U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Fuel Cells R&D Overview

Dr. Dimitrios Papageorgopoulos – Fuel Cell Technologies Office

2018 Annual Merit Review and Peer Evaluation Meeting

June 13 – 15, 2018

Fuel Cells: Pillar of H_2 & Fuel Cell Technologies R&D

Focus

Early-stage applied R&D and innovation in hydrogen and **fuel cell technologies** leading to:

- Energy security
- Resiliency
- Affordability
- Strong domestic economy

H_2 & Fuel Cells Program: Early-Stage R&D Areas

Fuel Cells

Hydrogen

GOAL: Advance fuel cell technologies for transportation, stationary and cross-cutting applications

Making Fuel Cells our Future, Today

Objectives and Targets

1. R&D to enable a direct hydrogen fuel cell power system for transportation competitive with incumbent and alternative technologies on a lifecycle cost basis

2. R&D of efficient, resilient and affordable fuel cell systems for distributed power generation (primary, back up, CHP)

3. Enable fuel cell technology advancements for cross-cutting applications (e.g. APUs, rail, material handling)

Fuel Cells MYRD&D Plan

http://energy.gov/eere/fuelcells/downloads/fuel cell technologies office multi year research development and 22

2025 Targets by Application

	Automotive	Stationary
Fuel Cell Cost	$40/kW $30/kW*	$1,000/kW** $1,500/kW***
Durability	5,000 hrs 8,000 hrs*	80,000 hrs
Efficiency	65%	50% † 90% ‡

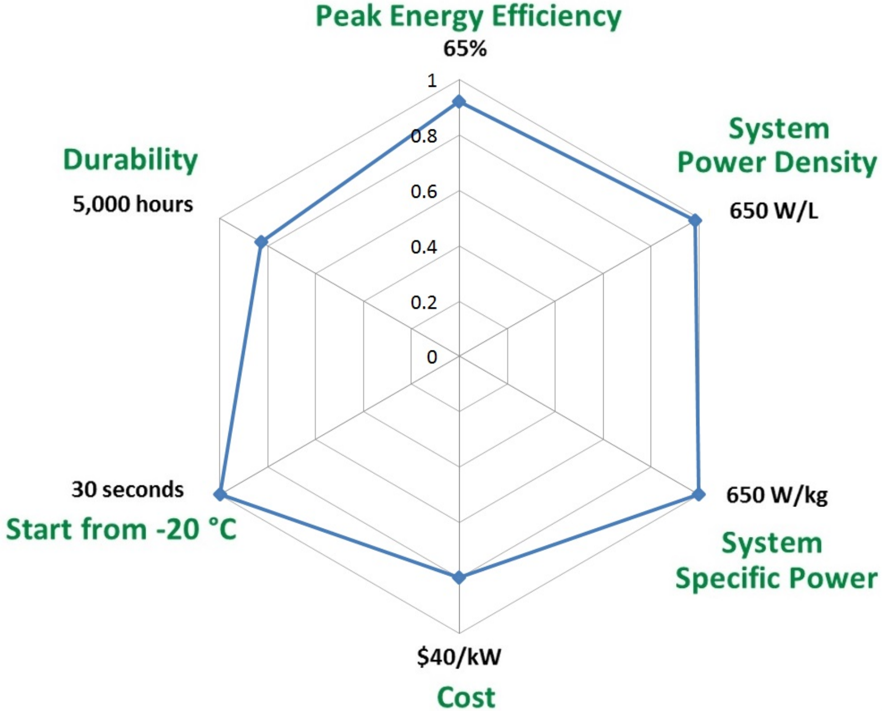
* Ultimate (Beyond 2030)

** For Natural Gas
*** For Biogas
† Electrical
‡ CHP

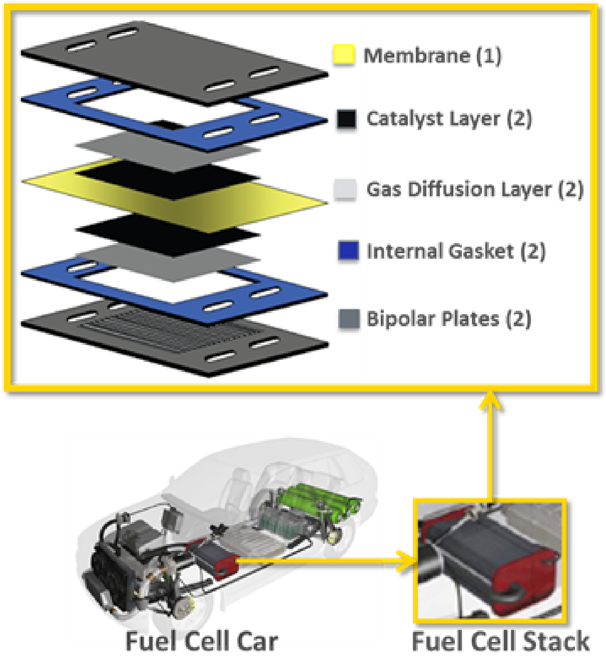
Market-driven targets allow fuel cells to compete with incumbent and advanced alternative technologies

Challenges and Strategy

Durability <u>and</u> Cost are the primary challenges to fuel cell commercialization and must be met concurrently



Early-stage materials and components R&D to achieve low-cost, high-performance fuel cell systems



Improvements in multiple components are required to meet 2025 targets

R&D portfolio focused on PEMFCs, but also includes longer-term technologies (e.g. AEMFCs) & higher temp fuel cells (e.g. MCFCs) for stationary applications

Challenges and Strategy

Early-stage R&D generates knowledge to foster significant fuel cell technology advances

BARRIERS

Cost
Durability
Performance

→

STRATEGY

Materials, components R&D to improve durability, reduce cost and enhance performance of fuel cells

