FC135: FC-PAD: Fuel Cell Performance and Durability Consortium

Presenter: Rod Borup

Tuesday, June 6th 2017

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
**FC-PAD: Consortium to advance fuel cell performance and durability**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Objectives</th>
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</table>
| Couple national lab capabilities with funding opportunity announcements (FOAs) for an influx of innovative ideas and research | • Improve component stability and durability  
• Improve cell performance with optimized transport  
• Develop new diagnostics, characterization tools, and models |

**Consortium fosters sustained capabilities and collaborations**

**Core Consortium Team***

- Argonne National Laboratory
- Los Alamos National Laboratory
- Berkeley Lab
- Oak Ridge National Laboratory
- NREL

Prime partners added in 2016 by DOE solicitation (DE-FOA-0001412)

**Structured across six component and cross-cutting thrusts**

- 1. Electrocatalysts and Supports
- 2. Electrode Layer
- 3. Ionomers, GDL, Bipolar Plates
- 4. Modeling and Validation
- 5. Operando Evaluation
- 6. Component Characterization

Lead: Rod Borup (LNL)  
Deputy Lead: Adam Z. Weber (LBNL)

[www.fcpad.org](http://www.fcpad.org)
FC-PAD Consortium - Overview

Fuel Cell Technologies Office (FCTO)

- FC-PAD coordinates activities related to fuel cell performance and durability
  - The FC-PAD team consists of five national labs and leverages a multidisciplinary team and capabilities to accelerate improvements in PEMFC performance and durability
  - The core-lab team consortium was awarded beginning in FY2016; builds upon previous national lab (NL) projects
- Provide technical expertise and harmonize activities with industrial developers
- FC-PAD serves as a resource that amplifies FCTO’s impact by leveraging the core capabilities of constituent members
Overall Objectives:

• Advance **performance and durability** of polymer electrolyte membrane fuel cells (PEMFCs) 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/cm² total
  • Performance @ 0.8 V: 300 mA / cm²
  • Performance @ rated power: 1,000 mW / cm²
• Improve component durability (e.g. membrane stabilization, self-healing, electrode-layer stabilization)
  • **Provide support to DOE Funded FC-PAD projects from FOA-1412**
  • **Each thrust area has a sub-set of objectives which lead to the overall performance and durability objectives**
### Timeline

<table>
<thead>
<tr>
<th>Project start date: 10/01/2015</th>
</tr>
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<tr>
<td>Project end date: 09/30/2020</td>
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</table>

### Budget

<table>
<thead>
<tr>
<th>FY17 project funding: $5,150,000</th>
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<tbody>
<tr>
<td>As proposed: 5-year consortium with quarterly, yearly milestones &amp; Go/No-Go milestones</td>
</tr>
<tr>
<td>Total Expected Funding: $25M (NLs only)</td>
</tr>
</tbody>
</table>

### Barriers

- Cost: $40/kW system; $14/kW_{net} MEA
- Performance @ 0.8 V: 300 mA/cm²
- Performance @ rated power: 1,000 mW/cm² (150 kPa abs)
- Durability with cycling: 5,000 (2020) – 8,000 (ultimate) hours, plus 5,000 SU/SD Cycles

### Partners/Collaborations

(To Date Collaborations Only)

- EWii, Umicore, NECC, 3M, GM, TKK, USC, JMFC, W.L. Gore, Ion Power, Tufts, KIER, PSI, UDelaarwe, CSM, SGL, NPL, NIST
- Partners added by DOE DE-FOA-0001412

- Mitigation of Transport Losses
- Durability targets have not been met
- The catalyst layer is not fully understood and is key in lowering costs by meeting rated power.
- Rated power @ low Pt loadings reveals unexpected losses
Couple national lab capabilities with future FOAs for an influx of innovative ideas and research.

Collaborations are also desired outside the FOA process.
Technology Transfer and Agreement Update – FC-PAD

- Multi-Lab Non Disclosure Agreement (NDA) – Executed
- Project-specific NDA Agreements – 3 of 4 are Executed
- Intellectual Property Management Plan (IPMP) - In process
- Material Transfer Agreement (MTA) – In process
- CRADA Template – Complete. Previously agreed upon format. Available for use.
- Tech Transfer & Agreements group conference call held in March to discuss TT/A strategy and status update
## FC-PAD Thrusts, Coordinators, NL Roles

| DOE: | Dimitrios Papageorgopoulos  
| Greg Kleen | Director:  
| Rod Borup  
| Deputy Director: | Adam Weber |

