FC-PAD
Fuel Cell – Performance and Durability
FC135: FC-PAD Consortium Overview
Presenter: Rod Borup

Wednesday, June 8th 2016

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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 multi-disciplinary team and capabilities to accelerate improvements in PEMFC performance and durability
  - The core-lab team consortium was awarded beginning in FY2016; builds upon previous natlonal 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

Los Alamos NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

BERKELEY LAB

OAK RIDGE National Laboratory

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

FC-PAD NL Consortium – Relevance & Objectives

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/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***
- ***Each thrust area has a sub-set of objectives which lead to the overall performance and durability objectives***

FC-PAD Overview & Relevance

Timeline

Project start date: 10/01/2015
Project end date: 09/30/2020

Budget

FY16 project funding: $5,000,000
As proposed: 5-year consortium with quarterly, yearly milestones & Go/No-Go
Total Expected Funding: $25M (NLs only)

Partners/Collaborations

(To Date Collaborations Only)

- IRD Fuel Cells, Umicore, NECC, GM, TKK, USC, KIER, 3M, JMFC, W.L. Gore, Ion Power, Tufts, KIER, PSI, UDelaware, 3M, CSM, SGL, NPL, NIST, CEA,ULorraine
- Partners to be added by DOE DE-FOA-0001412

Barriers

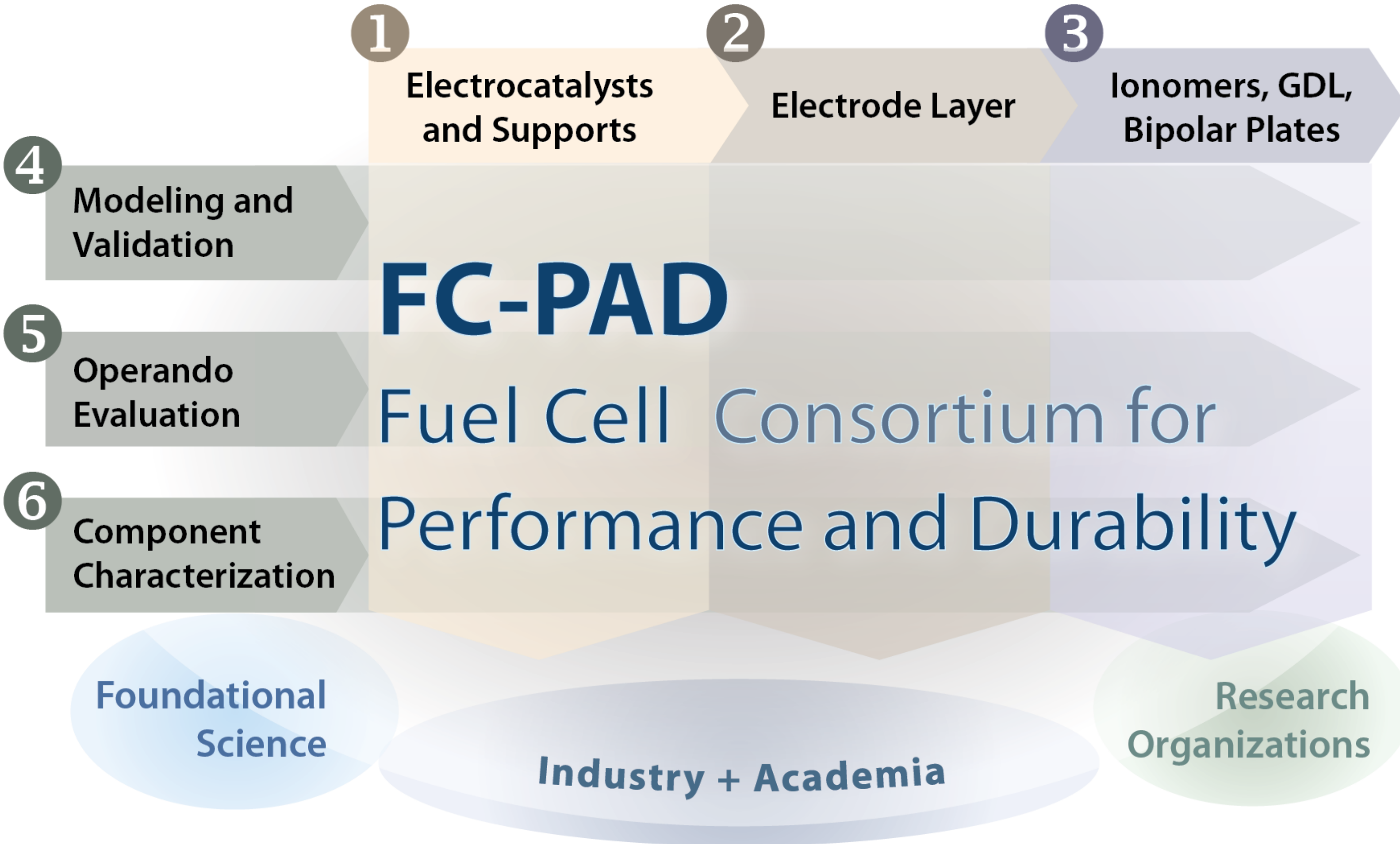
- Cost: $40/kW system;
  $14/kW$_{net}$ MEA
- Performance @ 0.8 V: 300 mA / cm^2
- Performance @ rated power: 1,000 mW / cm^2 (150 kPa abs)
- Durability with cycling: 5,000 (2020) – 8,000 (ultimate) hours, plus 5,000 SU/SD Cycles

- **Mitigation** of Transport Losses
- **Durability** targets have not been met

- The **catalyst layer** is not fully under-stood and **is key in lowering costs** by meeting rated power.
- Rated power@ low Pt loadings reveals unexpected losses

