FC171

Advanced PGM-free Cathode Engineering for High Power Density and Durability

Shawn Litster

Carnegie Mellon University
Pittsburgh, PA

April 30, 2019

DE-EE0008076

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

Overview

Timeline and Budget

- Project Start Date: 09/01/2017
- Project End Date: 08/31/2020
- Total Project Budget: $2,292,324
  - Total Recipient Share: $292,324
  - Total Federal Share: $2,000,000
  - Total DOE Funds Spent*: $415,142
    * As of 12/31/2018

Barriers

B. Cost

➢Reduce PEM fuel cell costs by replacing precious metal catalysts with PGM-free catalysts

C. Performance

➢Increase catalyst activity, utilization, and effectiveness to enable high fuel cell power density operation

A. Durability

➢Increase stability of PGM-free catalysts at relevant fuel cell voltage

Project Lead

Carnegie Mellon University

- PI: Shawn Litster
- Co-PI: Venkat Viswanathan
- Co-PI: Reeja Jayan

Partners

University at Buffalo, SUNY

- PI: Gang Wu

Giner, Inc.

- PI: Hui Xu

3M Company

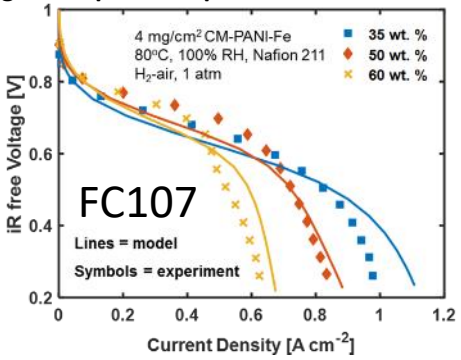
- PI: Andrew Haug

Electrocatalysis Consortium Members

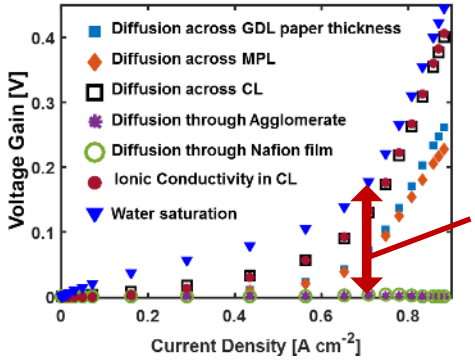
Challenges: PGM-free Cathode Performance and Durability

- Fe-doped MOF-based catalysts have shown promising activity and stability at 0.7 V during fuel cell operation
- Further increases in activity and stability are required to meet performance targets
- Electrode-scale transport losses significantly hinder PGM-free catalyst effectiveness due to ~10X greater cathode thickness resulting from lower volumetric activity
- Significant liquid water flooding and ohmic losses need to be addressed to realize PGM-free ORR activity measured by RDE in a fuel cell MEA
- Prior transport and MEA model analyses in FC107 (PI: Zelenay, LANL) showed gains in power density could be achieved by porous electrode engineering that are comparable to order of magnitude increases in active site density

Large transport overpotentials in thick cathodes

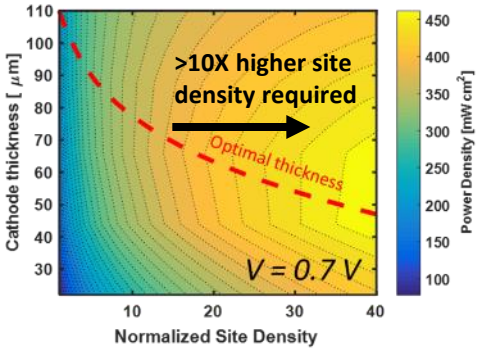


Transport process voltage gain

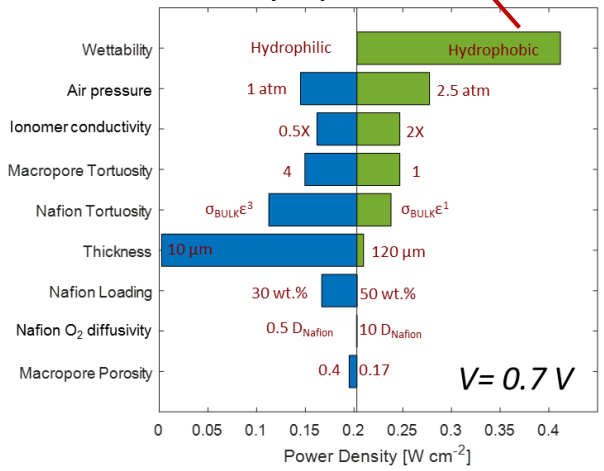


170 mV loss due to liquid water at 0.7 V

Power density vs. active site density

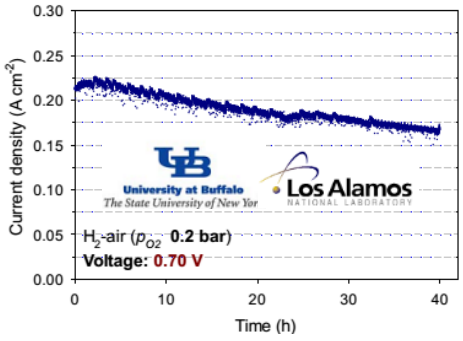


>100% increase in power density with hydrophobic cathode



Komini Babu et al., *J. Electrochem. Soc.*, 2017.

Durability of Fe-doped MOF at 0.7 V



Carnegie Mellon University

Technical Targets and Status

Property	DOE 2020 target	Present project status	Project end goal
PGM free catalyst activity (voltage at 0.044 A/cm²)	0.9 $V_{IR\text{-}free}$ (**2025**)	**0.89 $V_{IR\text{-}free}$** 0.028 A/cm² at 0.9 $V_{IR\text{-}free}$ 2018 AMR: 0.87 $V_{IR\text{-}free}$[a]	>0.9 $V_{IR\text{-}free}$
Loss in initial catalyst mass activity			<50%
Loss in performance at 0.8 A/cm²			
MEA air performance @ 0.8 V		**113 mA/cm²** 2018 AMR: 63 mA/cm²	>150 mA/cm²
MEA performance @ rated voltage		**410 mW/cm² at 0.67 V** 2018 AMR: 154 mW/cm²	Stretch goal: >450 mW/cm²

[a]Pre-project testing of UB Fe-MOF catalyst hand painted CCM at LANL

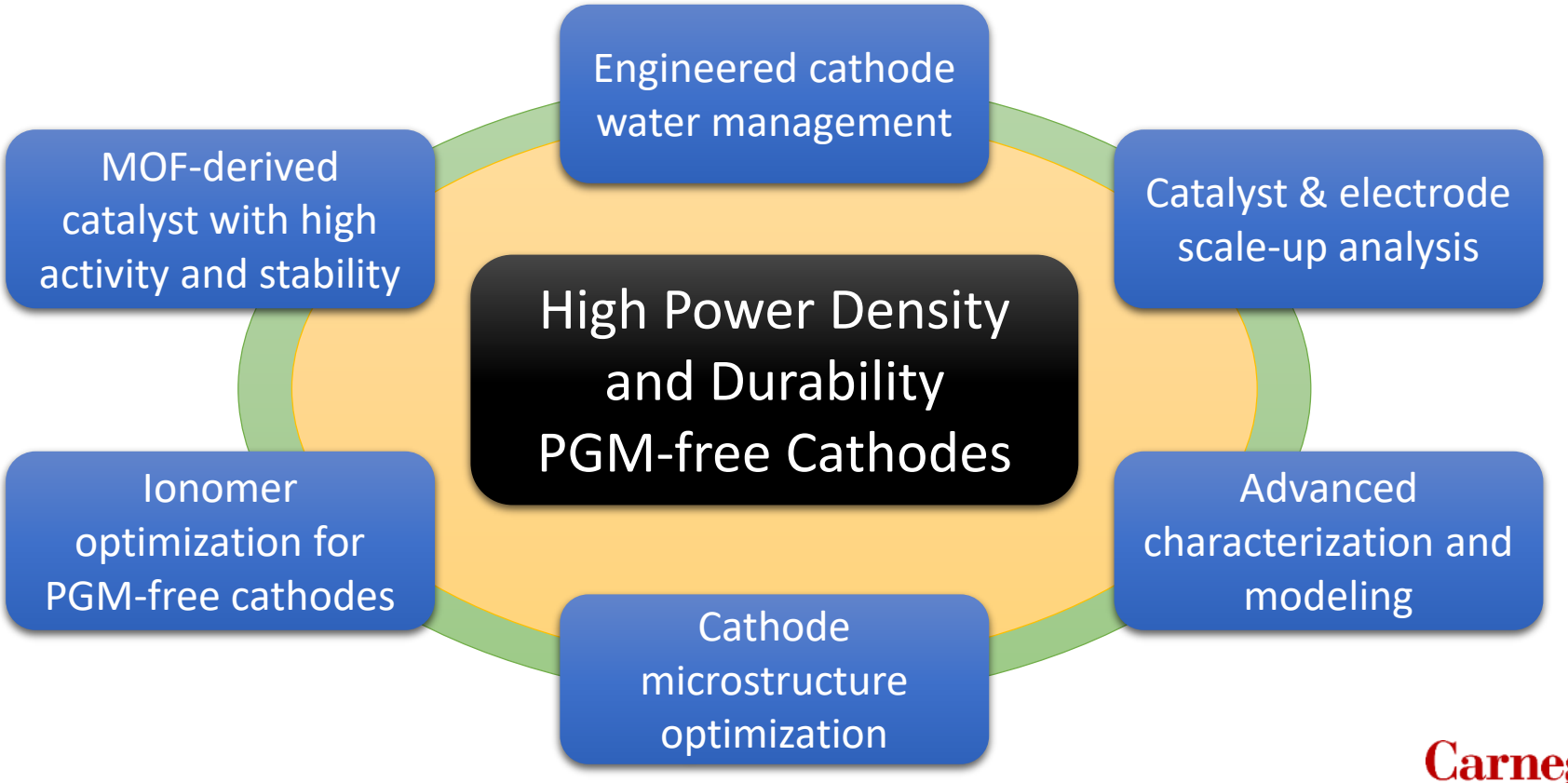
Objectives

- Enable high, durable power density with new cathode designs specifically for PGM-free catalysts
- Increase PGM-free catalyst activity and stability through synthesis using a simplified, low cost method
- Improve PGM-free mass activity through optimization of the ionomer integration
- Mitigate PGM-free cathode flooding for fast oxygen transport across thick electrodes

Carnegie Mellon University

Overview

1. Stable, high activity MOF-derived M-N-C catalysts (M = Fe, Co)
2. PGM-free cathode engineering for enhanced transport and catalyst utilization
3. Ionomer optimization for PGM-free cathodes



Carnegie Mellon University

Project Team

Carnegie Mellon University (University prime)

Prof. Shawn Litster (PI), Dr. Bahareh Tavokoli, Dr. Aman Uddin, Lisa Langhorst, Diana Beltran, Shohei Ogawa, Leiming Hu, Yuqi Guo, Prof. Venkat Viswanathan (co-PI), Hasnain Hafiz, Prof. Reeja Jayan (co-PI), Laisuo Su

Electrode design, hydrophobicity treatments, electrode fabrication, fuel cell testing, X-ray imaging, multi-scale modeling, DFT, project management.

University at Buffalo-SUNY (University sub)

Prof. Gang Wu (UB PI), Hanguang Zhang, Yanghua He, Xiaolin Zhao, Mengjie Chen, Hao Zhang

Catalyst development, synthesis, and experimental characterization.

Giner, Inc. (Industry sub)

Dr. Hui Xu (Giner PI), Shuai Zhao, Shuo Ding, Zach Green

Catalyst and MEA fabrication scale-up analysis and demonstration, fuel cell testing, support of hydrophobic cathode development.

3M Company (Industry sub)

Dr. Andrew Haug (3M PI)

Ionomer supply and optimization support.

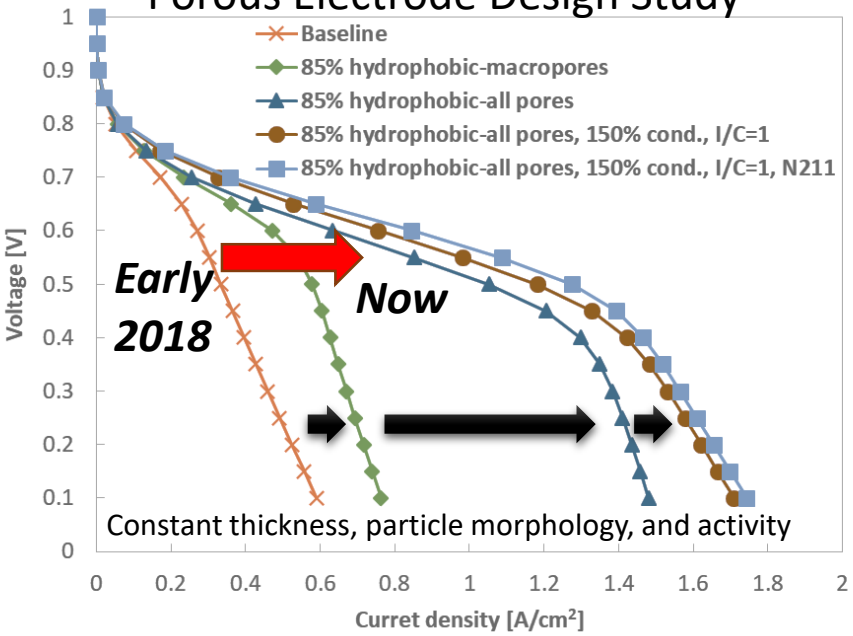
Electrocatalysis (ElectroCat) EMN Consortium Members (National Laboratories)

X-ray abs. spectroscopy, high-throughput electrodes (ANL), electron microscopy (ORNL), molecular probes studies (LANL & ANL), electrode development (NREL), fuel cell durability testing (LANL).