<table>
<thead>
<tr>
<th>Thrust Areas</th>
<th>ANL</th>
<th>LBNL</th>
<th>LANL</th>
<th>NREL</th>
<th>ORNL</th>
<th>Coordinator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro catalysts and supports</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Deborah Myers (ANL)</td>
</tr>
<tr>
<td>Electrode Layers</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Shyam Kocha (NREL)</td>
</tr>
<tr>
<td>Ionomers, Gas Diffusion Layers, Bipolar Plates, Interfaces</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Adam Weber (LBNL)</td>
</tr>
<tr>
<td>Modeling and Validation</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Rajesh Ahluwalia (ANL)</td>
</tr>
<tr>
<td>Operando Evaluation: Benchmarking, ASTs, and Contaminants</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Rangachary Mukundan (LANL)</td>
</tr>
<tr>
<td>Component Characterization and Diagnostics</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>Karren More (ORNL)</td>
</tr>
</tbody>
</table>

| Moderate Activity | High Activity |

- Coordination between thrusts
- Standardization of materials
- Input from associate steering committee members, FCTT, AMR reviewers
- Promote coordination between FOA projects (as possible)
- Achieve consensus for no-cost, non-FOA Collaborations from FC-PAD Core
Objective: How we get there

• Develop the knowledge base and optimize structures for more durable and high-performance PEMFC components
  • Understanding Electrode Layer Structure
    o Characterization
  • New Electrode Layer Design and Fabrication
    o Stratified (Spray, Embossed, Array), Pt - Deposition, Jet Dispersion
  • Defining/Measuring Degradation Mechanisms
    o Membrane, Catalyst Pt-alloy dissolution

FC-PAD Presentations

• FC135: FC-PAD: Fuel Cell Performance and Durability Consortium (Borup, LANL)
  – Overview, Framing, Approach, and Highlights/Durability
• FC136: FC-PAD: Components and Characterization (More, ORNL)
  – Concentrate on Catalysts and Characterization
• FC137: FC-PAD: Electrode Layers and Optimization (Weber, LBNL)
  – Concentrate on Performance - MEA construction and modeling
• FC155 (3M), FC156 (GM), FC157 (UTRC), FC158 (Vanderbilt) FOA-1412 Projects
Membrane Additives (Ce)
Evaluating Migration and Stabilization

Ce Migration between PEM and CL during Drive cycle testing:

- After MEA synthesis, Ce is equilibrated between the PEM and CLs
- During fuel cell operation, AST testing, Ce migrates to catalyst layers
- In conductivity cell, with applied potential, Ce migrates to cathode
- After 100% RH H₂ pump, Ce contents in cathode CL exceed ionic equilibrium
- After 50% RH H₂ pump, very little Ce measured in CLs

Ending Ce concentration correlated to membrane degradation

Ce in the form of CZO shows lower migration

After Ce migration, potential relaxation shows diffusion
Evaluating Cerium Migration Coefficients

- Operation results in cerium migration into the cathode CL due to proton flux
- Performance decay compared to a Ce-free MEA was attributed to Ohmic losses in CL ionomer
- Migration due to concentration and water gradients have also been identified

\[
\frac{\partial c}{\partial t} + \nabla \cdot \left( -D \nabla c - z u_m F c \nabla \phi_{ionic} \right) = 0
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>100% RH</th>
<th>50% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion Coefficient [x10^{-10} \text{ m}^2 \text{ s}^{-1}]</td>
<td>0.686</td>
<td>0.041</td>
</tr>
<tr>
<td>Mobility [x10^{-15} \text{ s mol kg}^{-1}]</td>
<td>7.2±0.8</td>
<td>0.68±0.04</td>
</tr>
</tbody>
</table>

\[
D_{eff} = \frac{D_o}{1 - c/c_{sat}} \quad u_m = \frac{D_{eff} n}{RT}
\]
Microelectrode Performance with Cations dosed into Nafion

- 100 μm Pt microelectrode with a ~5 μm thin film
- Sharp decrease in $E_{1/2}$; 0.60 V vs. 0.73 V
- Lower limiting current with contaminated ionomers $8.2 \times 10^{-2} \text{ (Ce)}$, $6.2 \times 10^{-2} \text{ (Co)}$ and $6.3 \times 10^{-2} \text{ (Ni)}$ mA cm$^2$ vs. $1.1 \times 10^{-1}$ mA cm$^2$
  - [Ce] based on measured migration into CCL
    - Ni, Co concentrations based on measured TEM after ASTs
Cation changes to PFSA Conductivity: Water/Cation - What Controls Conductivity?