→

Fuel Cell R&D

↕

Testing and Cost/Technical Assessments

→

FOCUS AREAS

Stack Components

Catalysts
Electrodes
Membranes
MEAs and Cells
Gas diffusion media
Bipolar plates

Performance and Durability

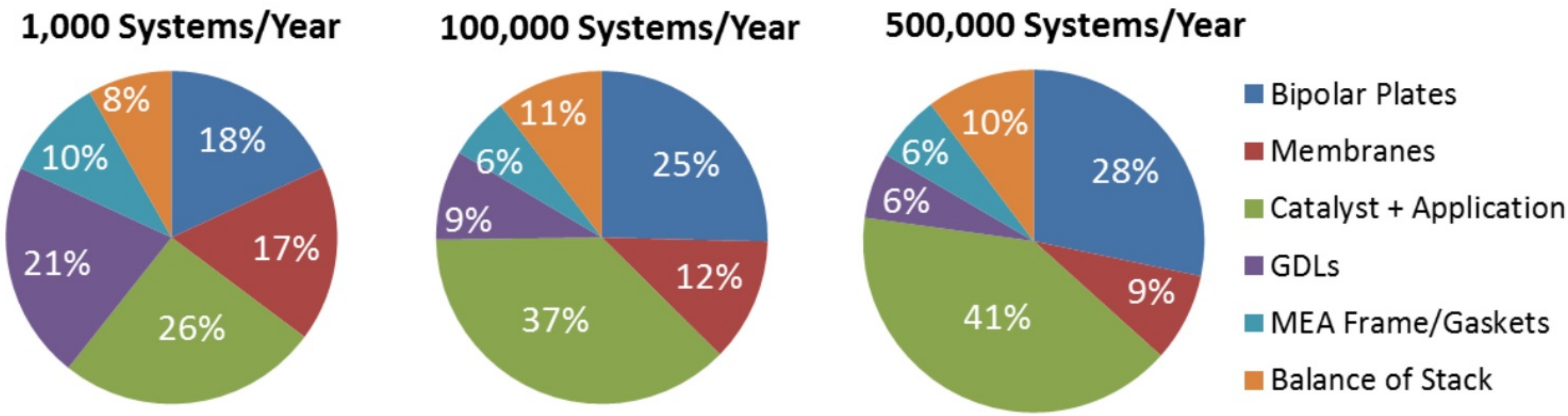
Mass transport
Degradation issues

BOP Components

Emphasis on longer-term high-risk research areas

Strategic Analysis Guides Fuel Cell R&D Priorities

PEMFC Stack Cost Breakdown



***Catalyst cost** is projected to be the largest single component of the PEMFC stack cost*

→

Strategy

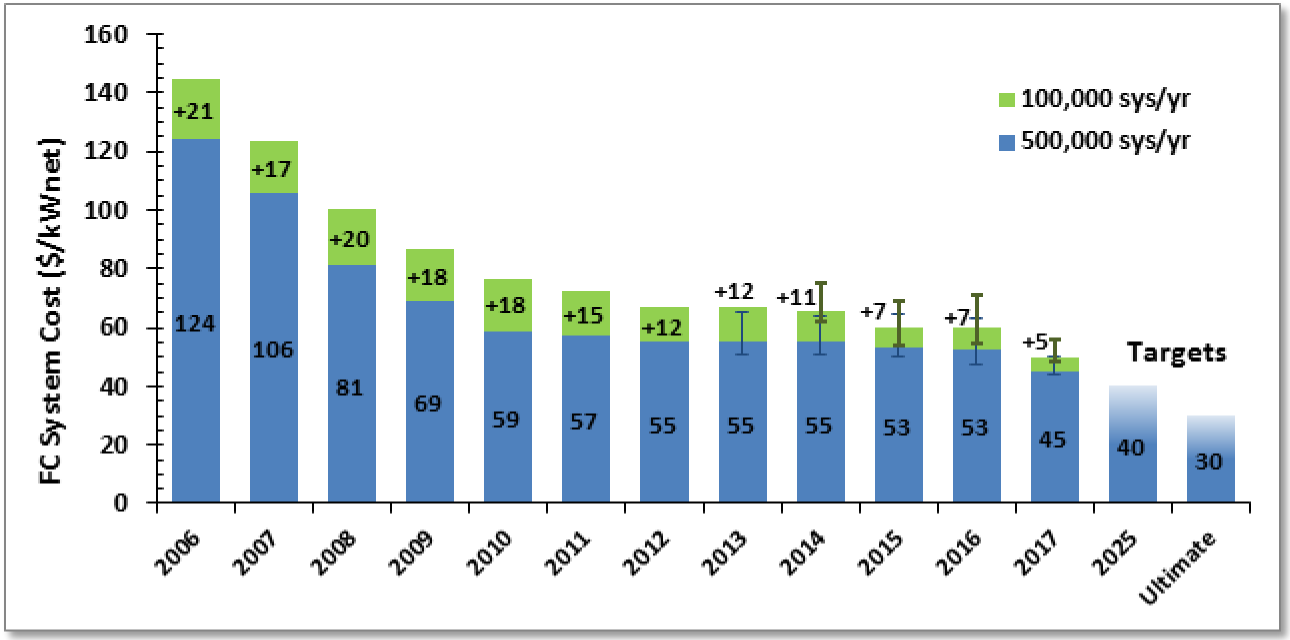
- ***Reduce or eliminate PGM levels in catalysts ****
- ***Improve MEA performance***

** PGM elimination mitigates US dependence on precious metal imports*

Fuel Cell Cost Improvements

Fuel Cell Cost Status

- **$50/kW*** for 100,000 units/year
- **$45/kW*** for 500,000 units/year
- **$180/kW*** for 1,000 units/year
- **$230/kW†** for currently commercialized on-road technology at 1,000 units/year