Model-based Road Map to Higher Power Density

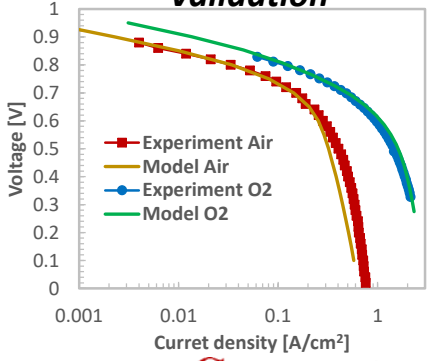
- Development of a well-validated multi-phase MEA model with cathode microstructure inputs
- Inputs relating catalyst synthesis to performance include active site density and activity, bimodal particle-size distribution, and pore-size distribution for both secondary and primary pores
- Actionable predictions to inform synthesis
- Significant performance improvement possible by electrode engineering, including increased hydrophobicity and ionomer conductivity
- Optimal cathode thickness versus active site density
- Predicted gains in power density at 0.7 V by electrode engineering are comparable to 4X increase in active site density

Porous Electrode Design Study

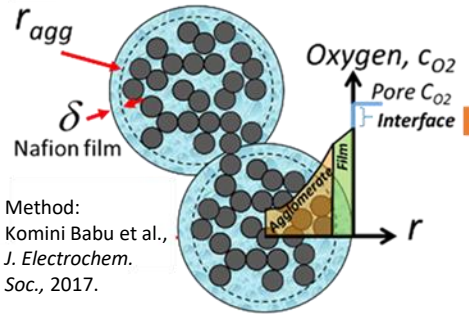


Cell temperature: 80°C; RH: 100%, 1 bar H_2/air-O_2 partial pressure

Validation



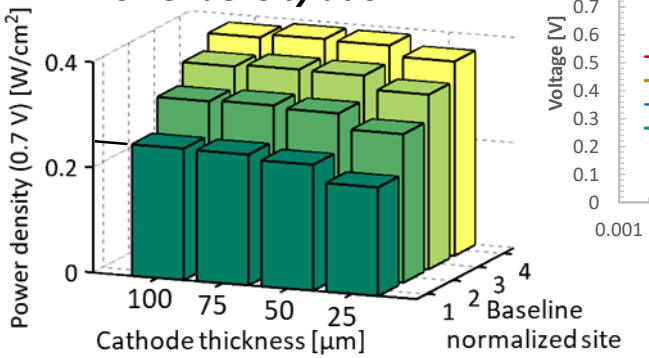
Agglomerate electrode model



Method: Komini Babu et al., *J. Electrochem. Soc.*, 2017.

Multiphase MEA model

Power density at 0.7 V

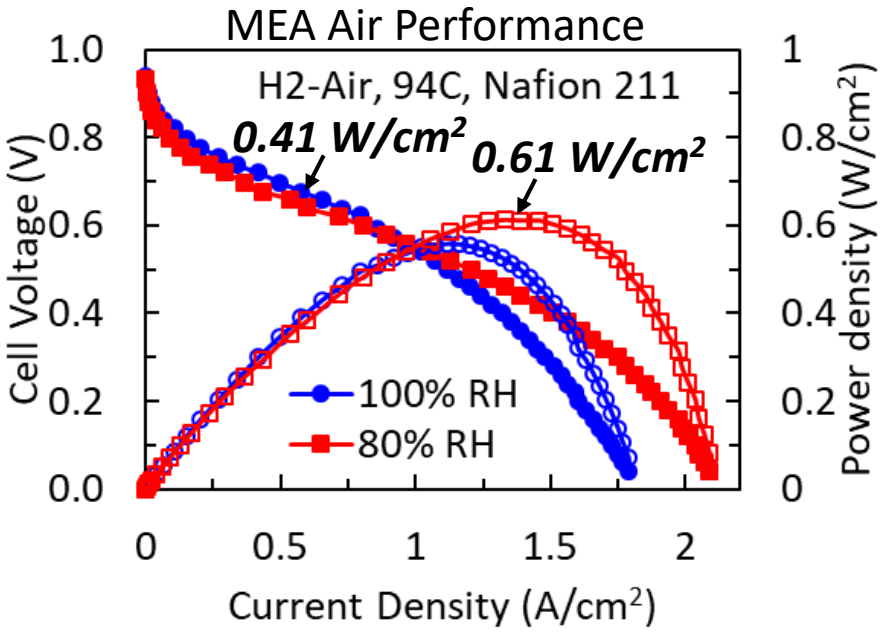


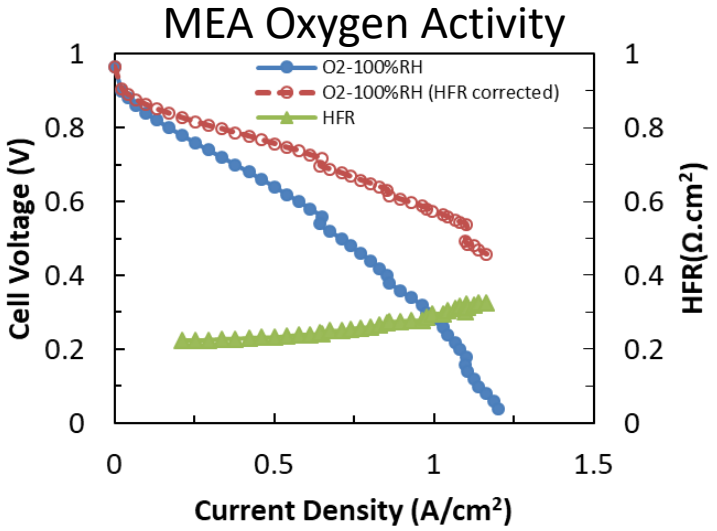
Input of active site density in carbon & single site activity

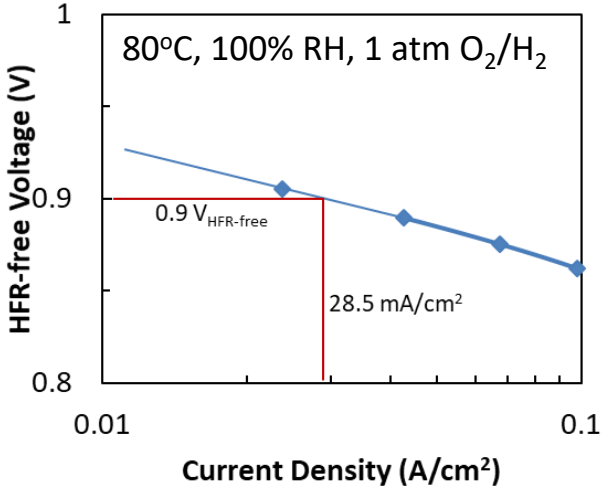
Carnegie Mellon University

MEA Performance Update – Fe-MOF Catalyst

- Achieved Year 1 and Year 2 Go/No-Go MEA activity target
- **28.5 mA/cm²** at 0.9 $V_{HFR\text{-}free}$ or **44 mA/cm²** at 0.89 $V_{HFR\text{-}free}$ in 1 atm O_2/H_2 PEFC at 80°C.
- Evaluation of air performance at automotive condition at 94°C with dry air and H_2 partial pressure of 1.7 atm.
- 0.41 W/cm² at rated voltage of 0.67 V for 94°C (100% RH) & 0.15 A/cm² at 0.8 V.
- 0.61 W/cm² maximum power density (air, 80% RH)





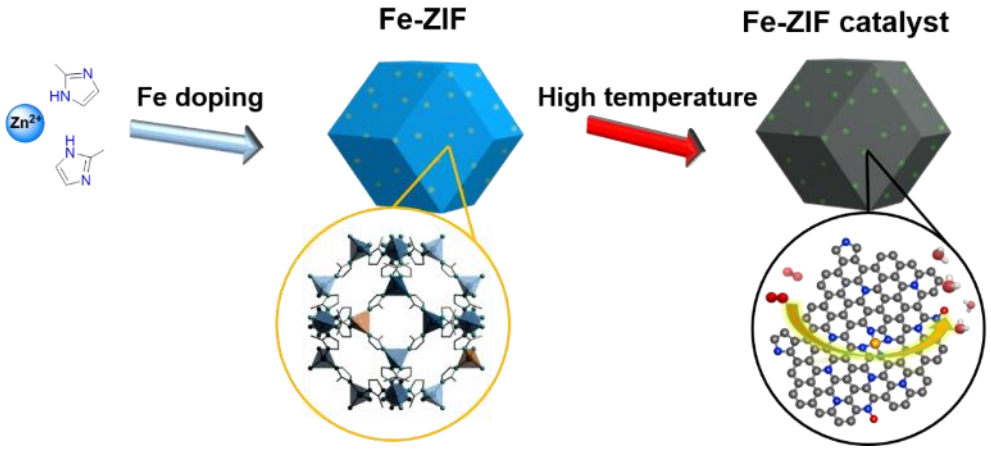


I/C 1 (Nafion 1100)
100 nm Fe-MOF catalyst
Loading: 6 mg/cm²
Nafion 117

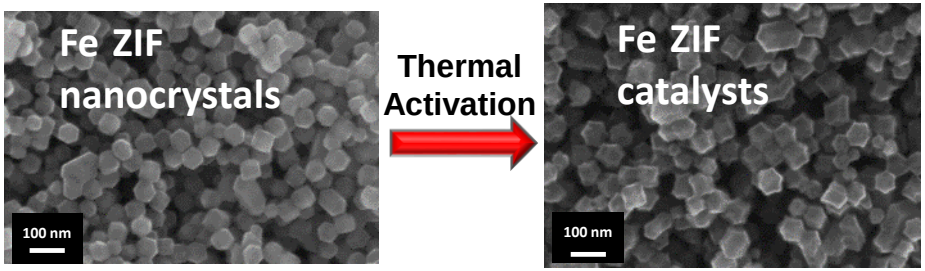
Carnegie Mellon University

Synthesis of Fe-MOF derived PGM-free catalysts

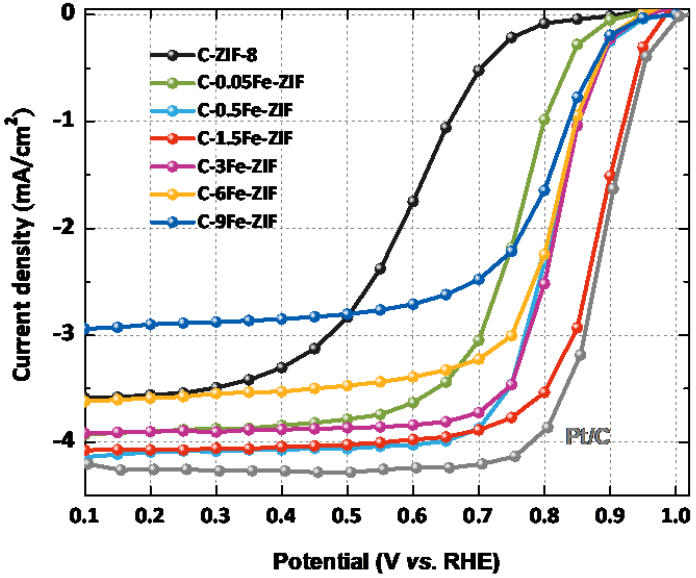
Chemically doped Fe into ZIFs with tunable Fe content