- Cation Solvation (local interactions)
  - **Dominant at low RH** (hydration)

- Ionomer network (mesoscale)
  - **Dominant at high RH** (hydration)

*Conductivity scales with water per charge*

\[
\kappa_{\text{local}} = F \cdot \frac{z}{\lambda} \cdot c_{M^+} \cdot \mu_{M^+} \\
\kappa_{\text{eff}} = \kappa_{\text{local}} \cdot \phi_{\text{water}} / \phi_{\text{network}}
\]
PFIA Membrane: Proton Conductivity

**Conductivity: PFIA (vs PFSA)**
- Higher conductivity at mid-RH
  - even at the same water content
  - Presence of a different mechanism: owing to the additional protogenic group
- Better high-T conductivity

**Uptake: PFIA**
- Similar to PFSA, slightly higher lambda
- More hydrophilic side-chains
  - Help formation of H-bonded network
  - Even at low RH, explains the conductivity
Modeling Membrane Conductivity - Multiscale ionomer model - Impact of Equivalent Weight

- Model predictive across range of EWs
- Network and cation-polymer interactions cause resistances
- Increased conductivity at low EW from better network connectivity
- Ideal limit decreases with RH because of dilution of cations
- Network losses increase at low RHs
- Extracted conductive network skeleton from 3D TEM
- Effective membrane resistance: 0.11 S/cm (0.071 S/cm Experiment*) without any fitting

Shows inherent tortuosity of PFSA membranes
Technical Accomplishments: Effect of Operating Conditions with Sulfate Contamination

**Sulfate used to simulate membrane degradation fragments**

- Performance loss due to sulfate contamination is observed at cell potentials below 0.7 V
- Neither high (0.7 V & OCV) nor low cell potentials (0.25V) led to recovery
- Increasing RH led to partial recovery
- CV cycling shows recovery

**In-situ infusion experiments to characterize effects of $\text{SO}_4^{2-}$ contamination**

- Performance loss due to sulfate contamination is observed at cell potentials below 0.7 V
- Neither high (0.7 V & OCV) nor low cell potentials (0.25V) led to recovery
- Increasing RH led to partial recovery
- CV cycling shows recovery
2016 Reviewer Comments

Reviewer: ‘... suggested that the projects shift focus to a foundational understanding of degradation causes and novel fuel cell testing techniques.’
• This is a primary focus of the FC-PAD consortium.

Reviewer: ‘The project will likely have difficulty accessing SOA materials sets.’
• As a consortium, stronger access to materials than previously. GM, 3M, Vanderbilt have all provided materials to date. Other materials (e.g. advanced membranes, catalysts) obtained under non-analysis agreements (useful for benchmarking)

Reviewer: ‘The path forward to work with DOE-funded project teams is not clear. The extent to which the collaboration with new partners will be made is not clear.’
• Interactions with FOA-1412 projects should be more clear now that activities have started and work has been defined.

Reviewer: ‘Integration of new partners and coordination of the whole consortium could be a weakness if strong communication means are not clearly set.’
• POCs have been set. Steering committee set.

Reviewer: ‘... be very difficult to manage such activities unless a robust intellectual property/non-disclosure/confidential disclosure agreement is in place.’
• Technology Transfer and Agreement update was given. Progress made during FY17; more progress needs to occur. FC-PAD faces similar legal issues that other EERE consortium face (e.g. LightMat, HydroGen). Agreements between the various consortia being shared and duplicated as possible.
Collaborations (From FOA-1412)

- The core FC-PAD team consists of five national labs
  - Each Lab has one or more thrust roles and coordinators

Interactions with DOE Awarded FC-PAD Projects (FOA-1412)

Assigned a POC for each project to coordinate activities with project PI:

- 3M PI: Andrew Haug – FC-PAD POC: Adam Weber
- GM PI: Swami Kumaraguru – FC-PAD POC: Shyam Kocha
- UTRC PI: Mike Perry – FC-PAD POC: Rod Borup
- Vanderbilt PI: Peter Pintauro – FC-PAD POC: Rangachary Mukundan

- 35% of the National Lab budget defined as support to the Industrial FOA projects
- Support to these projects is primarily just beginning
- Equal support to each project
- Agreed upon 1-year SOW by ~ Feb 2017

Support Distribution

<table>
<thead>
<tr>
<th></th>
<th>3M %</th>
<th></th>
<th>GM %</th>
<th></th>
<th>UTRC %</th>
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## Collaborations (non-FOA activities)