60% cost reduction in the last 10 years

** SA Inc., bottom-up analysis of model system manufacturing cost, high volume manufacturing with next-gen lab technology*

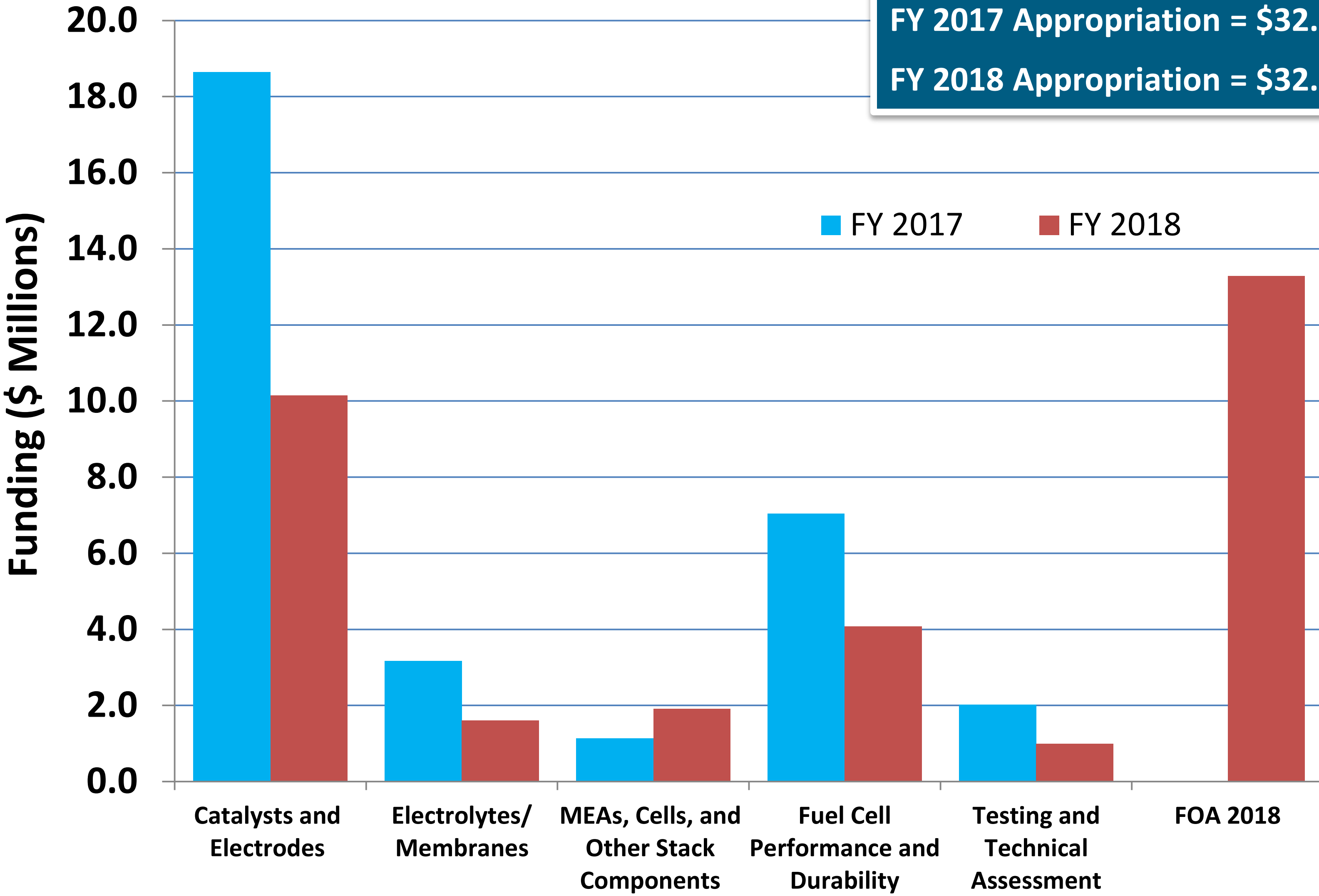
† SA Inc., bottom-up analysis of model system based on commercially available FCEVs