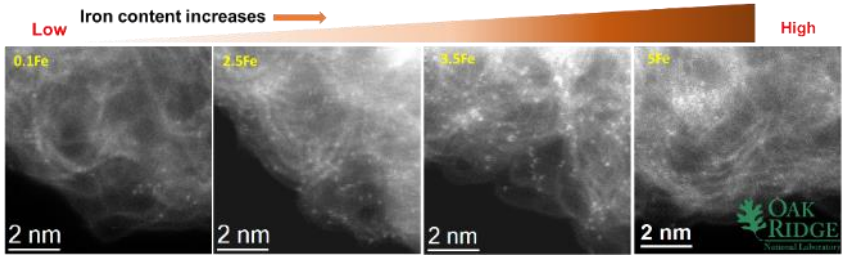
Uniform particle dispersion morphology



Optimizing Fe doping for activity



Evolution of Fe Clustering



Increase activity by increasing atomically dispersed Fe without clustering

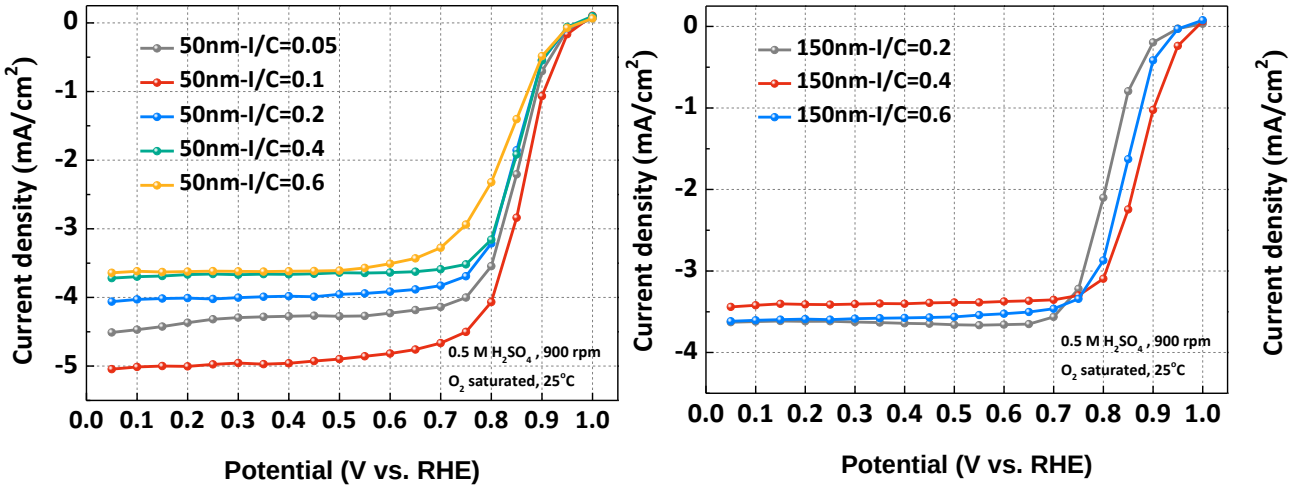
- Facile and scalable synthesis omitting multistep post-treatments
- Single heat treatment
- Tunable morphology and composition of catalysts from well-defined MOF nanocrystal precursors
- Applied to Fe and Co (CoN_4 in Technical Back-up slides)

Carnegie Mellon University

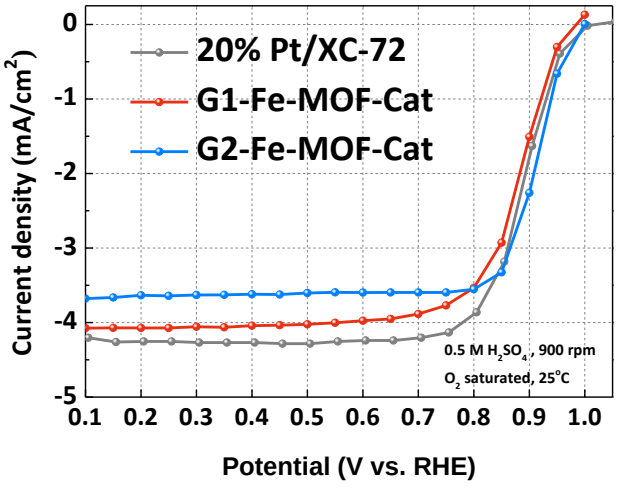
RDE Ionomer Effects and Enhanced Activity

- The RDE ORR activity of Fe-MOF catalysts are very sensitive to the Nafion content. The optimized Nafion content is highly dependent on the primary size of catalysts.
- RDE Nafion I/C variations can yield >0.05 V changes in half-wave potential.
- Only small amounts of Nafion is needed for the catalyst with small size (50 nm) of particles to achieve best performance in RDE measurements.
- New G2-Fe-MOF-Cat (**$E_{½}$ > 0.88 V**) outperforms the commercial Pt/C catalyst by carefully controlling thermal conditions and adding the additional iron sources.

Effect of Nafion content on Fe-MOF catalysts with different particle sizes



Best performance with optimized Nafion content



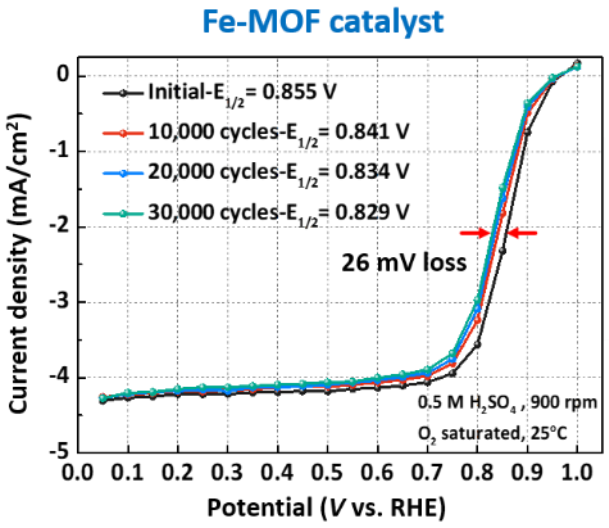
RDE testing at CMU with varying ionomer type (3M, Nafion) and EW in Technical Back-up Slides

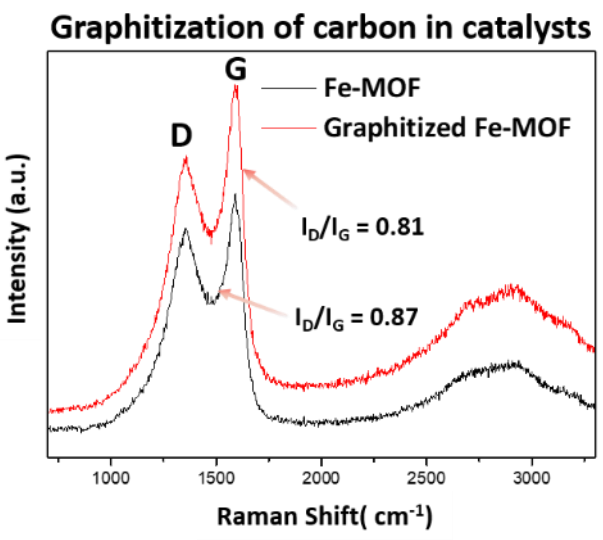
3M

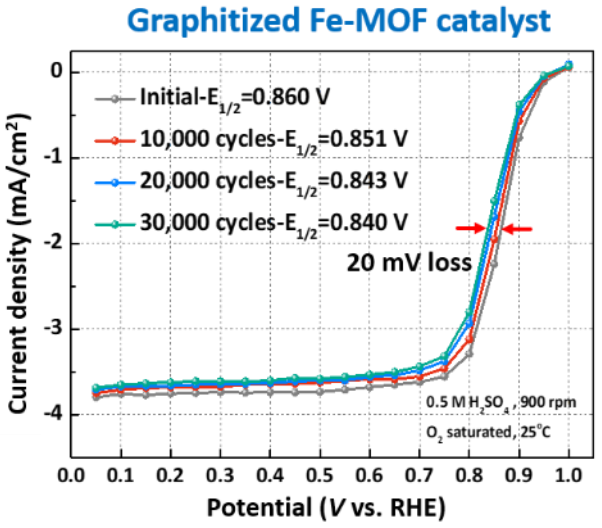
Carnegie Mellon University

Graphitized Fe-MOF: Enhanced Stability

- Achieved combined activity and durability for Year 1 Go/No Go with **20 mV loss** in half wave after **30,000 cycles** with an initial half wave of **0.86 V.**
- The modified Fe-MOF catalysts with increased degree of graphitization verified by Raman spectroscopy exhibited enhanced stability.







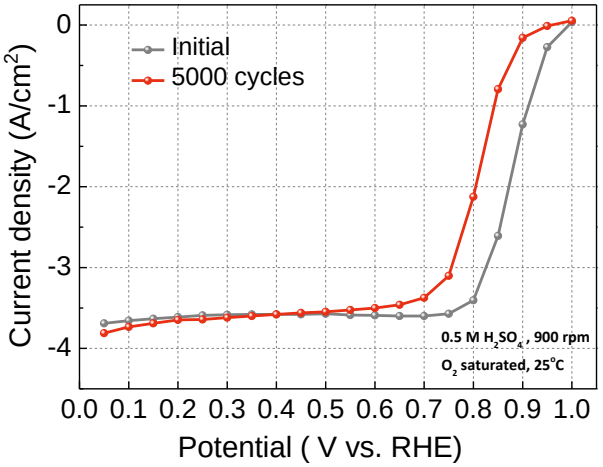
30,000 cycles from 0.6 V to 1.0 V at RDE only leading to 20 mV loss
Met the year 1 go/no-go milestone

Carnegie Mellon University

Enhanced Carbon Corrosion Resistance

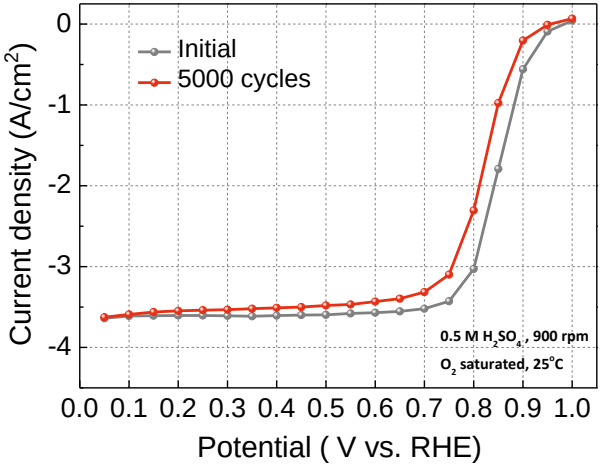
- Stability evaluation by cycling from 1.0 V-1.5 V further demonstrated the enhanced carbon corrosion-resistance via engineering the carbon structure of Fe-MOF catalysts.
- The stability of Fe-MOF catalysts are improved when increasing the order of carbon phase in catalysts.
- Detailed synthesis condition and comprehensive characterization are ongoing and will be reported in future meetings.

Amorphous Fe-MOF catalyst



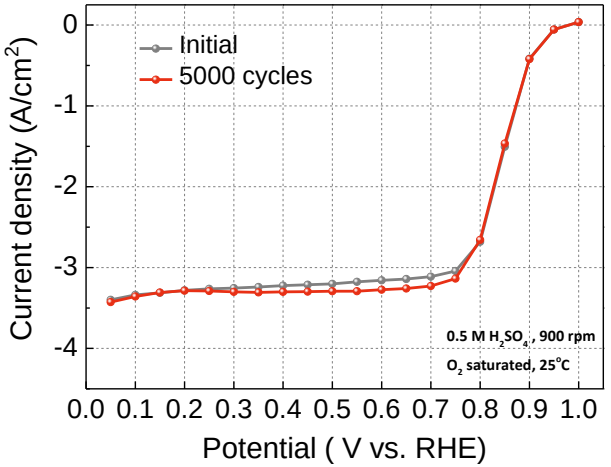
70 mV loss in $E_{½}$ for 5,000 cycles

Graphitized Fe-MOF catalyst



30 mV loss in $E_{½}$ for 5,000 cycles

Highly graphitized Fe-MOF catalyst



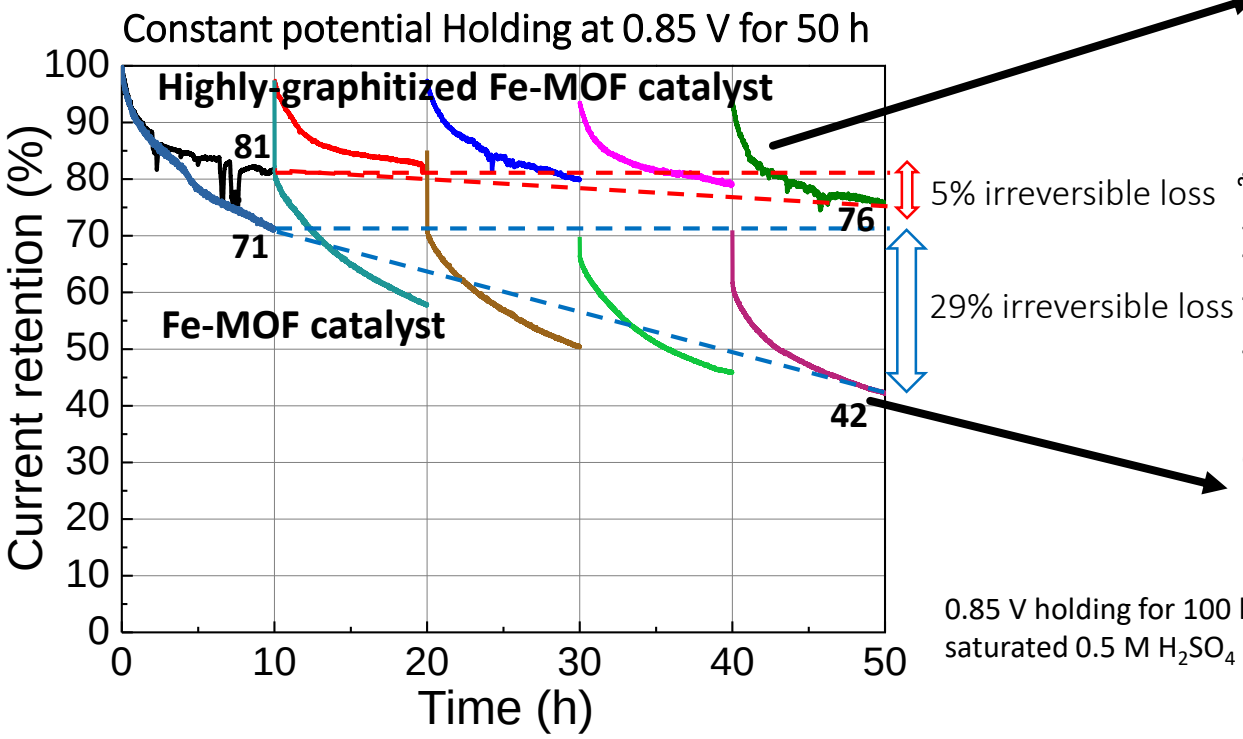
No loss in $E_{½}$ for 5,000 cycles

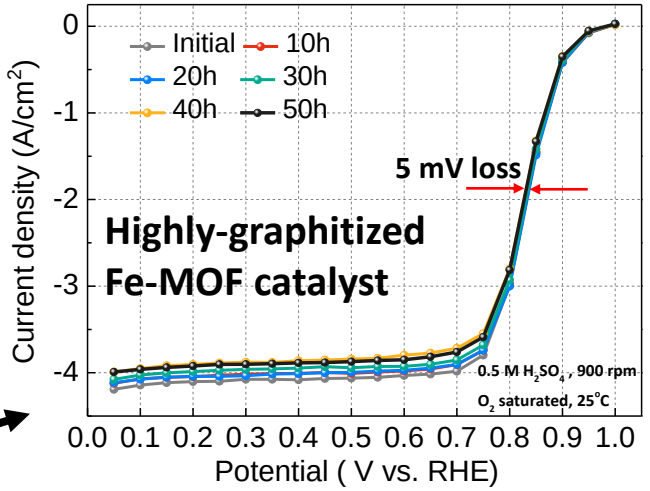
Cycling from 1.0-1.5 V at 500 mV/s under N_2 in 0.5 M H_2SO_4 for 5,000 cycles.

