory, Los Alamos, NM.

**45.** Natalia Macauley, Rod L. Borup, Rangachary Mukundan, Mahlon S. Wilson, Dusan Spernjak, K.C. Neyerlin, Shyam S. Kocha, and Stephen Grot, "Performance of Stratified Fuel Cell Catalyst Layer," Meeting Abstracts, pp. 2490–2490. The Electrochemical Society, 2016.

**46.** Dusan Spernjak (Invited), Rod L. Borup, Daniel S. Hussey, Piotr Zelenay, and Rangachary Mukundan, "Imaging Fuel Cell Components: From Flow Field Channels to Catalyst Layers," Meeting Abstracts, pp. 2493–2493. The Electrochemical Society, 2016.

**47.** 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, July 24–28, 2016.

**48.** D.A. Cullen, B.T. Sneed, and K.L. More, "Fuel Cell Electrode Optimization through Multi-Scale Analytical Microscopy," Gordon Research Conference, Easton, MA, August 7–12, 2016.

**49.** K.L. More (Invited), "Correlating Structure and Chemistry of PEM Fuel Cell Materials with Performance and Durability using Advanced Microscopy Methods," PRiME 2016, Honolulu, HI, October 3–7, 2016.

**50.** 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, November 15, 2016.

**51.** 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, November 28 – December 1, 2016.

**52.** 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, December 12–15, 2016.

**53.** K.L. More (Invited), B.T. Sneed, and D.A. Cullen, "Understanding Fuel Cell Materials Degradation Through the Use of Advanced Microscopy Methods," 231st Meeting of the Electrochemical Society, New Orleans, LA, May 29 – June 2, 2017.

**54.** 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, June 18–23, 2017.

**55.** Rangachary Mukundan, Dusan Spernjak, Daniel Hussey, David L. Jacobson, and Rod Borup, "Application of high resolution neutron imaging to polymer electrolyte fuel cells," Abstracts of Papers, 253rd ACS National Meeting & Exposition, San Francisco, CA, April 2–6, 2017.

**56.** 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," 230th Meeting of the Electrochemical Society.

**57.** R.L. Borup, R. Mukundan, D. Spernjak, D.A. Langlois, N. Macauley, and Y.S. Kim, "Recoverable Degradation Losses in PEM Fuel Cells," 230th Meeting of the Electrochemical Society.

**58.** A.M. Baker, D. Spernjak, E.J. Judge, S.G. Advani, and A.K. Prasad, "Cerium Migration in PEM Fuel Cells," 230th Meeting of the Electrochemical Society.

**59.** D.S. Hussey, J.M. LaManna, D.L. Jacobson, S.W. Lee, J. Kim, B. Khaykovich, M.V. Gubarev, D. Spernjak, R. Mukundan, and R.L. Borup, "Neutron Imaging of the MEA Water Content of Pemfcs in Operando," 230th Meeting of the Electrochemical Society.

**60.** K.L. More, D.A. Cullen, B. Sneed, D.J. Myers, R.L. Borup, and R. Mukundan, "Correlating Structure and Chemistry of PEM Fuel Cell Materials with Durability and Performance Using Advanced

Microscopy Methods," 230th Meeting of the Electrochemical Society.

**61.** 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," 230th Meeting of the Electrochemical Society.