<table>
<thead>
<tr>
<th>Institutions</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umicore</td>
<td>Supply SOA catalysts, MEAs</td>
</tr>
<tr>
<td>EWii</td>
<td>Supply SOA catalysts and/or MEAs</td>
</tr>
<tr>
<td>Ford</td>
<td>Ionomer imaging studies</td>
</tr>
<tr>
<td>TKK</td>
<td>Supply SOA catalysts</td>
</tr>
<tr>
<td>Johnson Matthey</td>
<td>Catalysts and CCMs (as part of FC106)</td>
</tr>
<tr>
<td>GM</td>
<td>Supply SOA catalysts and/or MEAs</td>
</tr>
<tr>
<td>Ion Power</td>
<td>Supply CCMs</td>
</tr>
<tr>
<td>GM/W.L. Gore</td>
<td>Supply SOA catalysts, SOA Membranes,</td>
</tr>
<tr>
<td>ANL–HFCM Group</td>
<td>SOA catalyst</td>
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<tr>
<td>Tufts University</td>
<td>GDL, MPL imaging</td>
</tr>
<tr>
<td>KIER</td>
<td>Micro-electrode cell studies</td>
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<tr>
<td>U Delaware</td>
<td>Membrane durability</td>
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<tr>
<td>Vanderbilt U.</td>
<td>Ink studies</td>
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<tr>
<td>PSI – Paul Scherrer Institute</td>
<td>GDL imaging</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>NTNU – Norwegian Technical University</td>
<td>GDL imaging</td>
</tr>
<tr>
<td>UTRC</td>
<td>Cell diagnostics</td>
</tr>
<tr>
<td>3M</td>
<td>Ionomers</td>
</tr>
<tr>
<td>Colorado School of Mines</td>
<td>Membrane diagnostics</td>
</tr>
<tr>
<td>SGL Carbon</td>
<td>GDL Supplier</td>
</tr>
<tr>
<td>NPL - National Physical Laboratory</td>
<td>Reference electrodes for spatial measurements</td>
</tr>
<tr>
<td>NIST – National Inst. of Standards and Tech</td>
<td>Neutron imaging</td>
</tr>
<tr>
<td>U. Alberta</td>
<td>GDL and flowfield modeling; ink studies</td>
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</tbody>
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Future Work

Other details in FC136, FC137 presentations

- Increase Integration of FOA projects
  - NL support mostly just starting; activities need to ramp-up
- Continue outreach to develop new collaborators

- Membrane, membrane additives and cation effects
  - Beam line work to measure cerium profile during in situ fuel cell operation
  - Stabilize Ce in localized areas of the membrane (CZO, Ce stabilized within fibers or capsules)

- Microelectrode work
  - Measurements with 10 – 100 nm thin ionomer film
  - Lower concentrations of Ni, Co, Ce to define lower limit of effect

- Micro continuum model for domain-scale physics
  - Include nanoscale interactions: electrostatics, solvation, finite size, image charge, dispersion forces
  - Model effect of elected cations relevant to leaching, for thin film ionomers
  - Incorporate isolation of nanoscale and mesoscale resistances

- Fuel Cell durability testing
  - Verify/validate differential cell hardware
  - Revamp durability protocols for use in differential hardware
  - Develop validated AST for GDLs

- Contaminants
  - Better define reversible degradation mechanisms
  - SO$_4^{2-}$ desorption conditions

Any proposed future work is subject to change based on funding levels.
Summary

- **Relevance:** Advance **performance** and **durability** of PEMFCs
- **Approach:** Coordinate activities related to fuel cell performance and durability
  - Collaborate and support industrial and academic developers (4 FOA awarded projects)
- **Accomplishments and Progress (selected):**
- **FY17:** 20 publications, 61 presentation, 2 Invention disclosures
  - Membrane & Ionomer
    - Membrane Additive Migration: Measured and modeled migration and diffusion coefficients
    - PFIA water uptake and conductivity comparisons with PFSA
    - Micro-continuum model - high inherent tortuosity of PFSA from 3D TEM (0.11 vs. 0.071 S/cm)
    - Microelectrode studies: Reduction in O2 diffusion from cations due to Ce, Ni Co
  - Fuel Cell Testing/Diagnostics (drive cycle, AST, limiting current), contaminant studies
    - Fuel Cell testing and catalyst cycling ASTs > 3 types of PtCo
    - SD/SU protocol on E-carbon, V-carbon and advanced-carbon based MEAs
  - Pt and Pt-alloy catalysts; Electrode Structure
    - Support structure, corrosion
    - Pt and alloy component dissolution measurements
    - Characterization of MEA/Ionomer Structure
  - Multiple variations of electrode designs to optimize high current density performance
    - Stratified (Spray, Embossed, Array), Pt - Deposition, Jet Dispersion
Acknowledgements