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

FC-PAD: Structural Approach

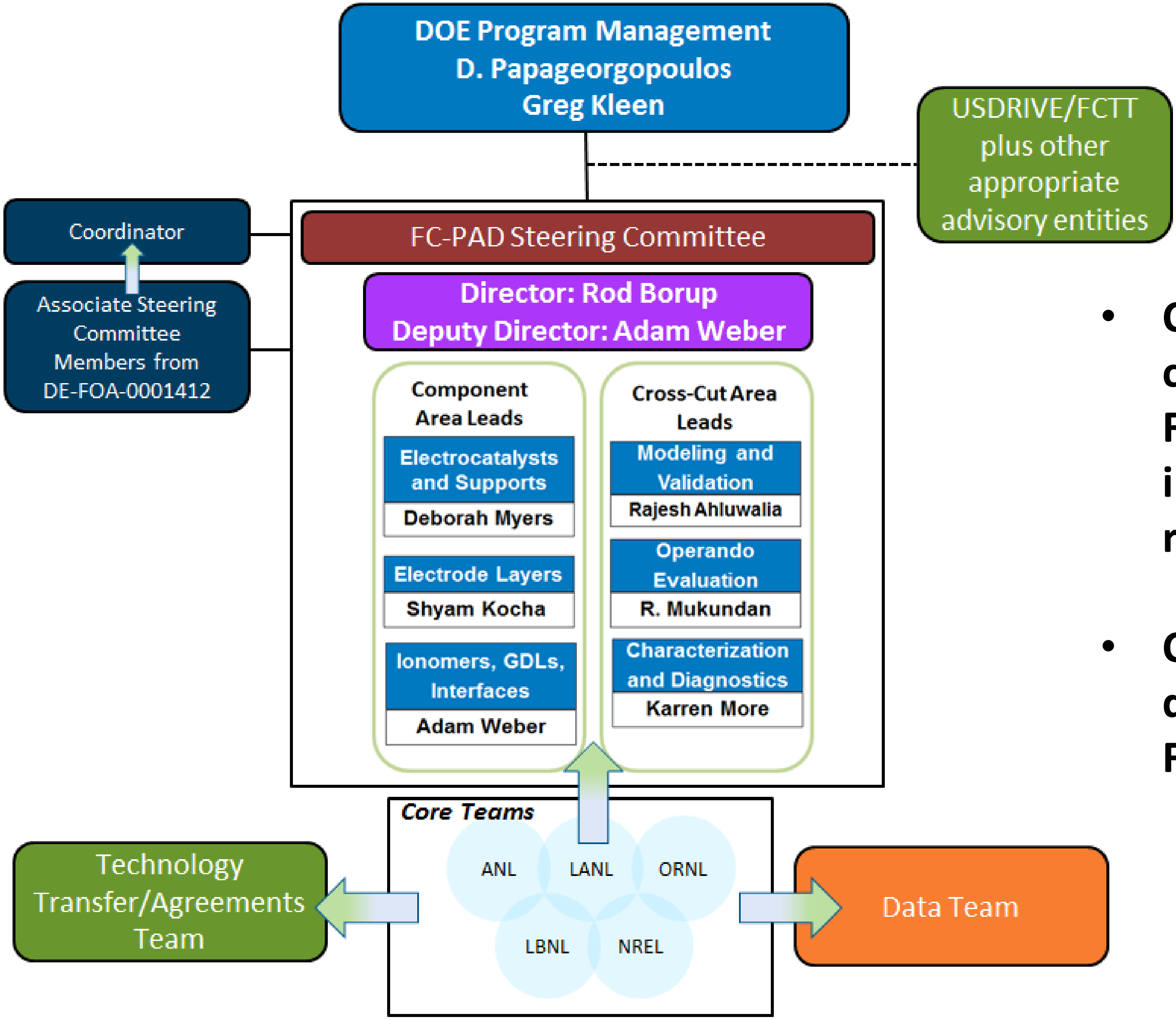


Lead: Rod Borup (LANL)
Deputy Lead: Adam Z. Weber (LBNL)

Energy Efficiency & Renewable Energy

FUEL CELL PERFORMANCE AND DURABILITY

FC-PAD Organization



- **Couple national lab capabilities with future FOAs for an influx of innovative ideas and research**
- **Collaborations are also desired outside the FOA process**

Example of Thrust Area Coordination

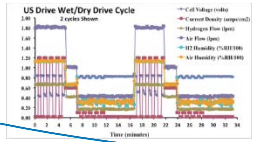
<u>Example</u>
Carbon Corrosion during drive cycle
ANL, LANL, ORNL

<u>Thrusts 1, 2, 3</u> - Components
Catalysts, Membranes, GDLs

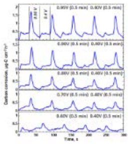
Samples
Component Design

<u>Thrust 5.</u> Operando Evaluation

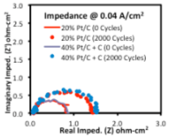
Durability Testing



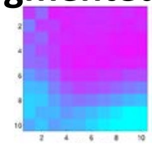
NDIR



EIS



Segmented Cell

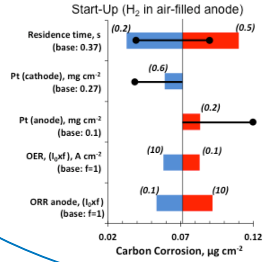


Data
Feedback

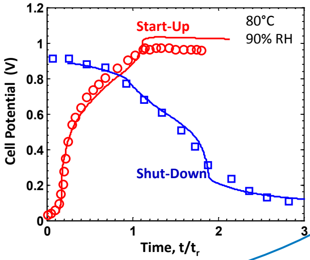
Samples
Data

<u>Thrust 4.</u> Modeling Validation

Model Output

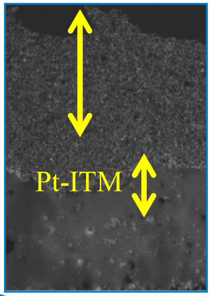


Parametric model

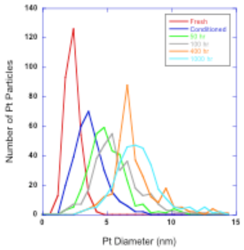


<u>Thrust 6.</u> Characterization

STEM



TEM



FUEL CELL PERFORMANCE AND DURABILITY

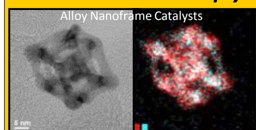
Highlights of FC-PAD NL Capabilities for Collaboration

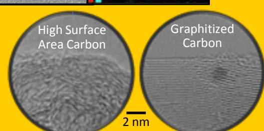
FC PAD
FUEL CELL PERFORMANCE AND DURABILITY

	Structural & Chemical Characterization		Performance Testing & Evaluation	Modeling & Theory

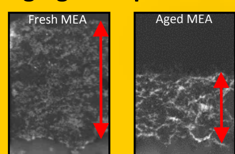
Catalyst & Catalyst Support / Electrode & MEA / Membrane & Ionomer

Analytical Electron Microscopy

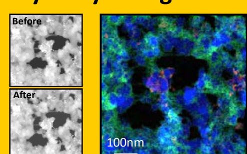




Imaging and spectroscopy



Catalyst-layer degradation

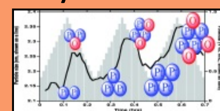


Ionomer mapping

Oak Ridge National Laboratory — MoreKL1@ornl.gov

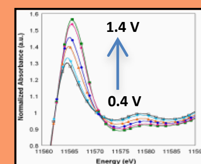
Advanced X-Ray Techniques

Spectroscopy and Scattering: catalyst atomic structure and particle size



Pt growth with cycling

Specialized *operando* cells



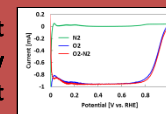
Pt oxidation with potential

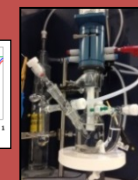
Combinatorial Activity Screening

Argonne National Laboratory — DMyers@anl.gov

Electrochemical Diagnostics

Catalyst activity measurement

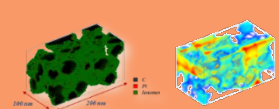




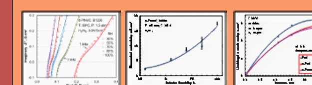
Advanced MEA Fabrication

NREL — Shyam.Kocha@nrel.gov

Electrode Simulations



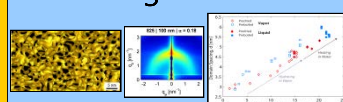
3-D electrode reconstruction and transport