https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf

Fuel Cell R&D Funding

FY 2017 Appropriation = $32.0 M

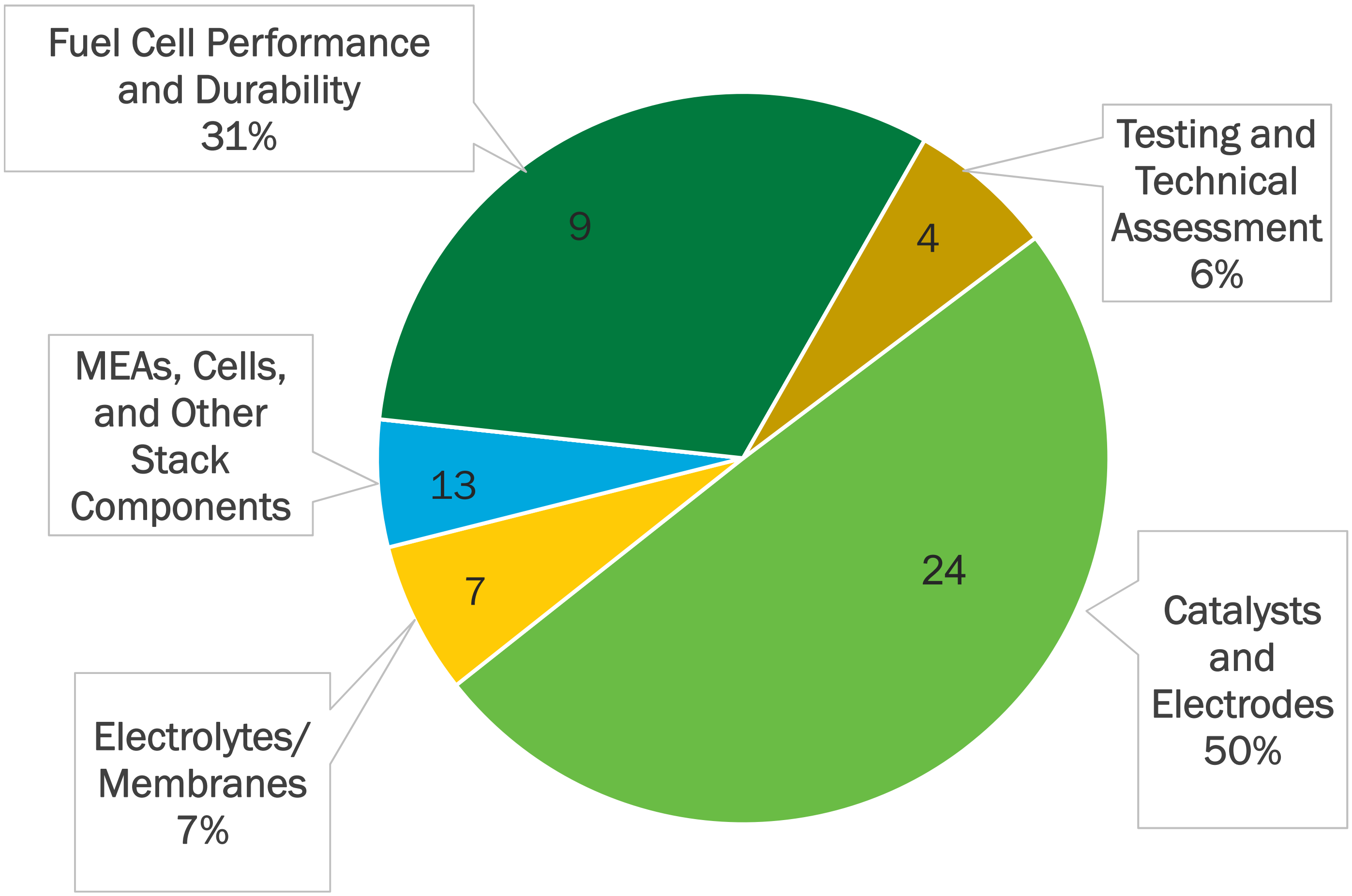
FY 2018 Appropriation = $32.0 M



Fuel Cell R&D Portfolio

Funding distribution of all FOA, LAB, SBIR/STTR projects

including number of current projects and % of portfolio funding



Current emphasis is on early stage applied R&D in the key areas of fuel cell components and materials, including catalysts and membranes, as well as fuel cell performance and durability

ElectroCat (Electrocatalysis Consortium)

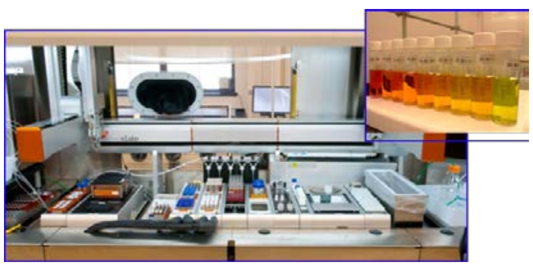
Goal

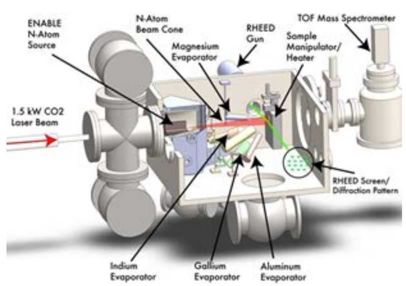
Accelerate the deployment of fuel cell systems by replacing platinum-based catalysts with **platinum group metal-free (PGM-free) catalysts**

Objectives

- Streamline access to unique PGM-free catalyst synthesis and characterization tools across national labs
- Develop missing strategic capabilities
- Curate a public database of information