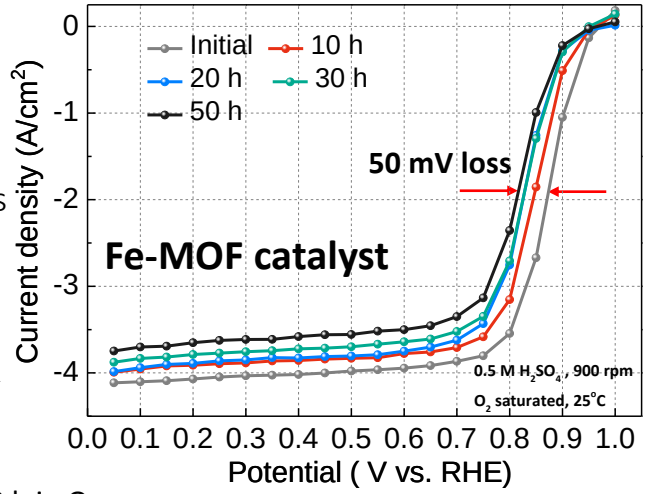
Carnegie Mellon University

Enhanced Catalyst Stability: 0.85 V holds

- Catalysts suffer from short-time and long-time activity loss including both reversible and irreversible components of loss.
- The highly graphitized Fe-MOF catalyst exhibits improved stability compared to prior Fe-MOF for 0.85 V hold over 50 h, only showing 5% irreversible loss in current.
- The graphitized Fe-MOF catalyst (not shown) exhibited 20% enhancement for the retention of current as well as less loss in the half-wave potential.







0.85 V holding for 100 h in O_2 saturated 0.5 M H_2SO_4

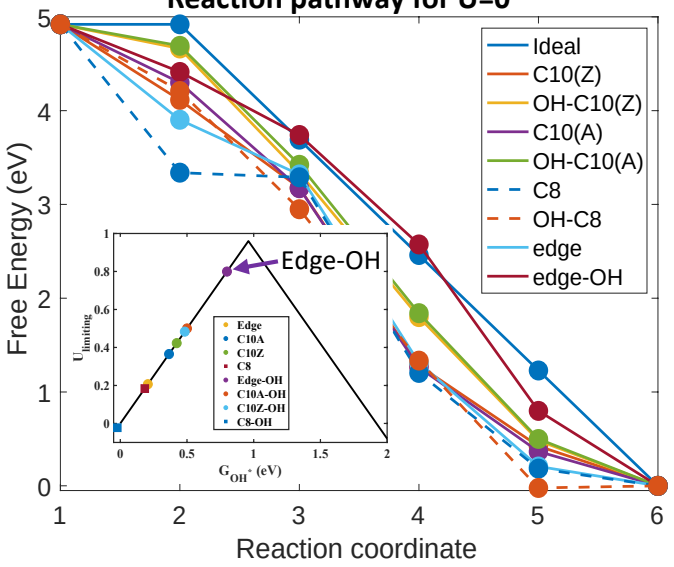
University at Buffalo
The State University of New York

Carnegie Mellon University

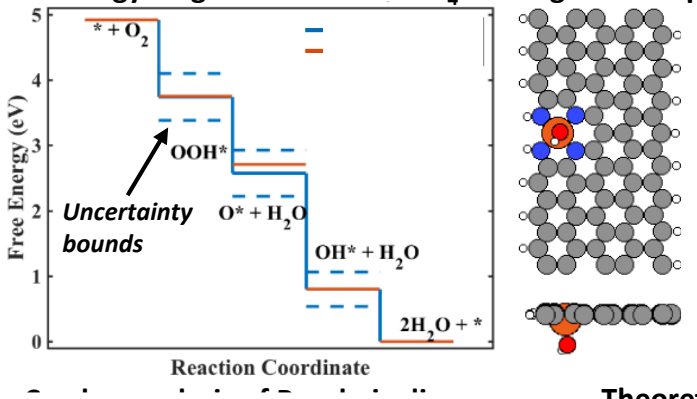
Theoretical Approach to PGM-Free Catalysts

Carnegie Mellon University

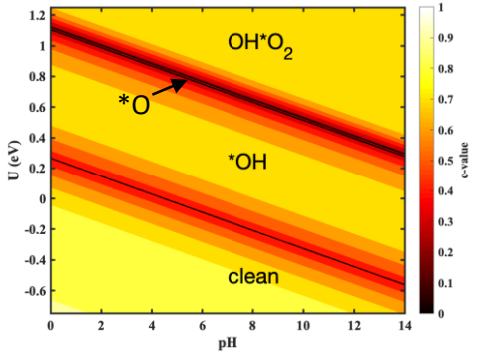
Reaction pathway for U=0



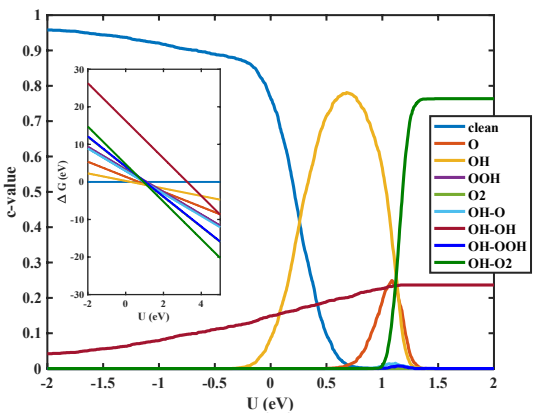
Free energy diagram: U = 0 for FeN_4-OH edge site

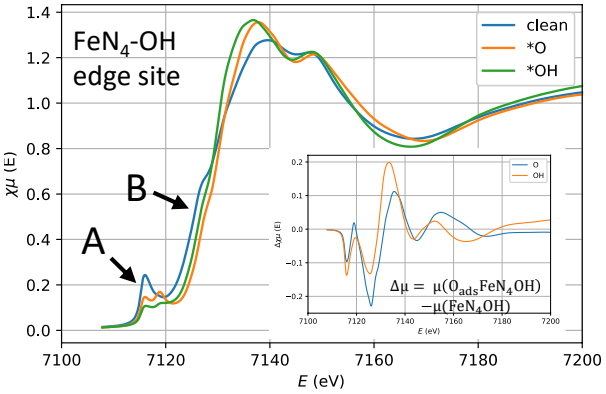


Pourbaix diagram for FeN_4 edge sites



Theoretical XANES analysis at Fe K-edge





- Reaction pathways and free energy diagrams for various FeN_4 active sites computed using first principles density functional theory (DFT).
- Activity volcano with limiting potential as a function of OH* adsorption energy with expected OH*-OOH* scaling.
- FeN_4 edge site with OH ligand shows highest thermodynamic limiting potential and the reaction pathway is close to the ideal case.
- Exchange and correlation is treated with BEEF-vdW functional to incorporate experimental uncertainty by training the parameters of the functional form on experimental data. Validated against Chung *et al*.
- Pourbaix diagram shows the active site with OH ligand forms a more stable surface for ORR compared to the active sites without OH ligand.

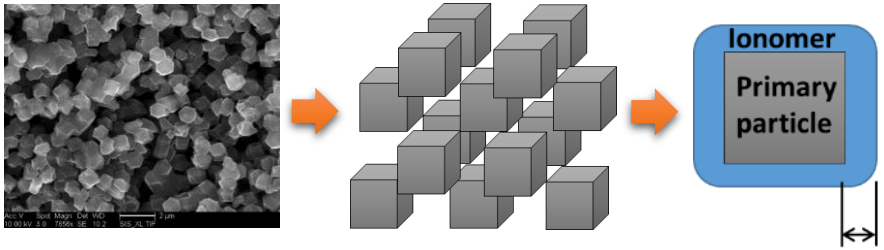
- BEEF-vdw confidence value (c-value) indicates how many functionals agree with optimal.
- X-ray absorption near edge structure (XANES) spectras at Fe K-edge calculated by ab initio real space multiple-scattering method implemented in FEFF9 program.
- Edge hosted FeN_4 with OH ligand shows significant distortion of the Fe-N square-planar symmetry at A. Ligand formation with ORR intermediates shows Fe-N switching behavior.
- Active sites with adsorbents show K-edge at B shifts to higher energy, confirming the Fe2+/Fe3+ redox transition.
- The delta-mu analysis shows moderate adsorption strength between the active sites and the key ORR intermediates which attributes the high ORR activity of the active site considered.

Chung et al., 2017 *Science*, *357*(6350), 479.

MEA Ionomer Integration

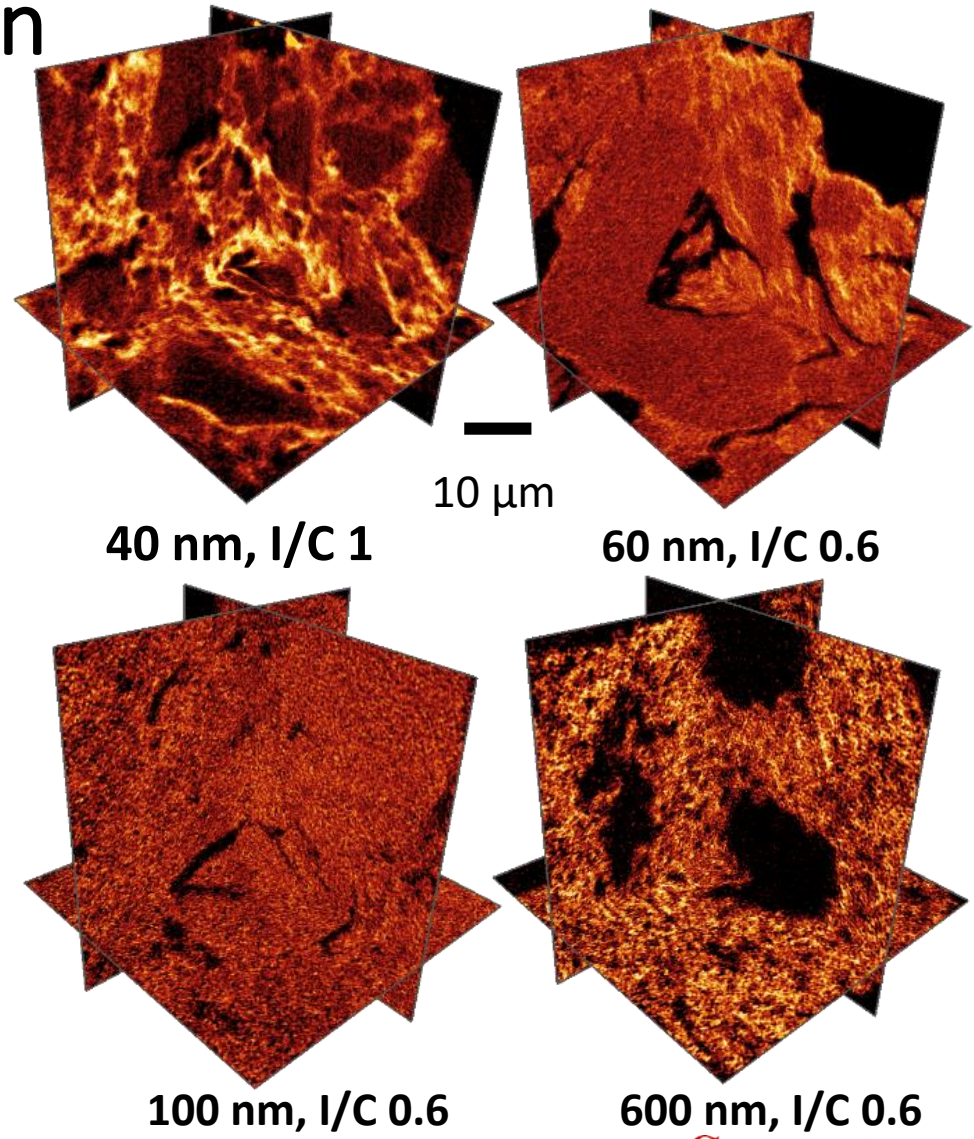
I/C	Ionomer thickness (nm) of primary particle sizes				
	40 nm	80 Nm	100 nm	150 nm	600 nm
0.6	3	5	7	10	40
0.8	4	7	9	13	54
1	5	9	11	17	67
RF	5000	2500	2000	1300	330