Quantify various losses

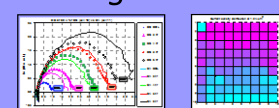
Argonne National Laboratory — Walia@anl.gov

Advanced Component Diagnostics



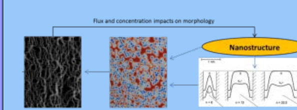
Bulk and thin-film morphology and properties

Advanced MEA Diagnostics



Los Alamos — Mukundan@lanl.gov

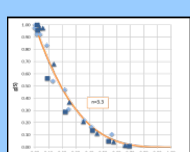
Multiphysics, Multiscale Models

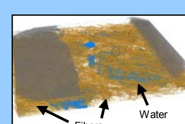


Membrane simulations

GDL & Cell

Transport property measurements



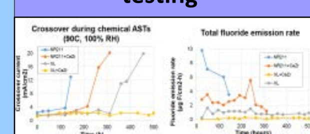


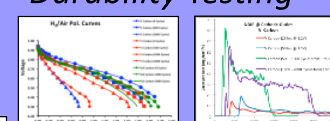
X-ray tomography

Berkeley Lab — AZWeber@lbl.gov

Performance & Durability Testing

Long-term durability testing

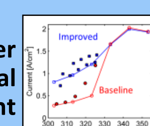




Component-specific degradation testing

Los Alamos — Borup@lanl.gov

Optimize water and thermal management



Berkeley Lab — AZWeber@lbl.gov

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

Logos and names/emails listed with facilities do not represent the only laboratory working on a specific topic.

FY16 FC-PAD Consortium Milestones

Argonne National Lab

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables
Q1	12/31/2015	Progress Measure	Ex situ measurement of steady state concentration and dissolution rates of dissolved Pt and base metal from SOA Pt alloy catalysts
Q2	3/31/2016	Progress Measure	Develop and test protocol for characterizing performance and durability of SOA Pt alloy-based cathode catalyst layers (CCL)
Q3	6/30/2016	Milestone	Publish model of thermodynamics and kinetics of Pt and base metal dissolution

Complete for TKK Pt3Co

Complete

Lawrence Berkeley National Lab

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables
Q1	12/31/2015	Progress Measure	Measurement of structural and transport properties of reinforced PFSA membrane including impact of hygrothermal ageing and anhydrides
Q2	3/31/2016	Progress Measure	Measurement of critical ionomer thin-film properties including simultaneous water uptake and swelling, gas permeability, and surface conductivity
Q3	6/30/2016	Milestone	Agreement (< 10 % deviation) between 1+2-D performance model and segmented cell data for two relative humidities

Complete, including pub.

Complete

On Track

Los Alamos National Lab

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables
Q1	12/31/2015	Progress Measure	Quantification of gas-phase transport improvement of electrospun fibers in cathode electrode layer by Electrochemical Impedance Spectroscopy (EIS)
Q2	3/31/2016	Progress Measure	Compare the spatial distribution of reversible degradation during power cycling and constant power operation
Q3	6/30/2016	Milestone	Publish in situ measurement of cerium (or other anti-oxidant) concentration profile in the electrode layer and membrane as a function of potential and current density

Complete

Complete

Complete; pub. submitted under review, additional measurements in progress

FY16 FC-PAD Consortium Milestones

National Renewable Energy Lab

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables	
Q1	12/31/2015	Progress Measure	Propose relevant diagnostic techniques for the identification of local Pt transport resistance	Complete
Q2	3/31/2016	Progress Measure	Fabricate, integrate, and evaluate electrode layers with modulated properties (e.g. catalyst wt%, carbon type) that can affect local Pt resistance in low-loaded PEMFCs	Complete
Q3	6/30/2016	Milestone	Quantify changes in local Pt transport resistance before and after durability measurements of down-selected electrode materials	In Progress

Oak Ridge National Lab

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables	
Q1	12/31/2015	Progress Measure	Establish critical measurement protocol via cross-sectional TEM/STEM+EDS for several Pt-alloy catalysts to understand alloy catalyst degradation (dissolution) during testing (coordinate with ANL activities)	Completed
Q2	3/31/2016	Progress Measure	Initiate study of ionomer structural changes in low Pt-loaded MEAs subjected to extensive fuel cell operation	Completed; mores samples to be characterized
Q3	6/30/2016	Milestone	Establish complete database of Pt-alloy, Ce/ceria, carbon corrosion effects, and ionomer distribution observations as input data for model development; necessary data, e.g., testing protocols, and materials will be coordinated with ANL and LANL	In Progress; awaiting more samples

FC-PAD Annual Milestone

QTR	Due Date	Type	Progress Measures, Milestones, Deliverables	
Q4	9/30/2016	Milestone	Quantify Cerium migration within the membrane in microns/sec at 4 different RHs (25%, 50, 75% and 100%) at T = 90oC under both applied potential (0.5, 1.0V) and applied current (0.5 and 1.0 A/cm2). Propose a method to improve cerium localization by 25% during durability drive cycling.	In Progress On Track for completion

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Accomplishments: Coordination, Outreach, Web-site

Data Sharing: Internal Web-Site

- Operational in ~ December 2015
- Internal with hierarchical authorization

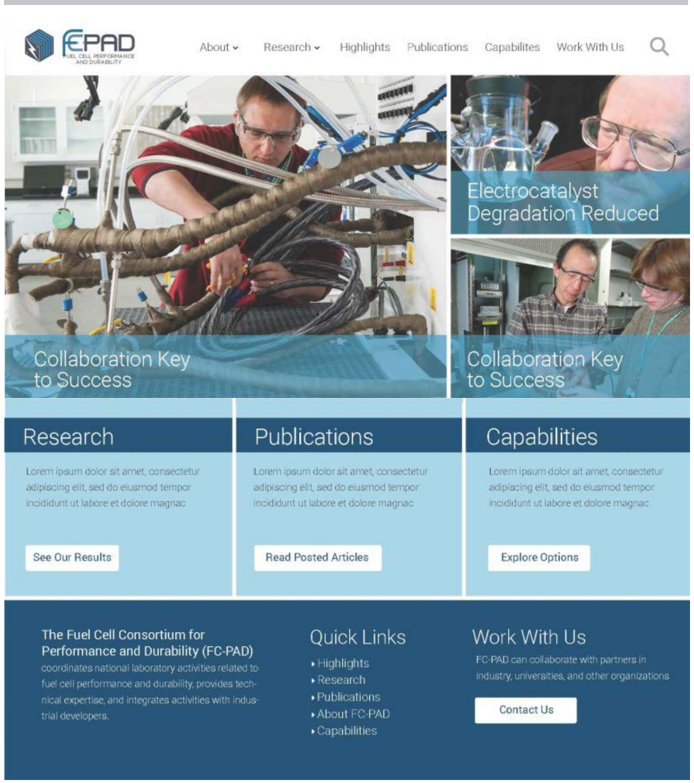
External Web-Site: Operation ~ June 2016