Core Lab Team





High-throughput materials discovery, characterization, and testing

Design and synthesis of PGM-free catalysts and electrodes, modeling

www.electrocat.org

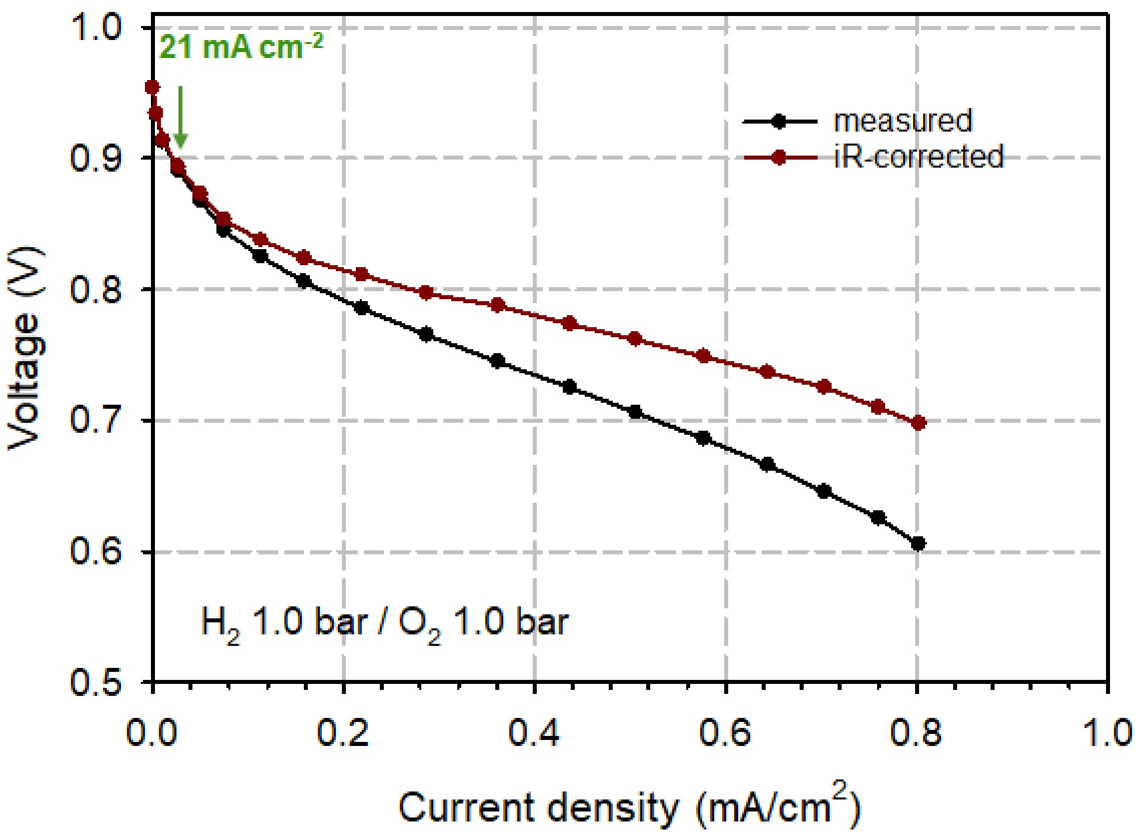
Accomplishments and Next Steps

- Updated capability set
- Demonstrated significant progress in **(a)** catalyst development, **(b)** active-site characterization, and **(c)** high-throughput PGM-free catalyst modeling and synthesis
- Partnered with 4 newly awarded FOA projects
- Add partners through FY18 FOA

Accomplishment: PGM-Free Mass Activity

ElectroCat
Electrocatalysis Consortium

Demonstrated MEA performance of 21 mA/cm^2 at 0.9 $V_{IR\text{-}free}$ with H_2/O_2, a 30% improvement over 2016 baseline



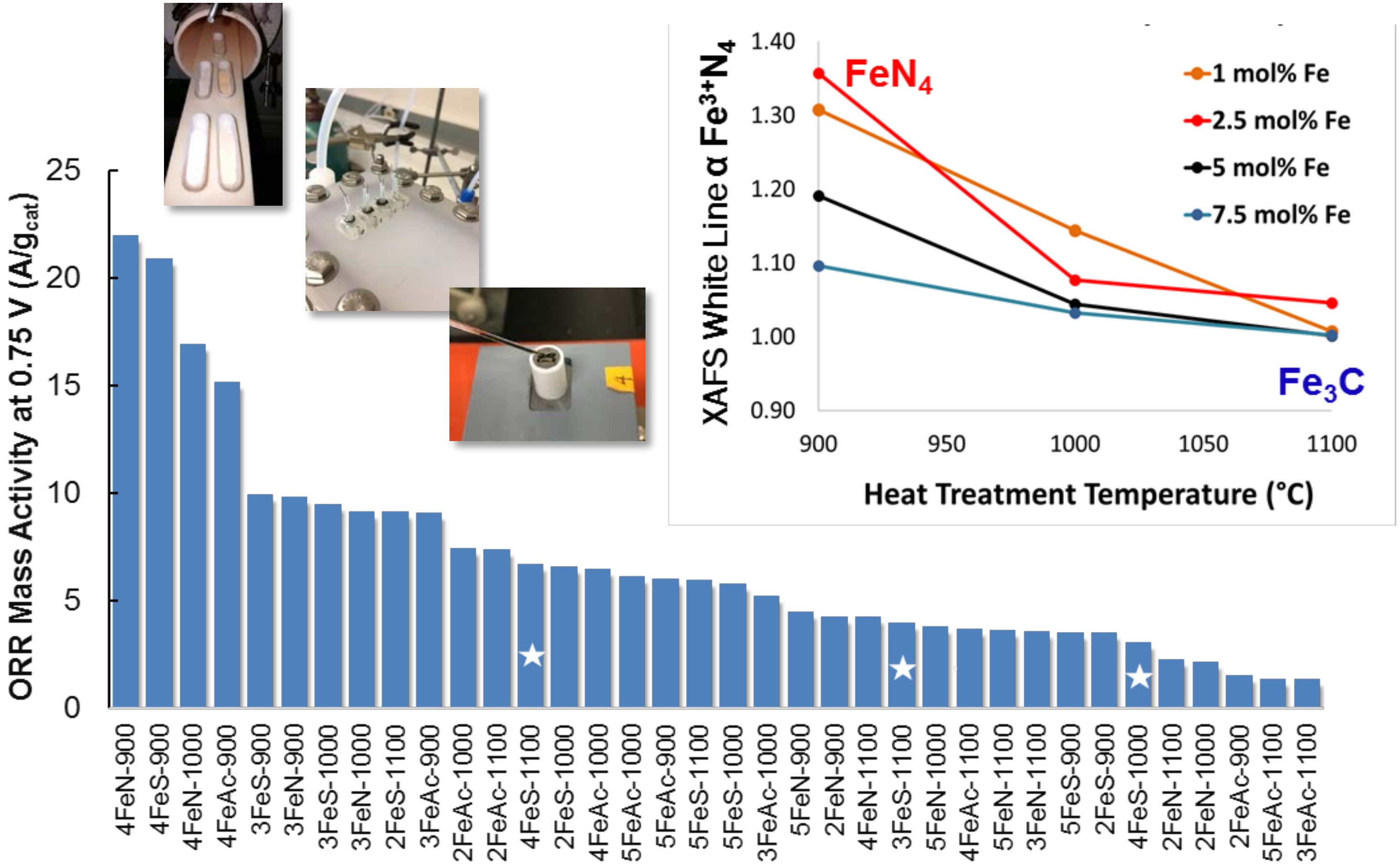
Cyanamide (CM)-polyaniline (PANI) precursors for Fe-N-C catalyst; Zn removed during pyrolysis as pore-forming agent