RF: Primary particle roughness factor at 4 mg/cm^2



- Estimate primary particle's ionomer film thickness as function of particle size and I/C
- Increased particle size increases primary pore size and improves ionomer infiltration into aggregates
- Highly uniform distributions for >80 nm
- Excess ionomer forms thick films around aggregates

Nano-CT: 3D Mapping of Ionomer in MEAs



Ink I/C and H2O/IPA ratios verified by ANL high-throughput testing (Backup slides)

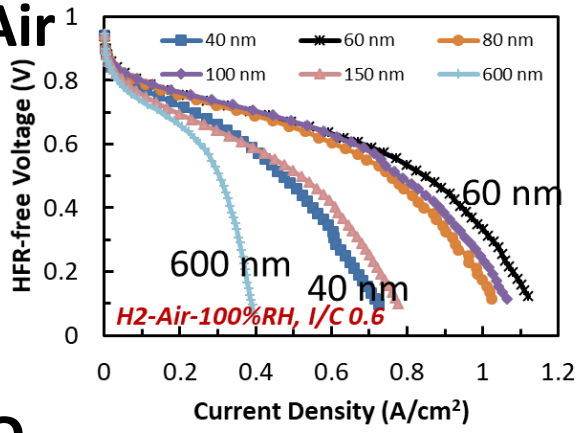
Carnegie Mellon University

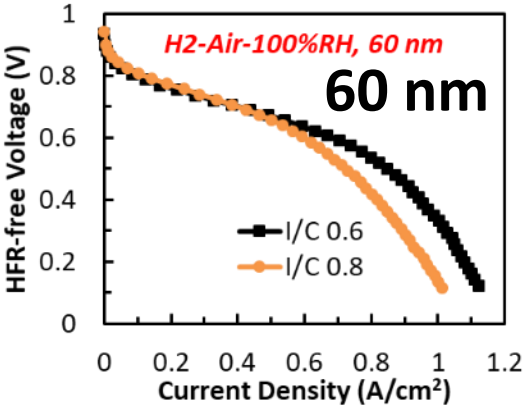
Argonne NATIONAL LABORATORY

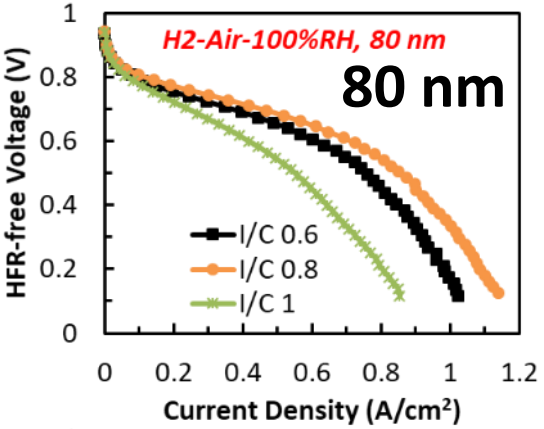
Effect of Particle Size and Ionomer Loading

- Optimum in 60-100 nm range with 100 nm providing repeatable performance
- Trade-offs between activity, conductivity, and mass transport
- Best activity and mass transport using 80 nm catalyst with an I/C of 0.8

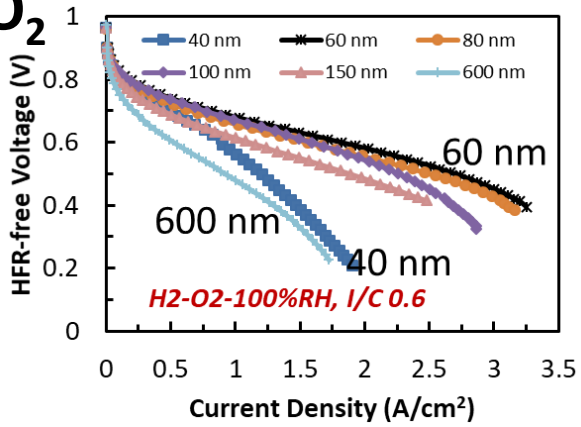
Air

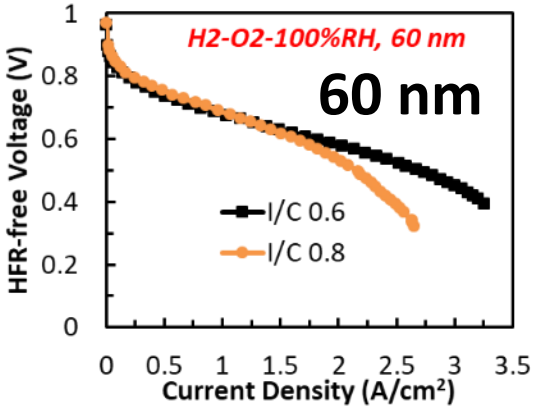


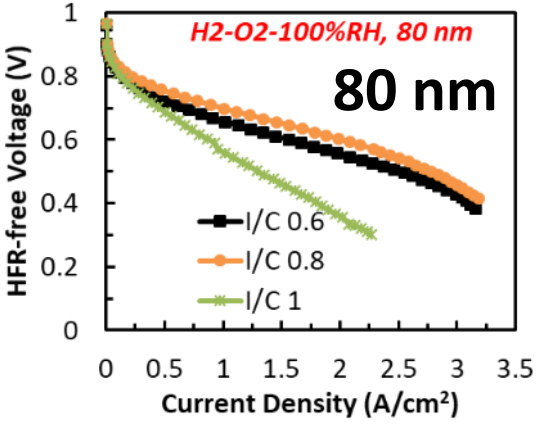




O_2





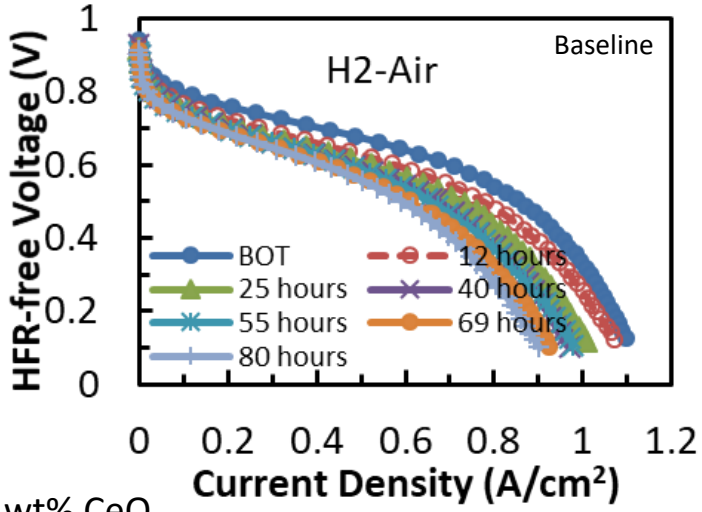


Catalyst loading: 4 mg/cm^2, Cell temperature: 80°C; Flow rate H_2/air or O2: 200/200 sccm, RH: 100%, 1 bar H_2/air or O2 partial pressure. Nafion 212

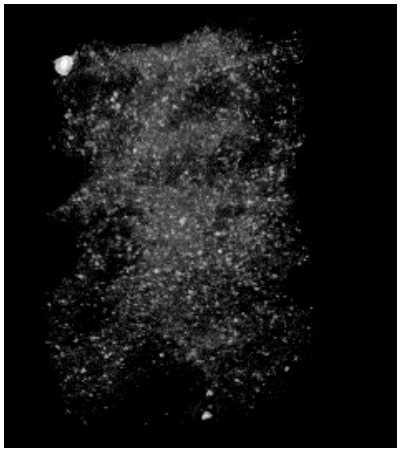
Carnegie Mellon University

MEA Durability

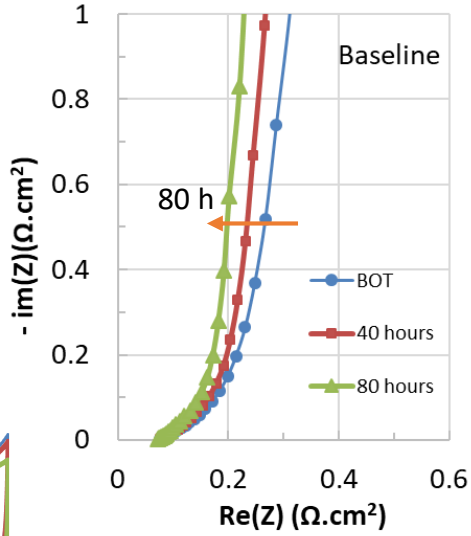
- Aggressive 80 h durability test for PGM-free at 0.7 V
- Two regimes of performance loss: short and long time-scales
- Evidence that initial rapid 10 h decay is reversible
- Short time performance loss is not due to flooding:
  Seen in RDE testing and not reversed by 40% RH dry out
- Irreversible decay rate is ~1 mA/cm^2/h
- No loss of proton conductivity
- Investigation radical scavenger additive