www.fcpad.org

Communication

- Outreach: External presentations of FC-PAD > 10 times and public webinar
- FC-PAD Face-to-Face Kickoff meeting held Nov. 2015 (Los Alamos)
- FC-PAD Face-to-Face mid-year meeting held May 2016 (Berkeley)
- Durability and Transport Working Group meetings held May 2016 (Berkeley)
- Multiple thrust area coordination conference calls held biweekly
- Multiple personel exchange/visits between NLs

www.fcpad.org



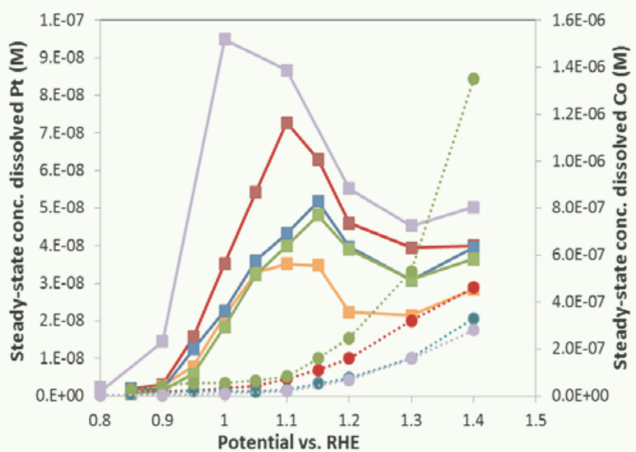
- FC-PAD website describes FC-PAD's organization, research focus, and contributors
- Presents recent research publications
- Helps users access supporting laboratory capabilities, partnership information, and other resources

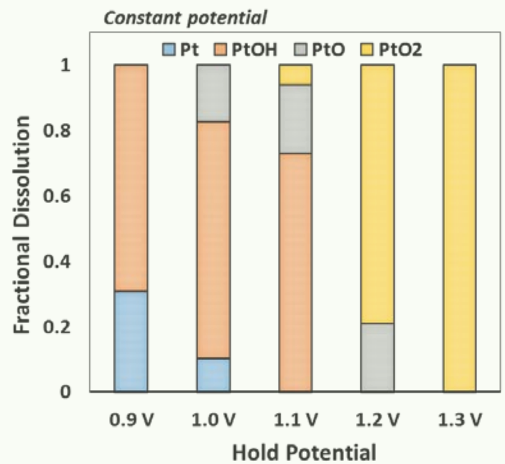
FCPAD FUEL CELL PERFORMANCE AND DURABILITY

FC136 - Thrust 1: Electrocatalysts and Supports
Coordinator: Debbie Myers

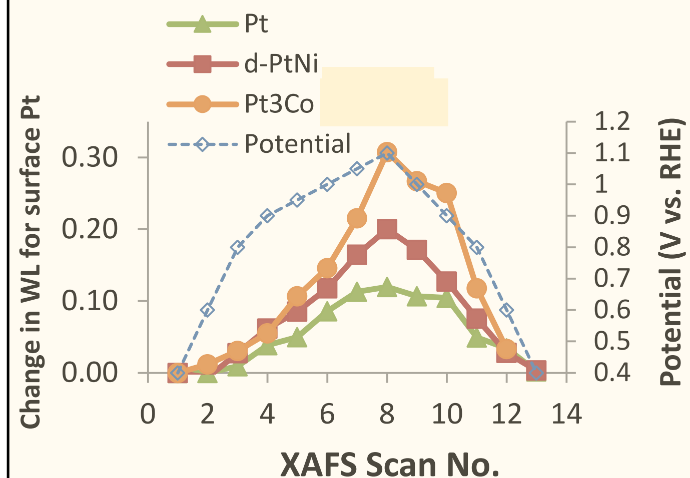
- **Catalyst and catalyst support durability and degradation mechanisms**
- **Catalyst/support interactions**
- **Ex-situ analysis of impact catalyst instability on CCL properties**

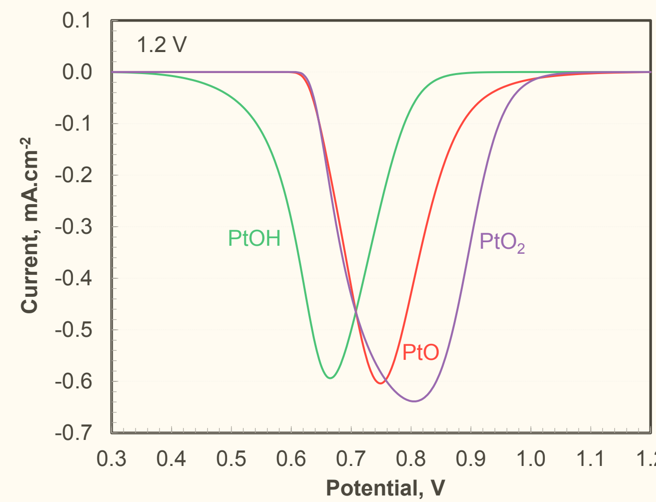
Potential Dependence of Pt and Co dissolution



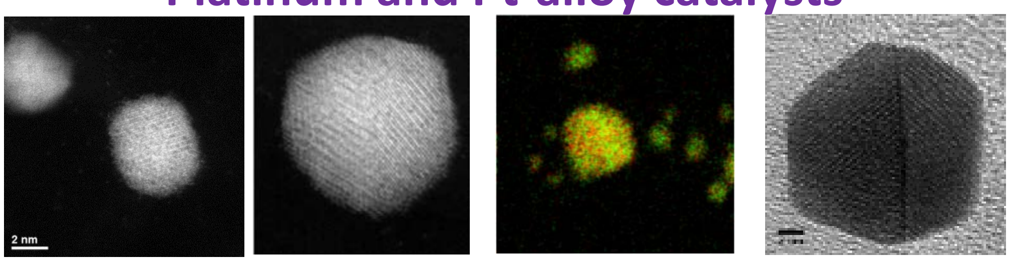


Extent of oxidation (XAFS)