Anode: 0.3 mg_{Pt} cm^{-2} Pt/C H_2, 200 sccm, 1.0 bar H_2 partial pressure; **Cathode**: ca. 4.8 mg cm^{-2} O_2, 200 sccm, 1.0 bar air partial pressure; **Membrane**: Nafion®,211; **Cell**: 5 cm^2; 80°C

Accomplishment: High-Throughput (HT) Synthesis & Characterization

ElectroCat
Electrocatalysis Consortium

HT materials with potentially > 5× ORR activity of baseline compositions identified in HT hydrodynamic screening



2:1 at% Fe, 3:2.5 at% Fe, 4:5 at% Fe, 5:7.5 at% Fe, FeN: Fe Nitrate, FeS: Fe Sulfate, FeAc: Fe Acetate

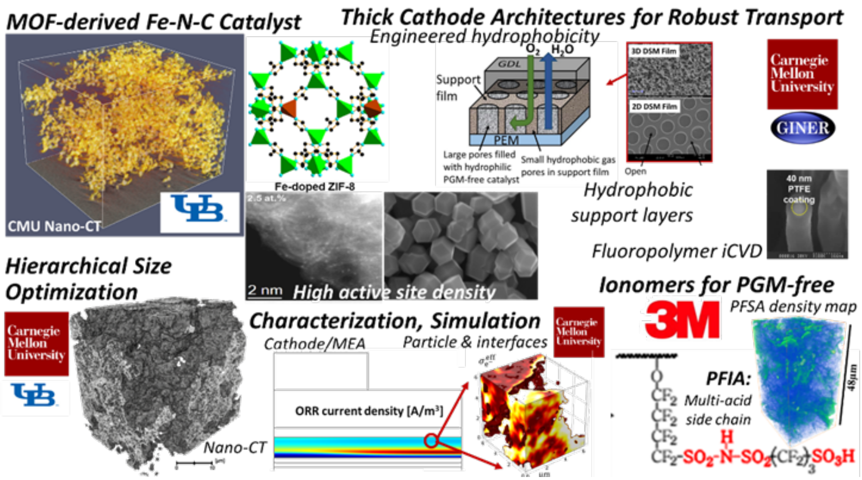
★ *Baseline materials explored by batch synthesis prior to initiation of combinatorial synthesis task*