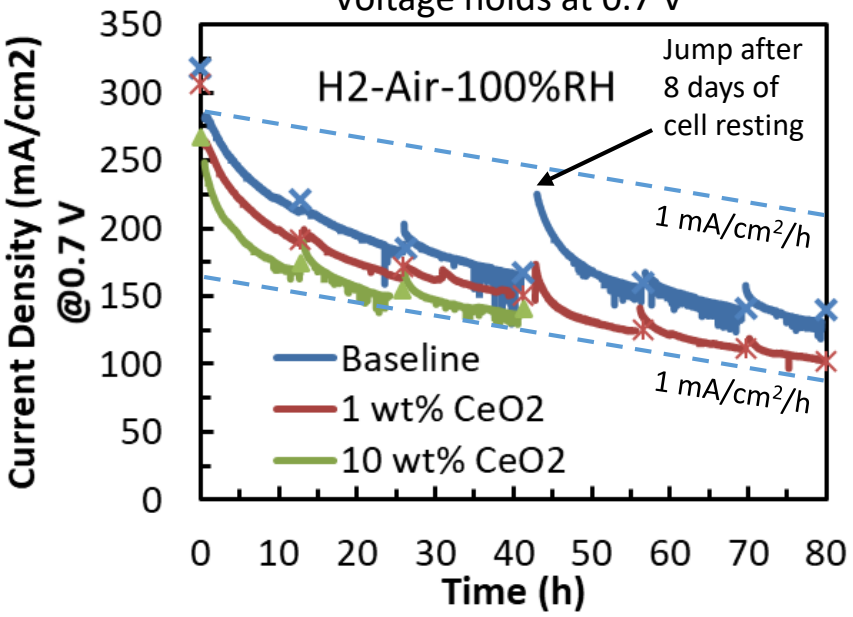
Nano-CT of 10 wt% CeO_2

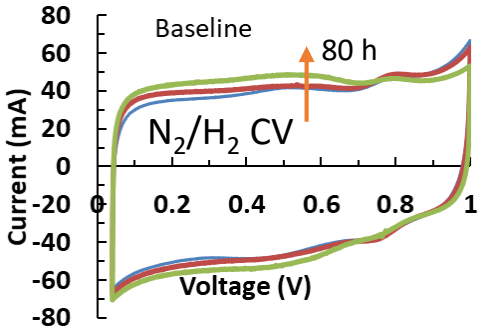


N_2/H_2 EIS Nyquist plot



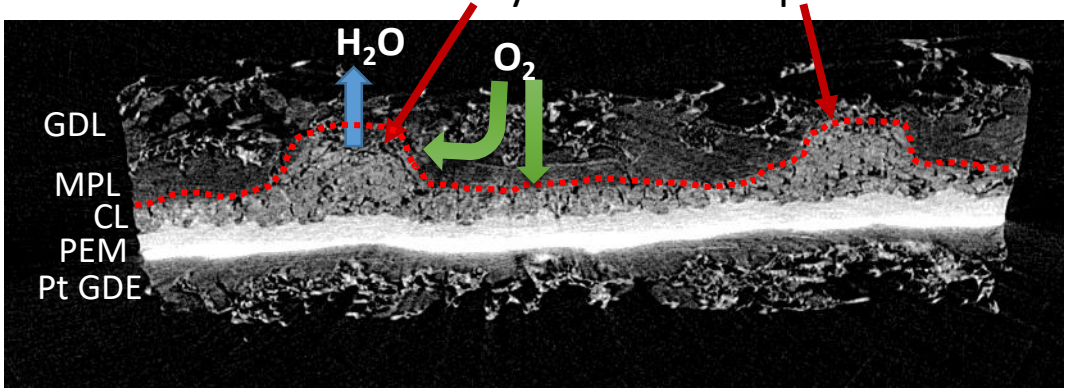
Voltage holds at 0.7 V

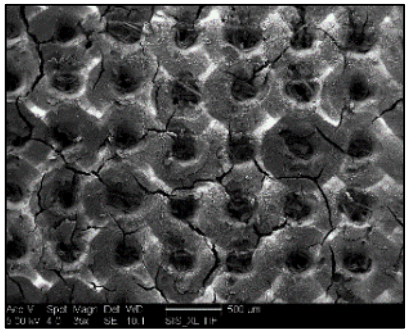




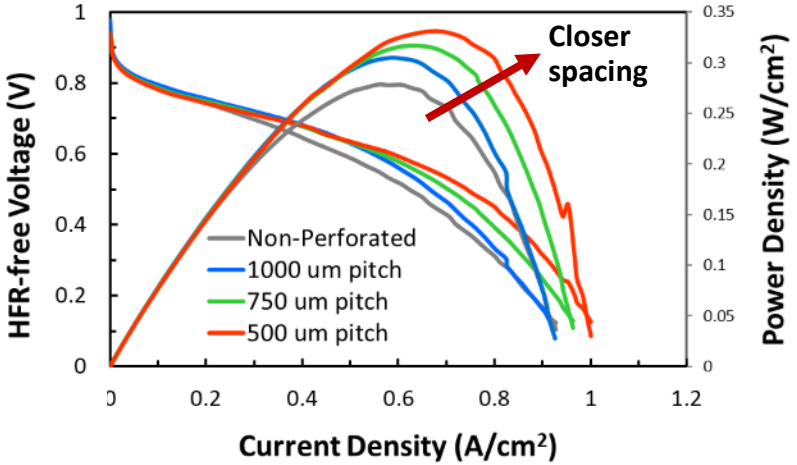
Carnegie Mellon University

Microstructured Cathode-MPL



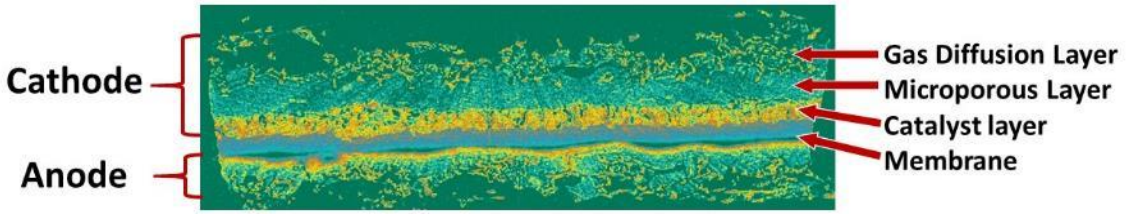


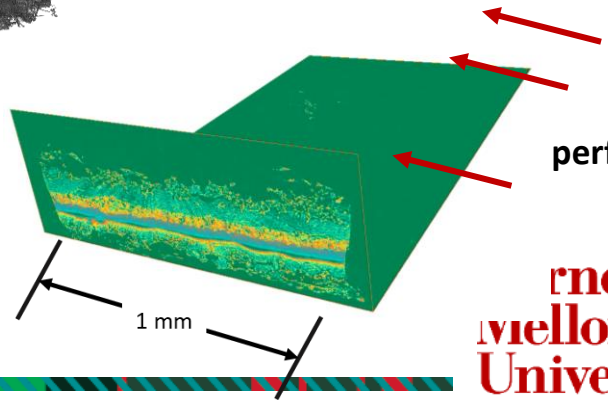
Perforated MPL
150 µm diameter
500 µm spacing



80 nm catalyst loading: ~4 mg/cm², Cell temperature: 80°C; Flow rate H_2/air or O_2: 200/200 sccm, RH: 100%, 1 bar H_2/air; Nafion 212

- Laser perforations only through the microporous layer (MPL)
- Catalyst ink fills perforations up to the carbon fiber backing of the GDL
- Increased interfacial area between MPL and cathode for enhanced O_2 transport
- Low capillary pressure pathway for liquid water removal
- 20% increase in maximum power density with finest spacing





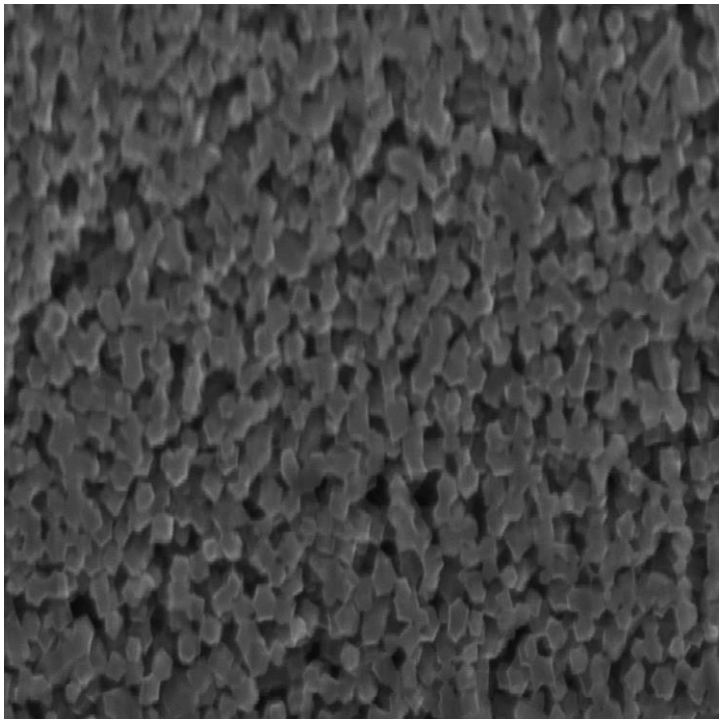
rnegie
llon
University

High-throughput nm-scale 3D Imaging: PFIB-SEM

- Analyzing PGM-free electrode structure requires large volumes for macrostructure but sub-10 nm resolution to accurately resolve primary particles.
- Outside of either X-ray CT or Ga FIB-SEM capabilities
- Plasma FIB (PFIB): CMU's Helios PFIB Dual Beam SEM for large volume 3D characterization
- PFIB cross-section significantly higher through-put versus conventional gallium ion FIB-SEMs
- No intrusive damage artifacts to PEFC electrode structure imaging or Ga-ion embedding

Image: https://www.fei.com/products/dualbeam/helios-G4-PFIB-CXe-for-materials-science/

- Cross-sectional PFIB-SEM imaging of optimized cathode with 100 nm catalyst with an I/C ratio of 0.6
- First known application of PFIB-SEM to PEFCs
- 2 nm pixels and 4 nm thick slices
- Visualization of 3D primary particle network over large electrode length scales



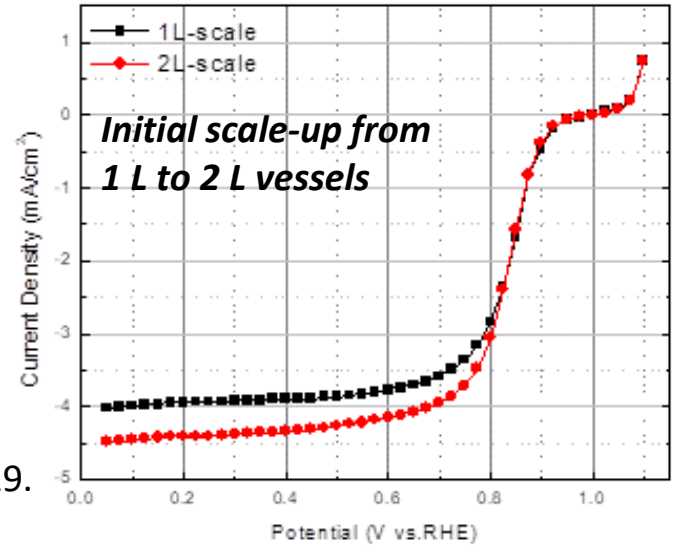
Future work: *3D segmentation for morphological parameters and model inputs*

Carnegie Mellon University

Catalyst Synthesis Scale-Up

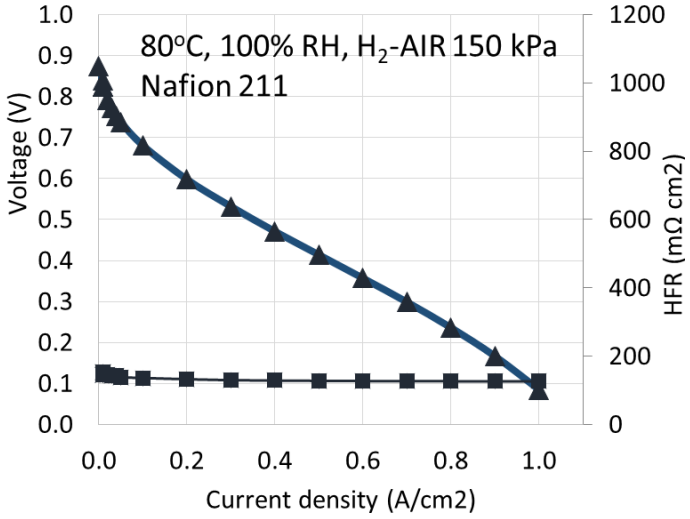
- Giner leading scale-up of catalyst synthesis and MEA fabrication
- Electrode optimization studies require large amounts of down-selected catalyst with reproducible properties
- Initial process development and validation of Fe-MOF catalysts at Giner in 1 L and 2 L volumes.
- Behavior consistent from small batch to 2 L
- New 20 L reactor: First 6 g precursor batch produced from 6 L in 02/19.
- Initial RDE and MEA testing promising to reach small batch performance with refined processing

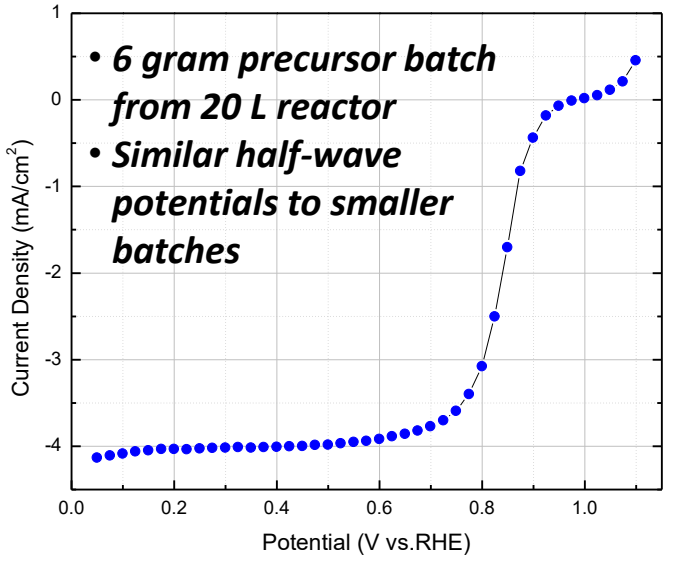
RDE testing of Fe-MOF catalyst at Giner



20 L Reactor

MEA performance from 1st large-scale batch Fabricated and tested at Giner





GINER Carnegie Mellon University

Reponses to Last Year AMR Reviewers' Comments

- *Several similar comments of concern on the stability of Fe-based catalysts: "A weakness is that the approach is focused mostly on the highest-activity PGM-free materials but these materials seem to be inherently unstable under typical operating conditions. Based on initial results, it seems likely that the project will result in a high-performance PGM-free MEA, but the durability will be as poor as that of previous high-performing PGM-free MEAs."*
    - Durability is a key focus of the project. Several recent findings and developments have presented a pathway to significant improvements in stability with Fe. These include identifying a significant fraction of the performance loss may be reversible and that the carbon corrosion mitigation and long term stability can be significantly improved through synthesis with a higher degree of graphitization without substantially reducing activity.
- *Several similar comments of concern on MEA power density and 0.9 V current: "This project has met the initial half-wave-potential goal of 0.87 V vs. the reversible hydrogen electrode, but the power produced is well behind that shown by other developers." "current density at 0.9 V is still far away from the milestone and first go/no-go review target."*
    - The MEA power density results presented at the 2018 AMR were from the first half of Year 1. With refined ink processing and deposition, we have now met and exceeded our year 1 MEA power density milestone and our Years 1 and 2 go/no go target for MEA current at 0.9 V.
- *Multiple comments of concern on the potential overlap with the Giner Mn project: "One concern is that, other than Dr. Litster's work and switching Mn for Fe, it is not clear how different this project is from the Giner-led ElectroCat project. The work may be overlapping. It is okay if the project leverages that work, but the team should make it clearer that the two projects are not being funded to do the same work."*
    - The high activity of the Fe-doped MOF catalysts places a high emphasis in this project on mass transport, ionomer integration, and Fe-catalyst stability. Giner's role in this project is to support the water management support development for CMU, Fe-doped catalyst scale up, and large format MEA fabrication and testing, thus there is no overlap in their work between this project and the Giner Mn project, but good synergies exist. The CMU project utilizes distinct modeling and imaging techniques, focused on transport and MEA fabrication. There is also a substantial aspect of the CMU led project on UB stabilizing the highly active Fe site of its catalyst.