Platinum and Pt-alloy catalysts



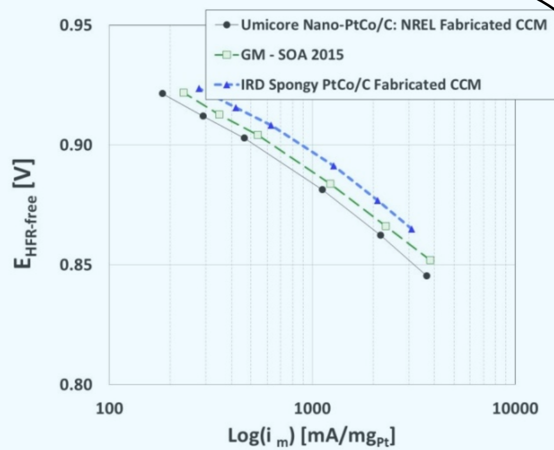
FCPAD FUEL CELL PERFORMANCE AND DURABILITY

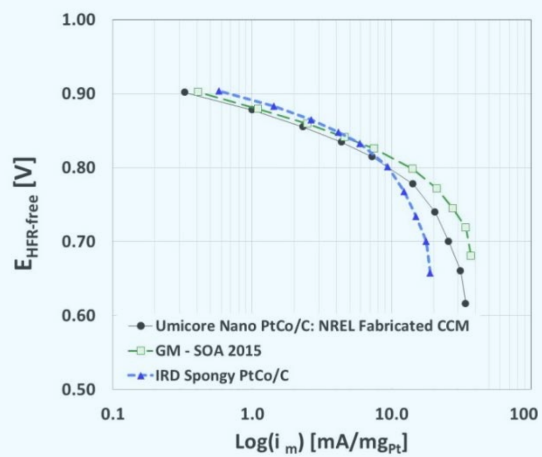
Examine different catalyst structures

FC137 - Thrust 2: Electrode Layers
Coordinator: Shyam Kocha

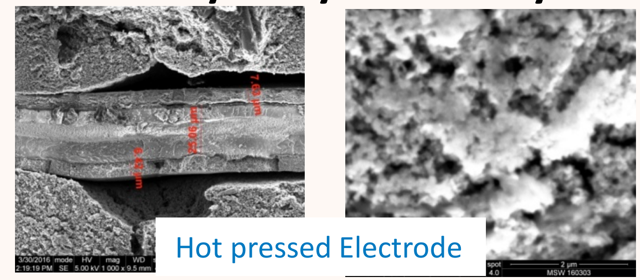
- **Low Pt-loaded electrode layers**
- **Transport in low-loaded catalyst layers**
- **Electrode-layer design and fabrication**

Electrode Layer Diagnostics
Higher Tafel kinetics do not (always) correspond to better high current density performance

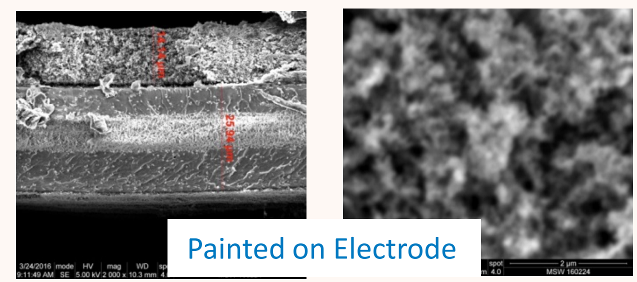




Catalyst Layer Porosity

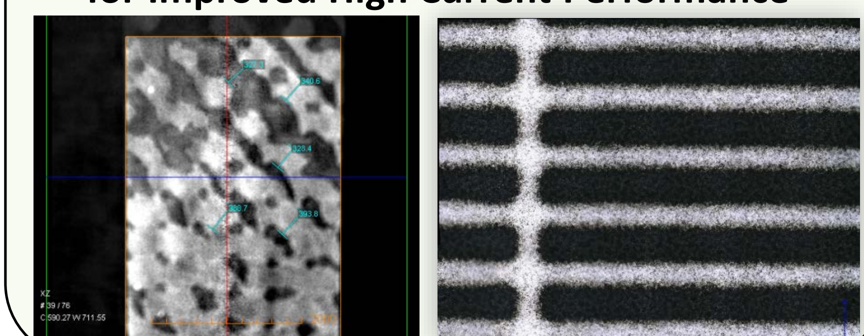


Uniform/thinner electrode - better kinetics



≈ 80% greater porosity in the sub 100nm range - better mass transport

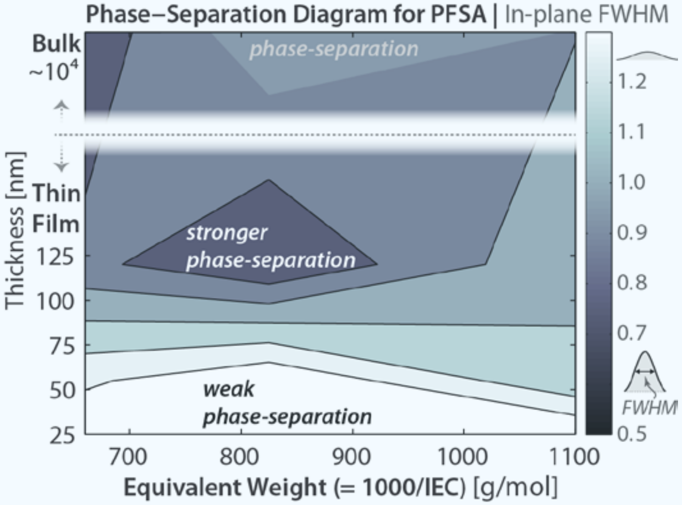
Stratified Electrode Structures for Improved High Current Performance

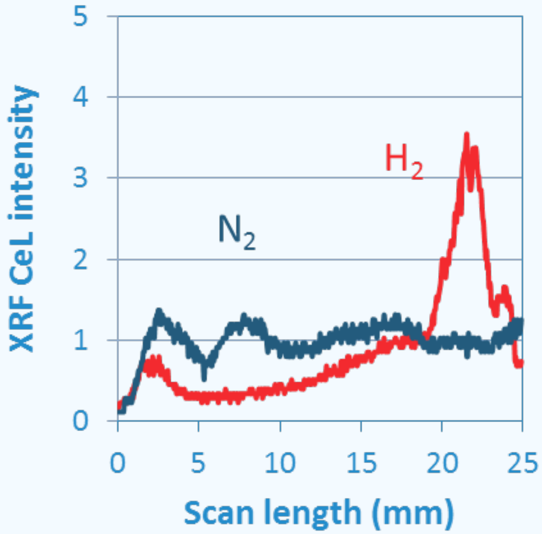


FUEL CELL PERFORMANCE AND DURABILITY

FC138 - Thrust 3: Ionomers, GDLs, Interfaces
Coordinator: Adam Weber

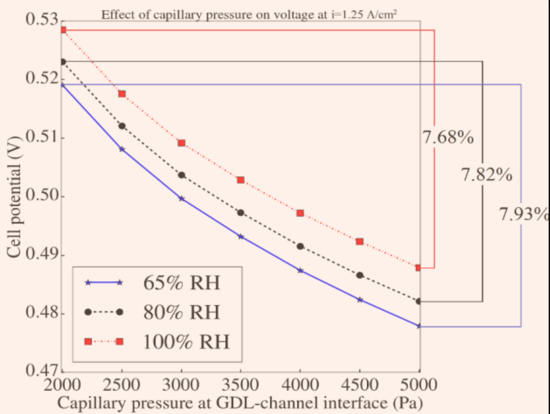
Membranes and Ionomer films





- Thin-film phase diagrams for catalyst-layer optimization
  - Low EW has stronger phase separation
- Cerium migration driven by proton flux