DOE EERE: Energy Efficiency and Renewable Energy
Fuel Cell Technologies Office (FCTO)

Fuel Cells Program Manager & Technology Manager:
- Dimitrios Papageorgopoulos
- Greg Kleen

Organizations we have collaborated with to date

User Facilities
- DOE Office of Science: SLAC, ALS-LBNL, APS-ANL, LBNL-Molecular Foundry, CNMS-ORNL, CNM-ANL
- NIST: BT-2
**Microelectrode Experimental setup**

**Conductivity measurements:**
- Performed in a temperature/ humidity controlled chamber using a 2 probe conductivity cell
- NR211 exchanged in $5 \times 10^{-3}$ M Ce$(SO_4)_2$, $5 \times 10^{-4}$ M CoClO$_4$ or $5 \times 10^{-4}$ M NiClO$_4$ solutions for 30 min
- Concentration measured by XRF: same targets as above
- Re-protonation in 0.5 M H$_2$SO$_4$, only traces of contaminants remaining

**ORR measurements:**
- ORR performance of a 100 μm Pt microelectrode with a ~5 μm thin film
- Measurements done in an O$_2$-saturated environment, 10 mV/s scan rate
- 25°C, 100% RH
- Thickness measured using laser profilometry
- Concentration of contaminants on deposited Nafion film measured by XRF:
  - Target [Ce] ~ 15 mg cm$^{-3}$
  - Target [Co], [Ni] ~ 4.7 mg cm$^{-3}$
Target CL ionomer concentration calculations

- **Ce concentration in the CL ionomer**
  - 2,000h OCV hold at 100% RH $\rightarrow$ 15 mg$_{\text{Ce}}$/cm$^3$ [1]
    - Migration due to degradation is minimized at 100% RH

- **Co and Ni concentrations in the CL ionomer:**
  - $[F] = 3.8$ mg/cm$^2$ for a 25 μm membrane [3] $\rightarrow$ 1.52 g$_F$/cm$^3$ = 8x10$^{-2}$ M$_F$/cm$^3$
  - $[\text{Co}] = [\text{Ni}] = 8x10^{-5}$ M$_{\text{Co/Ni}}$/cm$^3$ $\rightarrow$ 4.71 mg$_{\text{Co/Ni}}$/cm$^3$

<table>
<thead>
<tr>
<th>Contaminant ion</th>
<th>Concentration in CL ionomer (mg/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>15 [1]</td>
</tr>
<tr>
<td>Co</td>
<td>4.7 [2,3]</td>
</tr>
<tr>
<td>Ni</td>
<td>4.7 [2,3]</td>
</tr>
</tbody>
</table>

[2] Personal communication with David Cullen, March 17, 2017
What Controls Conductivity?

- Cation Solvation (local interactions)
  - **Dominant at low RH** (hydration)

- Ionomer network (mesoscale)
  - **Dominant at high RH** (hydration)

Conductivity *scales with water per charge*, not per poly(anion)
# FY17 Milestones (Selected Joint)

## FC-PAD Annual Milestone (Joint Milestone for all NL’s; Shared Fate)

<table>
<thead>
<tr>
<th>Milestone Name/Description</th>
<th>End Date</th>
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<tbody>
<tr>
<td>Local platinum resistance vis H2 and O2 limiting current measurements on at least 4 different MEAs compared</td>
<td>12/30/2016</td>
</tr>
<tr>
<td>Compare high density performance of 4 different cathode (including stratified) electrode layers, including variations on higher land versus channel catalyst loadings, microstructural Pt layer densification, electrode layer thickness masking creating micron size electrode features and effect of Nafion electrospun fibers. <em>Down-select MEA designs which do not show a path to equivalent or better performance to traditional SOA electrode layer designs</em></td>
<td>6/30/2017</td>
</tr>
<tr>
<td>Benchmark and characterize the durability and performance of a series of Pt-X/C (minimum 3 different types of SOA Pt alloys; catalysts meeting 400 mA/mg-Pt ORR mass activity BOL performance) catalysts and electrode layers using FCTT catalyst AST and drive cycle protocols and compare with that of Pt/C catalysts; quantify the degree of degradation of Pt-based alloy catalysts and define the life-time (BOL to EOL) performance advantage of Pt-X alloys over Pt. Dealloying will be quantified by post-cycling TEM characterization and ex situ XAFS, WAXS, etc. evaluation.</td>
<td>9/30/2017</td>
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Joint between LBNL/NREL