Carnegie Mellon University

Future Work

- **Improving understanding of activity loss regimes** through electrochemical characterization in RDE and MEA in combination with DFT modeling and XAS.
- **Improving durability** by tuning synthesis and resulting carbon structure for greater carbon oxidation resistance and metal-atom retention
- **Improving the understanding of the active site** through DFT modeling and molecular probes studies with Los Alamos and XAS studies at Argonne
- **Increasing mass activity** by adjusting MOF precursor synthesis and pyrolysis step
- **Inmpoving cathode water management** by modifying electrode microstructure and mixed wettability
- **Reducing voltage losses** by optimizing catalyst ink composition and processing, including ionomer type, EW, and loading for MEAs based on learning from RDE.
- **Increasing catalyst supply rate** by scaling up synthesis of down-selected catalysts
- **Streamlining MEA production** by establishing improved cathode ink deposition methods for catalyst coated membranes (CCMs) and gas diffusion electrodes (GDEs)

Carnegie Mellon University

Summary

Approach

An integrated approach to achieving PGM-free cathodes with high power density and durability through three key approaches utilizing the strengths of the project team:

1. **Advanced MOF-derived M-N-C catalysts** with a high activity and durability. Features a low cost synthesis of atomically dispersed active sites at high spatial density
2. **PGM-free specific cathode architectures** that address the substantial flooding and transport resistances in thicker catalyst layers by introducing engineered hydrophobicity through additives and support layers
3. **Advanced ionomers** with low EW for increased activity and offering high proton conductivity for low ohmic losses across the electrode and more uniform catalyst utilization for improved durability

Accomplishments and Progress in First Seven Months

- Atomically dispersed catalyst using Fe- and Co-doped MOF have demonstrated high activity
- New graphitized Fe-MOF catalysts show superior stability and resistance to carbon corrosion
- Established an understanding of aggregate and primary particle size effect on ionomer integration & performance
- Identified a significant fraction of MEA performance loss is reversible
- Microstructuring of cathode and MPL interface with laser perforated MPL for enhanced water management

Collaboration and Coordination with Other Institutions

- Rapid iteration cycle with catalyst development at UB and MEA fabrication and testing at CMU.
- Catalyst scale-up at Giner using UB developed process
- Ionomer integration at CMU using 3M ionomer
- ElectroCat consortium actively collaborating on XAS, XRF, electron microscopy, and electrode fabrication

Relevance/Potential Impact

- Advancing synthesis of atomically dispersed active sites at high density with a simplified, low cost approach in order to meet activity and stability targets.
- Establishing new cathode designs specifically for PGM-free catalysts such that active sites are efficiently utilized to enable high power densities with durable performance.

Proposed Future Work

- Improving stability with more durable carbon phases
- Using combination of electrochemical characterization and DFT modeling to understand the two regimes of degradation
- Increasing mass activity through morphology and active site density
- Increasing power density with engineered water management
- Reducing ohmic voltage losses, water flooding and activity with improved ionomers
- Increasing catalyst supply rate through scale-up
- Streamlining MEA production with standardized fabrication methods

Carnegie Mellon University

Acknowledgements

Carnegie Mellon University

Aman Uddin
Lisa Langhorst
Diana Beltran
Shohei Ogawa
Leiming Hu
Yuqi Guo
Xiaomin Xu
Bahareh Tavakoli
Venkat Viswanathan (CMU co-PI)
Hasnain Hafiz
Gurjyot Sethi
Reeja Jayan (CMU co-PI)
Laisuo Su

University at Buffalo-SUNY

Gang Wu (UB PI)
Hanguang Zhang
Yanghua He
Mengjie Chen
Hao Zhang

Giner, Inc.

Hui Xu (Giner PI)
Shuai Zhao

3M Company

Andrew Haug (3M PI)

DOE Fuel Cell Technologies Office

David Peterson (Technology Manager)
Simon Thompson
Dimitrios Papageorgopoulos
Adria Wilson
Dan Berletti

Electrocatalysis Consortium (ElectroCat)

Argonne National Laboratory

Debbie Myers
Vojislav Stamenkovic
Eric Coleman
Jae Park

Los Alamos National Laboratory

Piotr Zelenay
Hoon Chung
Siddharth Komini Babu

National Renewable Energy Laboratory

KC Neyerlin
Luigi Osmieri
Sunilkumar Khandavalli
Scott Mauger

Oak Ridge National Laboratory

Karren More
David Cullen

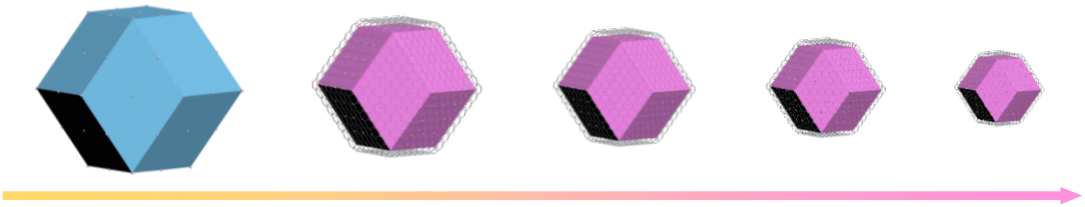
Technical Backup Slides

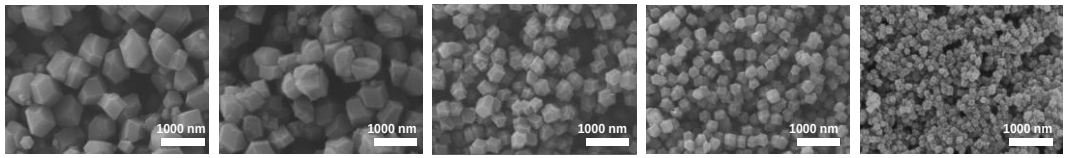
Carnegie Mellon University

Novel synthesis of Co-N-C catalysts

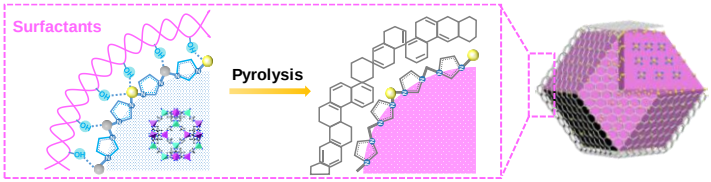
University at Buffalo
The State University of New York

surfactant assisted MOFs strategy

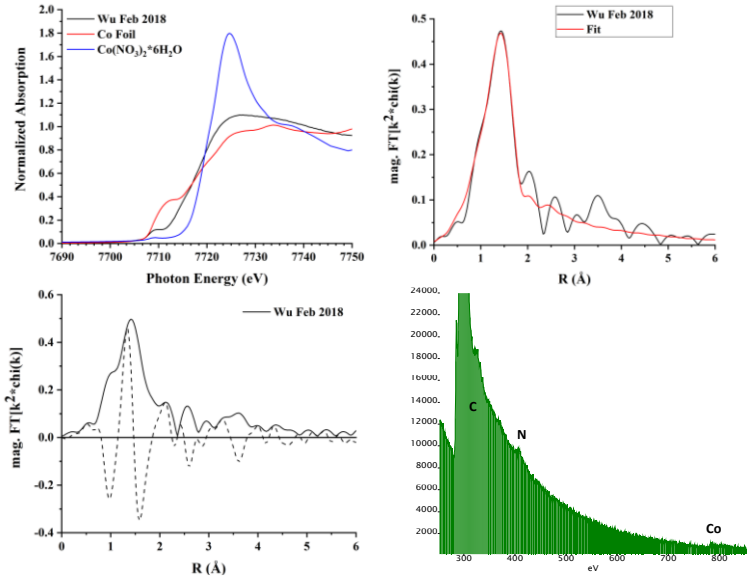




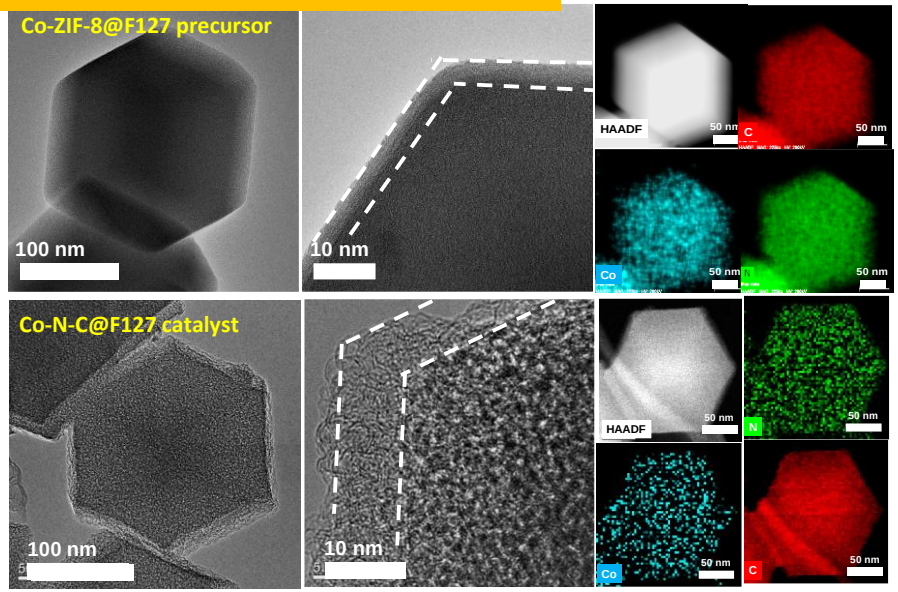
Non-surfactant	SDS (Mw = 288 g/mol)	CTAB (Mw = 364 g/mol)	F127 (Mw = 12,600 g/mol)	PVP (Mw = 40,000 g/mol)

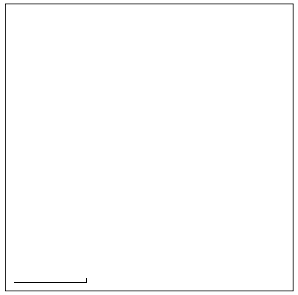


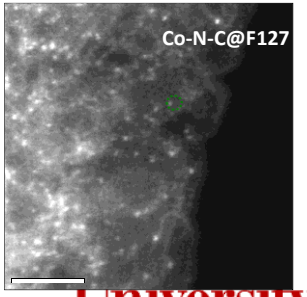
High density atomically dispersed CoN_{2+2} sites



Core shell structured Co MOF catayst





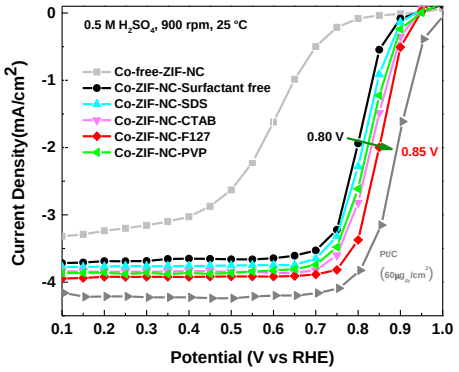


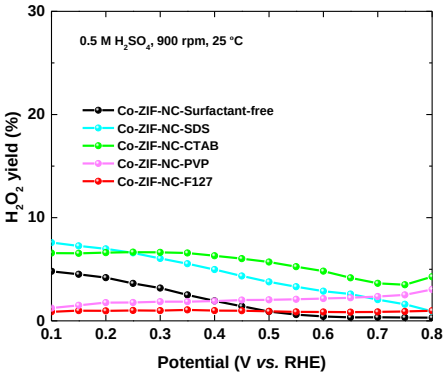
He et al., *Energy & Environmental Science,* 2019

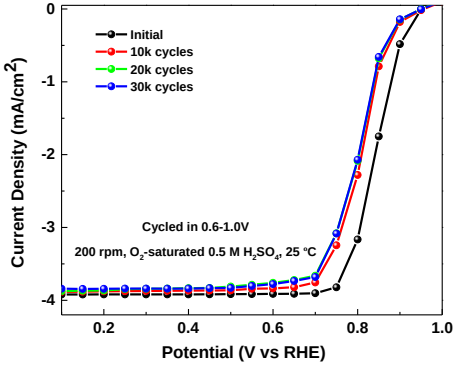
He et al., *Energy & Environmental Science,* 2019

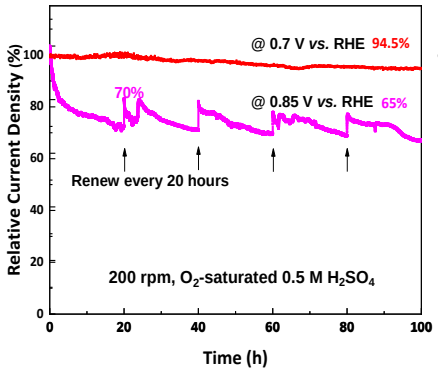
Enhanced performance of Co-N-C catalysts