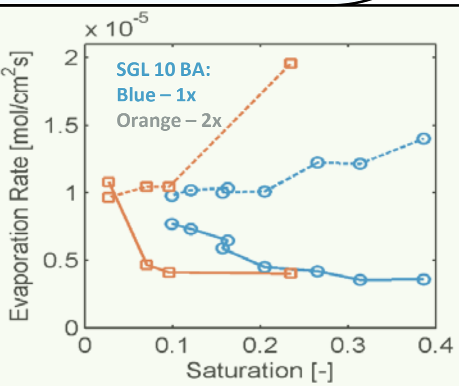
Interfaces

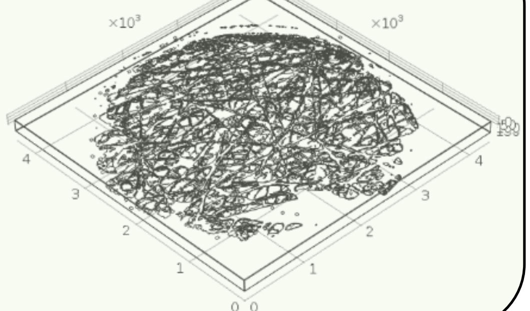


- Time-averaging can be used for GDL boundary fluctuations

Gas Diffusion Layers

- Explore water and thermal management
  - Determine evaporation rates using x-ray tomography



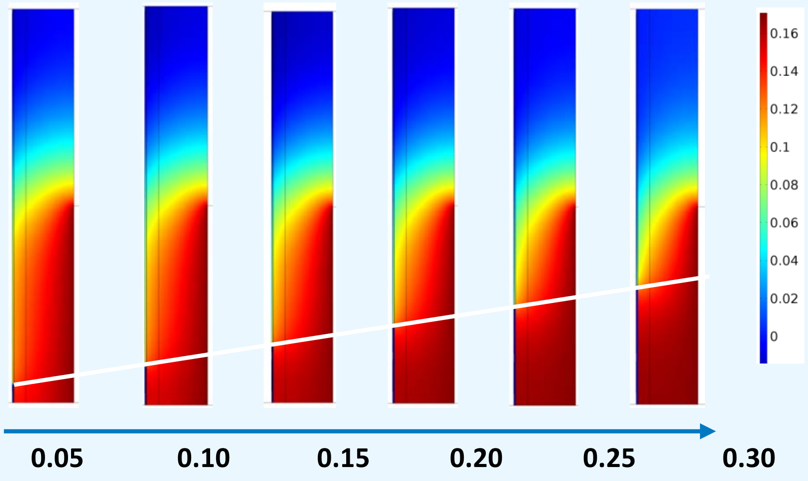


FUEL CELL PERFORMANCE AND DURABILITY

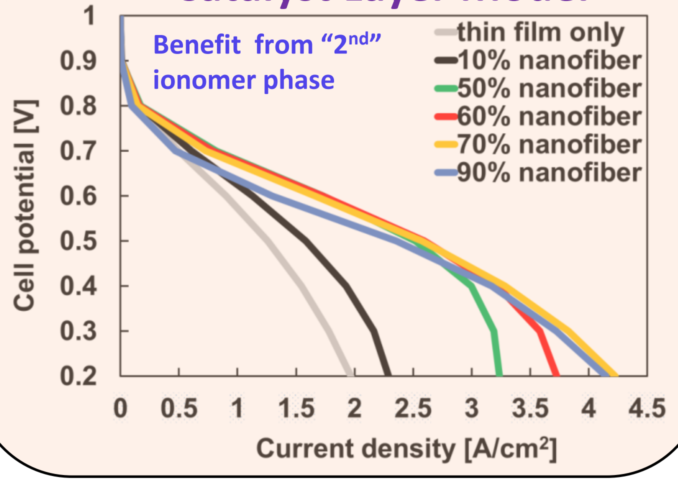
Thrust 4: Modeling and Validation
Coordinator: Rajesh Ahluwalia

- **Model development and validation, Analysis**
- **Model deployment**

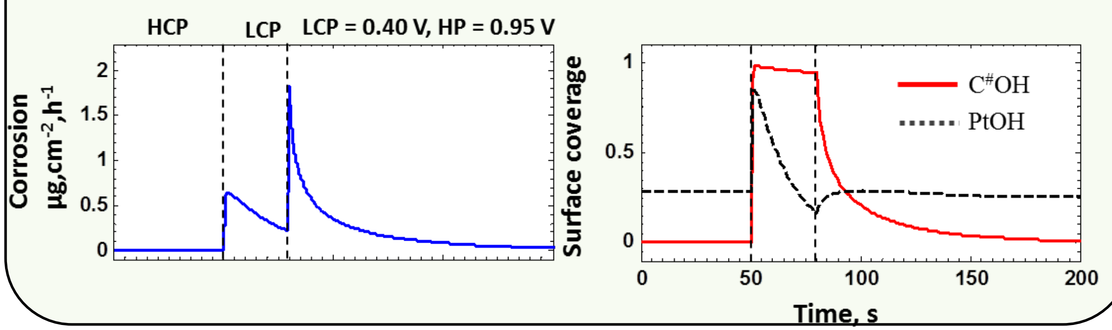
Changes in oxygen profile



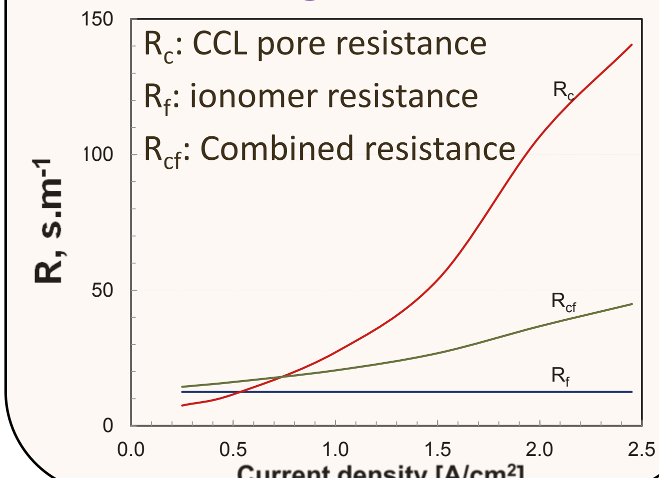
Thin film/Nanofiber Catalyst Layer Model