ElectroCat FOA Projects Added in 2017

ElectroCat
Electrocatalysis Consortium

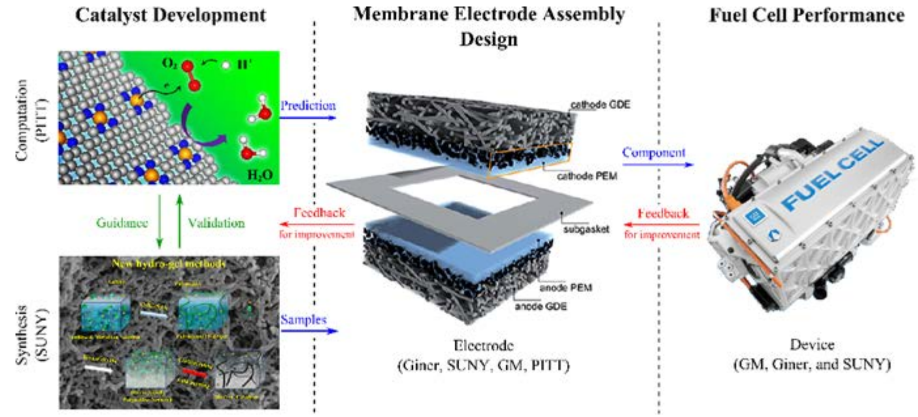
Carnegie Mellon University

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



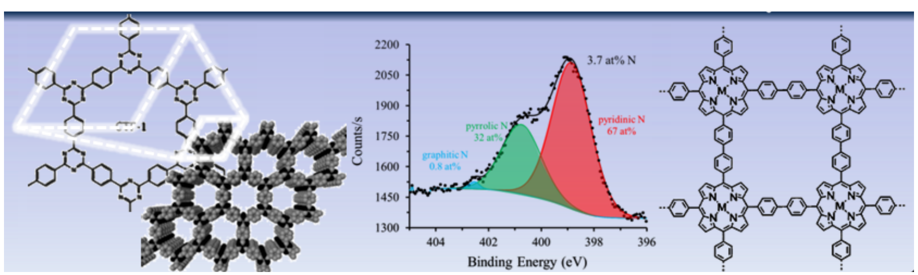
Giner Inc

Durable Mn-based PGM-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells



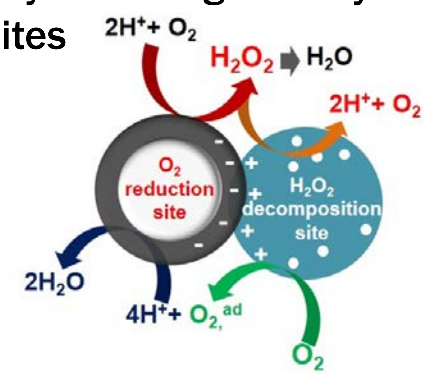
Greenway, LLC

PGM-free Engineered Framework Nano-Structure Catalysts



Pacific Northwest National Lab

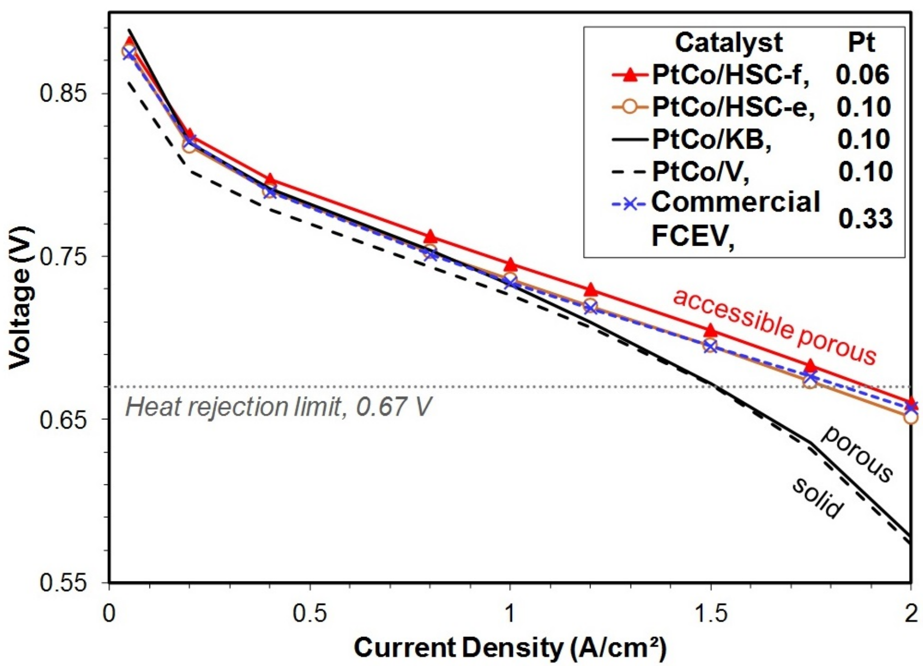
Highly Active and Durable PGM-free ORR Electrocatalysts through the Synergy of Active Sites

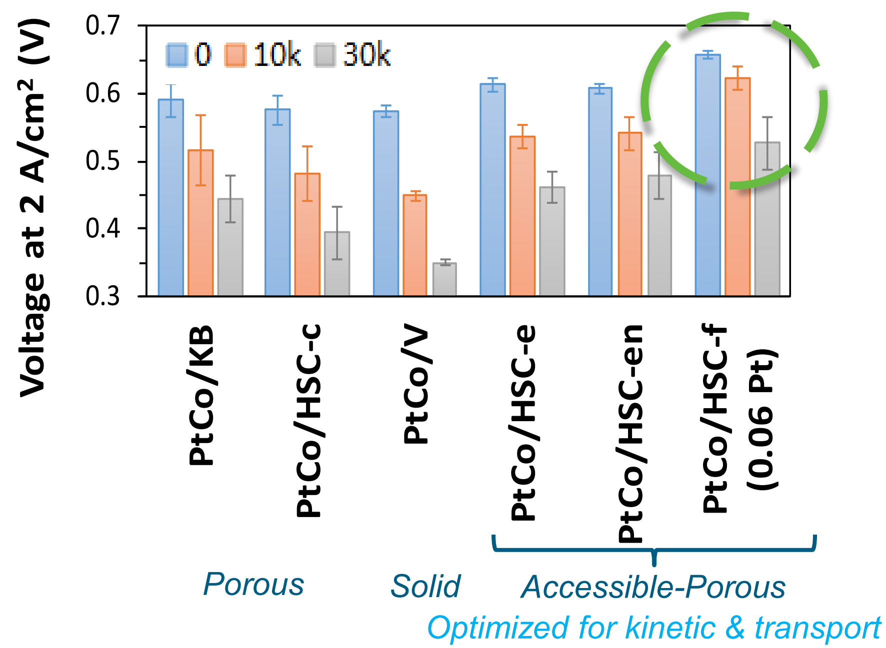


Accomplishment: Low Pt-loading alloy catalysts

PtCo/HSC-f: exceeds 8 kW/g_{PGM} target while demonstrating durable performance at high current density

Equivalent performance to current on-road technology with 5x less Pt





Have yet to meet performance and durability targets concurrently

ACS Energy Lett. (2018) 3, 618

A. Kongkanand et al., GM

FC-PAD: Fuel Cell Performance and Durability

Approach

Couple national lab capabilities with funding opportunity announcements (FOAs) for an influx of innovative ideas and research

Objectives

- Improve component stability and durability
- Improve cell performance with optimized transport
- Develop new diagnostics, characterization tools, and models

Consortium fosters sustained capabilities and collaborations

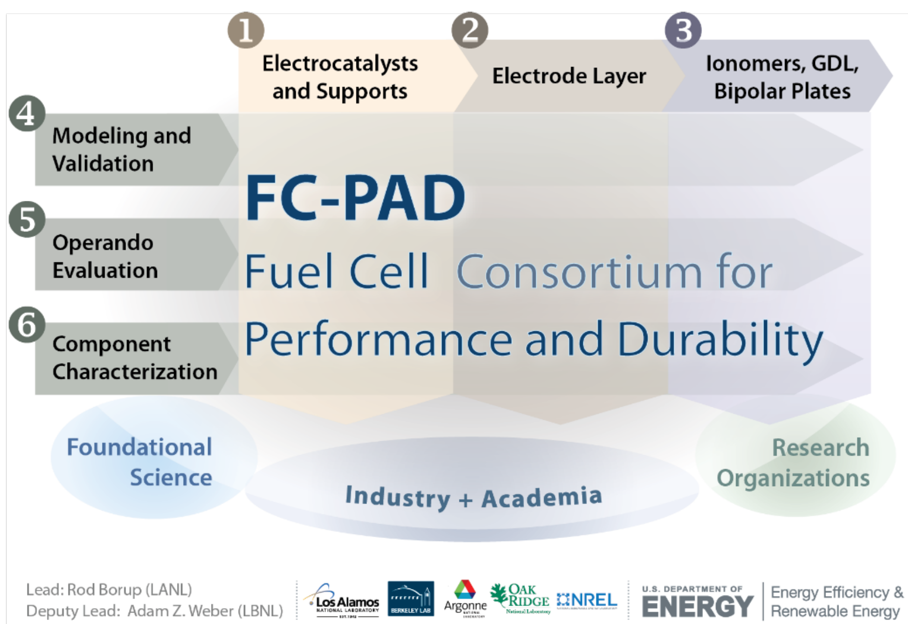
Core Consortium Team

Argonne National Laboratory, Los Alamos National Laboratory, Berkeley Lab, NREL National Renewable Energy Laboratory, Oak Ridge National Laboratory