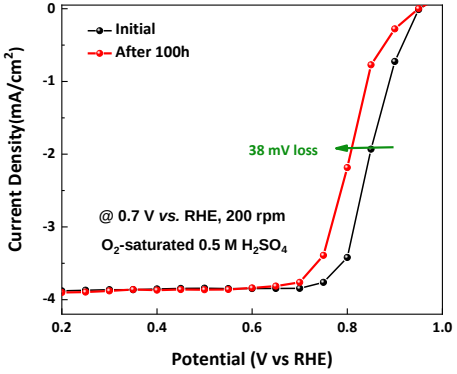
Catalyst activity and stability

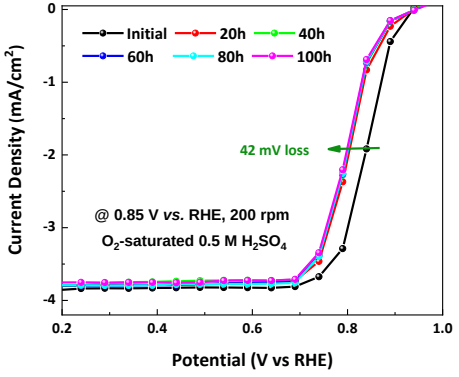




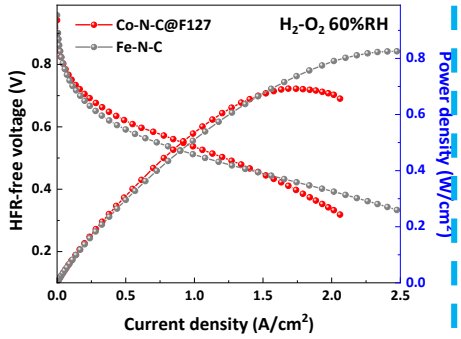


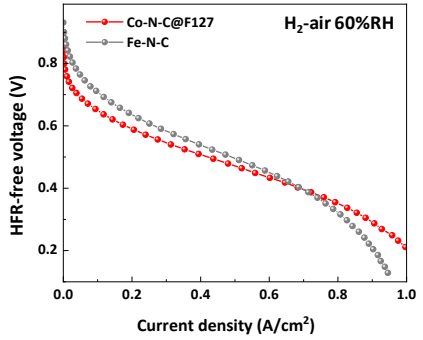






Fuel cell performance





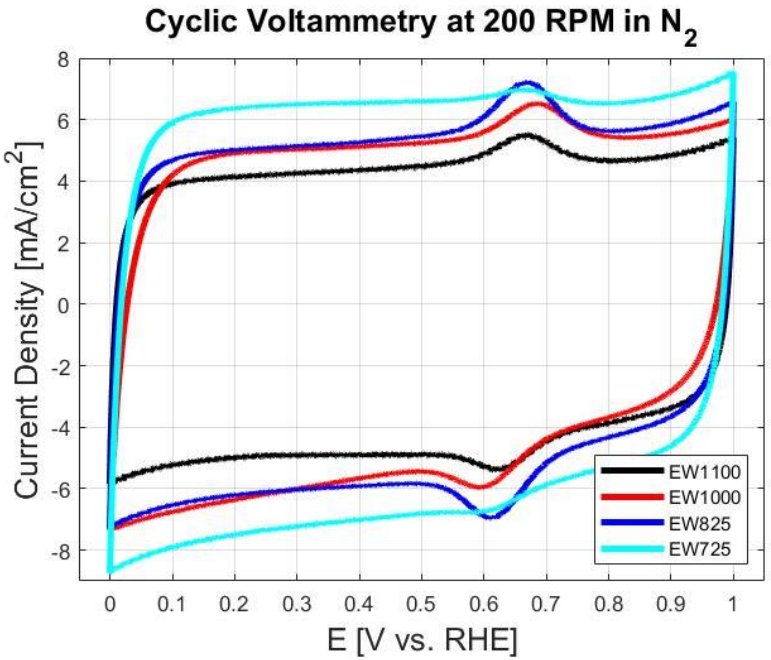
- Exhibited an unprecedented ORR activity with a half-wave potential ($E_{1/2}$) of 0.84 V (vs. RHE) as well as enhanced stability in the corrosive acidic media
- The performance of the new atomically dispersed Co site catalyst approaches that of the state-of-the-art Fe-N-C catalyst and represents the highest reported PGM-free and Fe-free catalyst performance

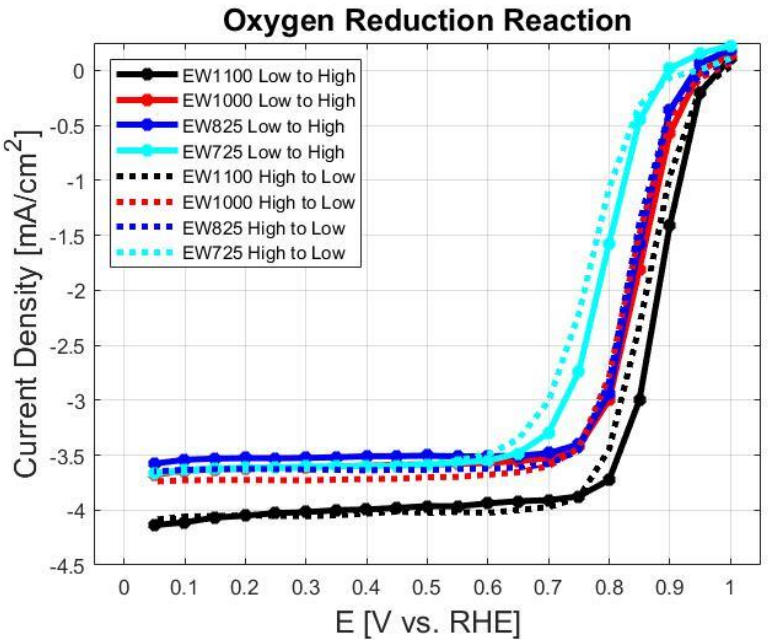
University at Buffalo
The State University of New York

Carnegie Mellon University

Ionomer type and EW effects in RDE

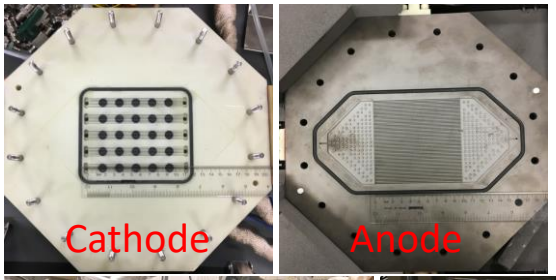
- Testing of 3M PFSA ionomers with 725 and 825 EW as well as Nafion ionomer with 1000 and 1100 EW
- Lower equivalent weight (EW) results in greater currents during CV for both 3M PFSA and Nafion
- Reduced ORR current with lower EW ionomers for both 3M PFSA and Nafion
- MEA testing to evaluate in-situ activity vs. proton conductivity trade-offs with EW variation



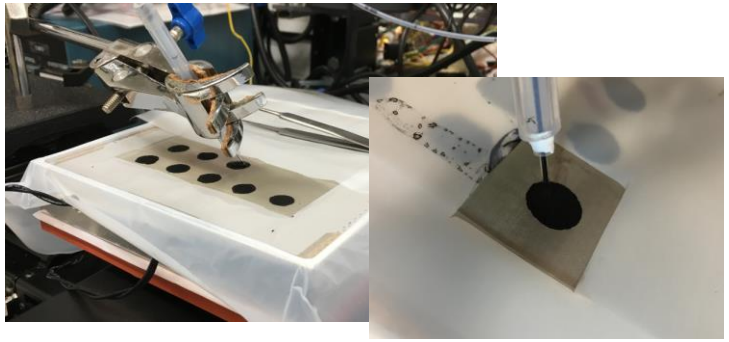


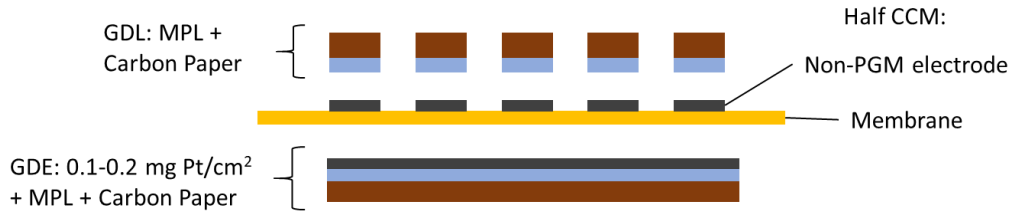
Combinatorial Fuel Cell Performance Testing

- ElectroCat Consortium support from Argonne National Laboratory
- High-throughput MEA test set up to expedite PGM-free electrode performance testing.
- NuVant 25 Segmented Electrode Hardware.

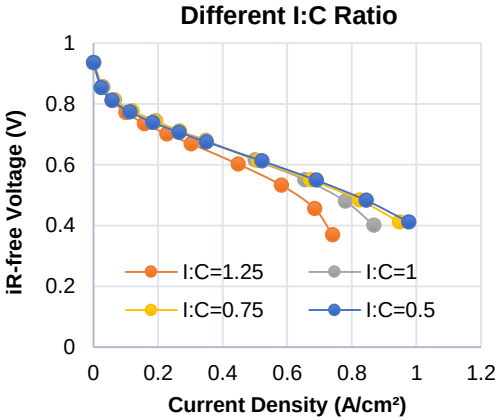


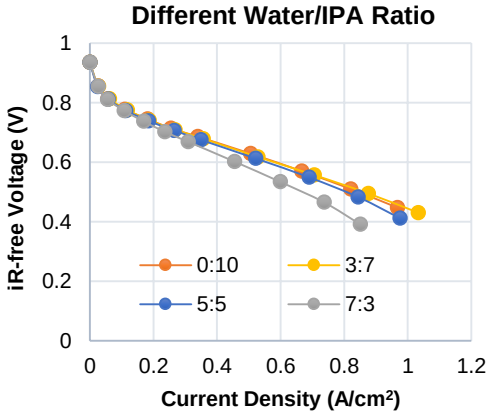
Automated ink deposition onto heated membrane to make 25-electrode catalyst-coated membrane





Effect of I:C ratio and solvent on Performance

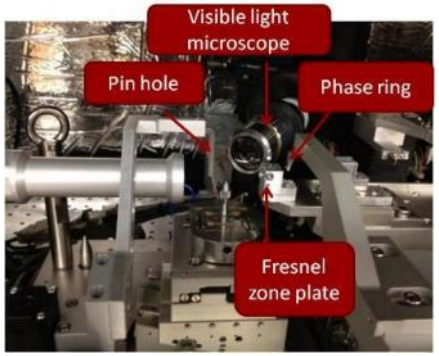




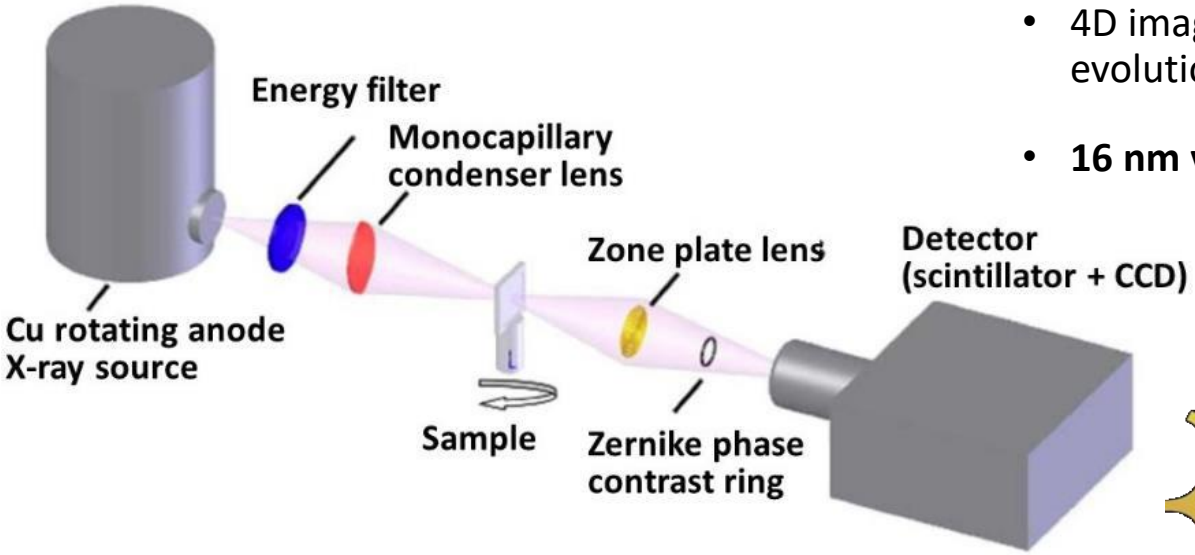
Anode: 0.2 mg_{Pt}/cm^2 onto 29BC GDL
Cathode: half CCM, Atomically dispersed Fe catalysts (UB-180604-HZ-2.5Fe-MOF-Cat), 4mg/cm^2
Cell temperature: 80°C; Flow rate H2/air: 200/200 sccm, RH: 100%, 1 bar H2/air partial pressure; Nafion XL

Argonne NATIONAL LABORATORY
University at Buffalo The State University of New York
Carnegie Mellon University

Nano-CT at CMU



User Facility: www.cmu.edu/me/xctf



- User facility with internal and external users. Primary use in electrochemical energy materials
- Xradia UltraXRM-L200 Nano-CT
- Laboratory 8 keV Cu rotating anode X-ray source
- Non-destructive imaging in ambient and controlled environments
- 4D imaging (space and time) for material evolution studies
- **16 nm voxels, 50 nm resolution**

NSF MRI award 1229090

Carnegie Mellon University