Carbon Corrosion



Oxygen Transport Resistances from Limiting Current Densities



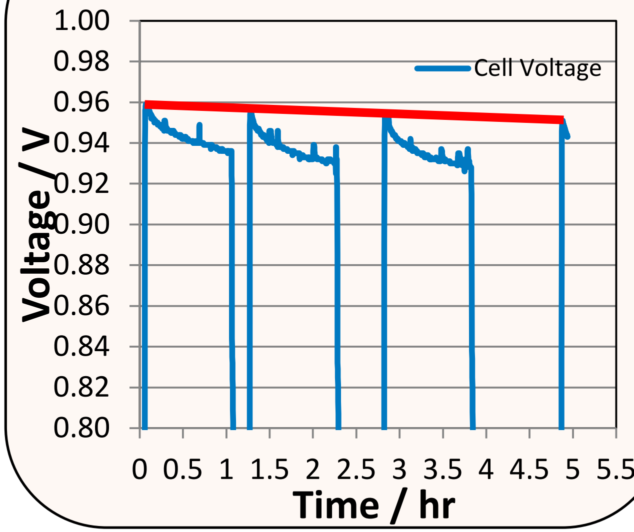
FCPAD FUEL CELL PERFORMANCE AND DURABILITY

FC139 - Thrust 5: Operando Evaluation

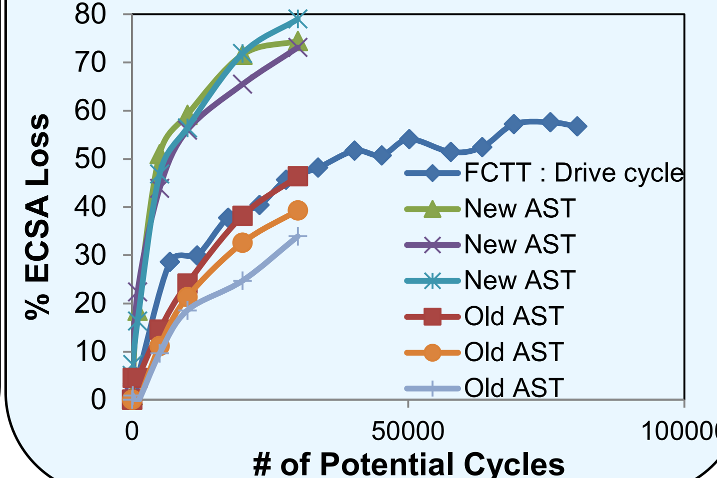
Coordinator: R. Mukundan

- **Performance and durability benchmarking**
- **Durability testing**
- **Accelerated Stress Testing and Development**
- **Contaminants**
- **Performance characterization**

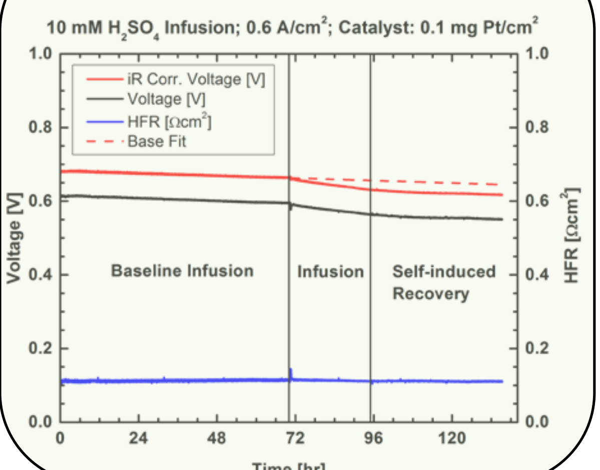
Recoverable Degradation



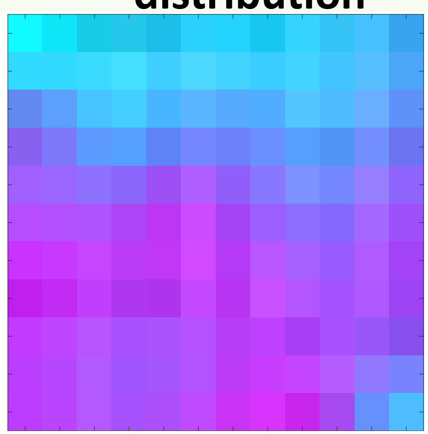
Accelerated Stress Testing Protocol Refinement/Development



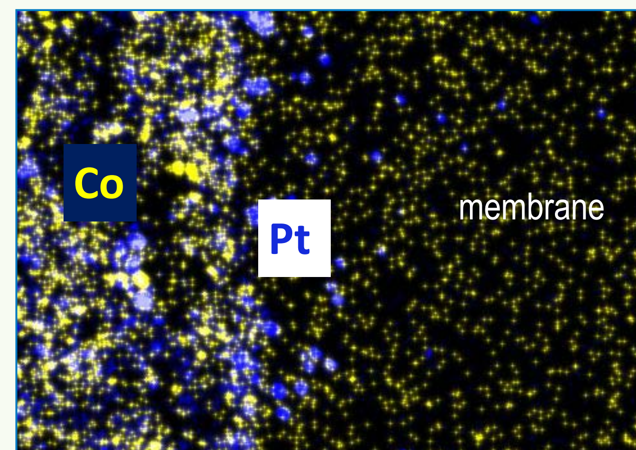
Contaminant Evaluation



Spatial current distribution



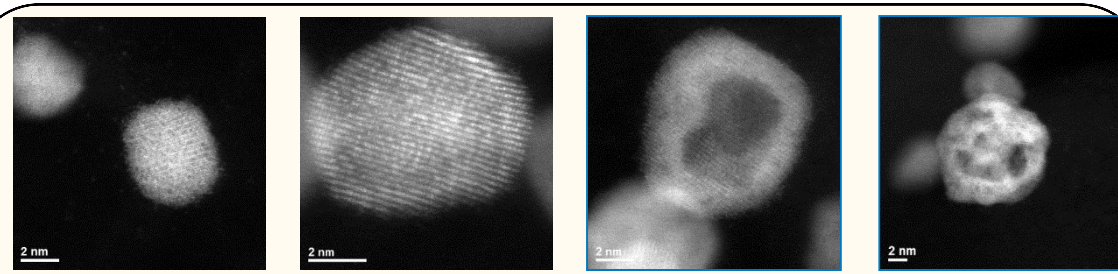
Alloy Catalyst AST Durability



Thrust 6: Diagnostics and Characterization

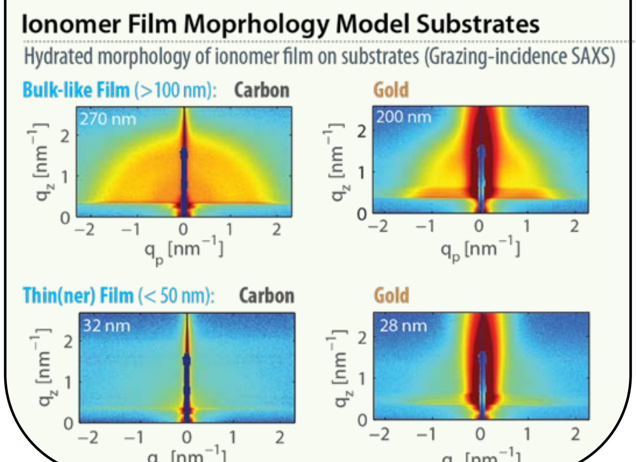
Coordinator: Karren More

- **Comprehensive Materials Benchmarking – sub-Å to µm-level Understanding**
- **Coordination across all six thrusts for durability/performance characterization**
  - Advanced Electron Microscopy
  - Neutron and X-ray Studies
  - Component Diagnostics

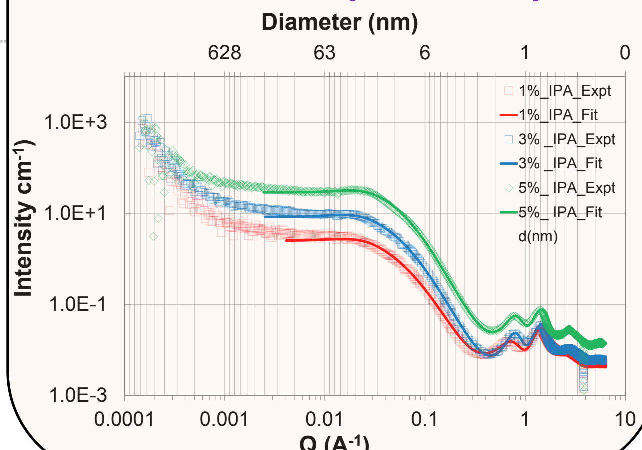


crystalline alloy Pt-X | "Core/Shell" Pt-X | "Donut" Pt-Ni | "Spongy" Pt_3Co

Ionomer Thin Film Measurements (LBNL-ALS)