Joint between LANL/NREL

Joint between All labs
Supplemental Slides
## Ce Additive Samples

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Ce contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>XL</td>
<td>As received Nafion XL PEM (6 μg/cm² ion-exchanged Ce)</td>
</tr>
<tr>
<td>XL+10 (doped)</td>
<td>Nafion XL PEM doped with additional 10 μg/cm² Ce using Ce acetate solution</td>
</tr>
<tr>
<td>XL+18 (doped)</td>
<td>Nafion XL PEM doped with additional 18 μg/cm² Ce using Ce acetate solution</td>
</tr>
<tr>
<td>XL+CZO-low</td>
<td>Nafion XL PEM with 10 μg/cm² CZO added to the cathode CL</td>
</tr>
<tr>
<td>XL+CZO-high</td>
<td>Nafion XL PEM with 55 μg/cm² CZO added to the cathode CL</td>
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</tbody>
</table>
• Use micro continuum model for domain-scale physics
  o Incorporate nanoscale interactions:
    – Electrostatics, solvation, finite size, image charge, dispersion forces
  o Electrochemical potential is driving force
    – Ion mobility modified for confinement and dielectric friction

• Upscaling via the mesoscale
  o Parallel channel model used initially
  o Fitting only tortuosity (no nanoscale fitting parameters)

• Model allows isolation of nanoscale and mesoscale resistances
Backup: Nanoscale Physics

**Electrochemical potential**

\[
\tilde{\mu}_+ = \tilde{\mu}_+^0 + k_b T \ln \rho_+ + z_+ e \Phi + \mu_{fs} + \mu_{solv} + \mu_{dsp} + \mu_{img}
\]

- **finite size**
- **dispersion**
- **ideal solution**
- **electrostatics**
- **solvation**
- **image charge**

---

Bikerman 1942

Bontha and Pintauro 1994

Karraker and Radke 2002

Onsager 1934
BOL polarization and FER

- Increased ion exchange in PEM results in increased ohmic resistance vs CZO which is still in oxide form
- FER is stable and lower than undoped XL until around 300h, when a catastrophic failure occurs. Not sure why this failure
Ce migration

- Catastrophic failure results in a lot of the Ce being depleted from the PEM and going into the CLs
- Agrees with the degradation/stabilization mechanism we discussed in our JECS paper last year (Big FER → Ce depletion from PEM → Ce stabilization in CLs)
Cell Hardware

- 5 cm² differential cell
- Loadings of 0.05 to 0.125 mg Pt/cm²_{elec} and a constant loading of 0.2 mg C/cm²_{elec} (i.e. electrodes diluted with like carbon)
- Measure limiting currents as a f(pO₂, RH) while keeping p_{total} = 101 kPa_{abs}


Hardware
Active Area 5, 50 cm²
Triple Serpentine FF
Spray Coated CCMs

Operating Conditions
0.90 V
80°C
100 kPa PO₂
Stoic~9.0
100 %RH

Protocol
Anodic Sweep
5 mins/point

# of Samples >20
# Publications and Presentations

## Publications Relevant to FC-PAD from Consortium Members:


Publications Relevant to FC-PAD from Consortium Members:

13. AM Baker, R Mukundan, D Spernjak, SG Advani, AK Prasad, RL Borup, Cerium Migration in Polymer Electrolyte Membranes, ECS Transactions 75 (14), 707-714


Publications and Presentations

Presentations Relevant to FC-PAD from Consortium Members:

Presentations Relevant to FC-PAD from Consortium Members:


Publications and Presentations

Presentations Relevant to FC-PAD from Consortium Members:

33. Firat Cetinbas, Rajesh Ahluwalia, Nancy Kariuki, Karren More, David Cullen, Brian Sneed, Robert Winarski, Jan Ilavsky, Vincent De Andrade, and Debbie Myers
Presentations Relevant to FC-PAD from Consortium Members:


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, Dec 13, 2016

44. R Borup, Video: Science in 60–A Clean, Renewable Power Source, LANL (Los Alamos National Laboratory (LANL), Los Alamos, NM (United States))


Presentations Relevant to FC-PAD from Consortium Members:


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