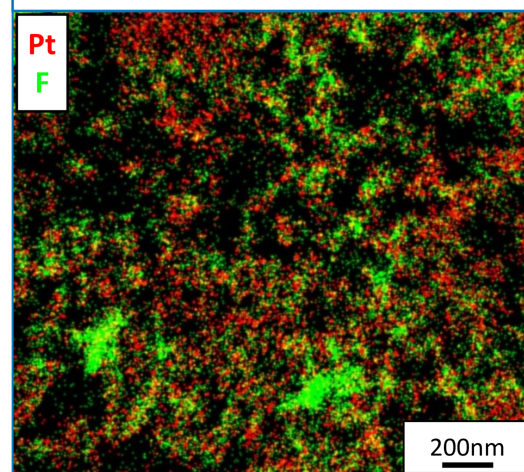


X-ray Scattering of Ionomer Solutions (ANL-APS)



CL Ionomer Mapping

Ionomer aggregate size range 50-400nm



Non-homogeneous ionomer distribution: dependent on density of Pt/C agglomerates and association with porosity

FC-PAD Consortium Go/No-Go Decisions

QTR	Due Date	Type	Go/No-Go Decision	Decision Criteria
Q4	9/30/2016	Go/No-Go Decision (Consortium)	Continue with research related to reversible degradation	Definition of a recovery procedure that results in > 95% recovery of known reversible degradation utilizing less than 30 sec of drive cycle time
Q8	9/30/2017	Go/No-Go Decision (Consortium)	Cell-level modeling continuation versus individual component modeling	Cell-level performance model validated to within 10% accuracy of polarization behavior under 3 humidities and 4 temperatures
Q12	9/30/2018	Go/No-Go Decision (Consortium)	Continuation of MEA optimization: has MEA integration met targets. If yes, shift focus to durability of MEA microstructure.	MEA with $< 0.125 mg_{Pt}/cm^2$ demonstrates $1 W/cm^2$ rated power and current $> 300 mA/cm^2$ at 0.8V
Q16	9/30/2019	Go/No-Go Decision (Consortium)	Continuation of research on specific individual component degradation	< 5 mV degradation at rated power (~1500 mA/cm^2) for any individual component over 5000 hr drive cycle with SD/SU or equivalent ATS procedures
Q20	9/30/2020	Go/No-Go Decision (Consortium)	Continue durability work on MEA components	Demonstrate single cell performance of 5000 hours (or equivalent ATS procedures) with < 30 mV loss at 1.5 A/cm^2 at total Pt loading of $< 0.125 mg_{Pt}/cm^2$

Collaborations

Institutions	Role
FC-PAD Consortium	ANL, LBNL, ORNL, LANL, NREL Each Lab has one or more thrust roles and coordinators
Umicore	Supply SOA catalysts
IRD Fuel Cells	Supply SOA catalysts and/or MEAs
NE ChemCat	Supply SOA catalysts
TKK	Supply SOA catalysts
Johnson Matthey	Catalysts and CCMs (as part of FC106)
GM	Supply SOA catalysts and/or MEAs
Ion Power	Supply CCMs
GM/W.L. Gore	Supply SOA catalysts, SOA Membranes,
USC – University of South Carolina	Supply CCMs
Tufts University	GDL imaging
KIER	Micro-electrode cell studies

Collaborations

Institutions	Role
FC-PAD Consortium	ANL, LBNL, ORNL, LANL, NREL
PSI – Paul Scherer Institute	GDL imaging
University of Delaware	Membrane durability
3M	Ionomers
Colorado School of Mines	Membrane diagnostics
SGL Carbon	GDLs
NPL - National Physical Laboratory	Reference electrodes for spatial measurements
NIST – National Inst. of Standards and Tech	Neutron imaging
CEA - Commissariat à l'énergie atomique et aux énergies alternatives	Durability testing protocols, microscopy
University of Lorraine, Nancy	SD/SU segmented cell measurements
FUTURE – DE-FOA-0001412	

Proposed Future Work

Plans FY16

- **Incorporate collaborators from DE-FOA-0001412 into FC-PAD**
  - Define mechanisms for collaboration
  - Lab and capability matching exercise
  - Identify roles for the FC-PAD core National Labs for supporting roles
  - Develop milestones for the FC-PAD National Labs related to newly awarded projects
- **Populate external FC-PAD website with relevant information**
- **Remaining Milestone -** Reversible Degradation: Definition of a recovery procedure that results in > 95% recovery of known reversible degradation utilizing less than 30 sec of drive cycle time

Plans FY17 (more details in Thrust area presentations)

- **Integrate new collaborators (industrial/academic/NLs) with core National Labs**
- **Continue outreach to develop new collaborators**

- **Thrust 1: Concentration on Pt-X alloys; developing understanding related to supports and durability**
- **Thrust 2: Optimize catalyst layers with SOA catalysts; implement alternative designs for CCLs**
- **Thrust 3: Investigate side-chain chemistry effects; relationship between cerium migration and durability**
- **Thrust 4: Thin-film structure/property modeling; modeling of CL/GDL/Channel interfaces**
- **Thrust 5: Segmented cell evaluation of durability; adoption/development of differential cell protocols**
- **Thrust 6: Characterization of CL structure; ionomer mapping and ionomer interactions with catalyst; provide characterization to collaborators**

Summary

- **<u>Relevance</u>: Advance performance and durability of polymer electrolyte membrane fuel cells (PEMFCs)**
- **<u>Approach</u>: FC-PAD was formed to coordinate activities related to fuel cell performance and durability**
  - FC-PAD builds upon previous NL projects; consists of five national labs and leverages a multi-disciplinary team
  - *Collaborate and support industrial and academic developers*
- **<u>Accomplishments and Progress</u>:**
  - FC-PAD NL consortium operating with integrated thrusts
    - Website operational (internal and external)
    - Outreach activities, including > 10 external presentation and site visits
  - Expansion of prior projects examining performance and durability of Pt-alloy catalysts
  - Multiple variations of electrode designs to optimize high current density performance
  - Modeling and experiments related to thin-film ionomer for catalyst layer optimization
  - New durability ASTs accepted by DOE/US DRIVE Fuel Cell Tech Team

FC-PAD: Additional Information

FC-PAD Website
Detailed FC-PAD slides by thrust area
WWW.FCPAD.ORG

Additional Information Available On-line:
From **DE-FOA-0001412:** http://energy.gov/eere/fuelcells/fc-pad

Fuel Cell Technologies Office Multi-Year RD&D Plan:
http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

Acknowledgements

- Fuel Cell Technologies Office (FCTO)
- Organizations we have collaborated with to date
- User facilities, including SLAC, ALS, APS, NIST BT-2, Center for Nanoscale Materials