Prime Partners

3M, GM, United Technologies Research Center, Vanderbilt

Structured across six component and cross-cutting thrusts



Expands the body of knowledge

Example: JES Focus Issue on PEMFC Durability

www.fcpad.org

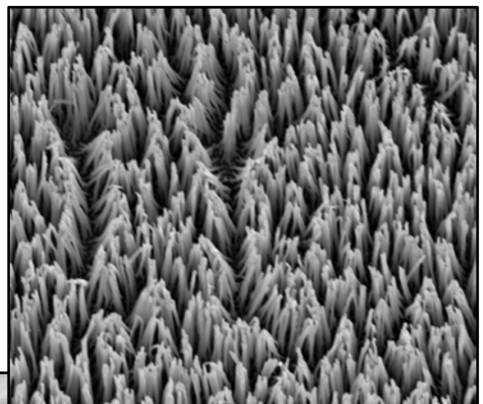
Accomplishments: FC-PAD

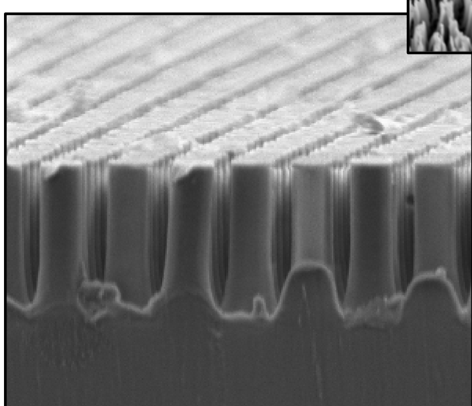
FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Novel catalyst layer architectures

Mesostructured electrodes with vertically aligned ionomer channels allow use of 50% less ionomer for H^+ transport

Nanowire

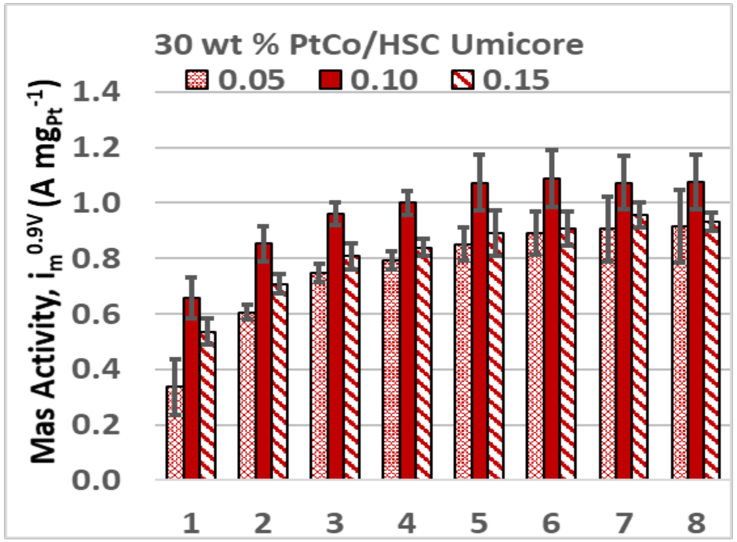




Array

Improved catalyst conditioning

Conditioning protocol developed demonstrating up to 2-3x difference in mass activity between initial and peak i_m for several commercial Pt and PtCo catalysts

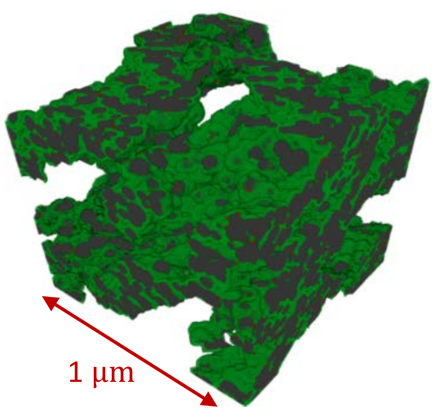


Accomplishments: FC-PAD

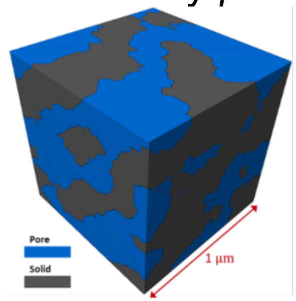
Characterization tools used to build catalyst layer microstructural model

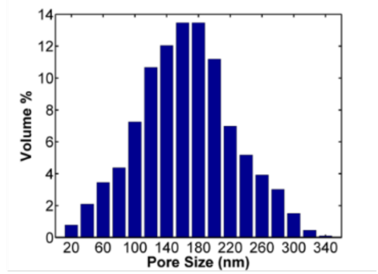
Allows for unprecedented, comprehensive view of catalyst layer micro- and nanostructure including heterogeneities across scales

Resulting microstructure

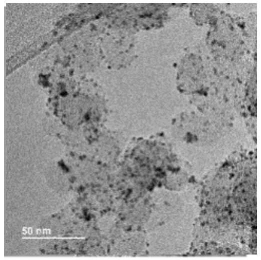


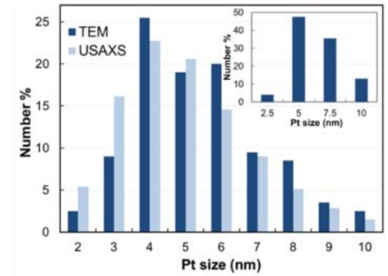
Secondary pore structure: nano-CT



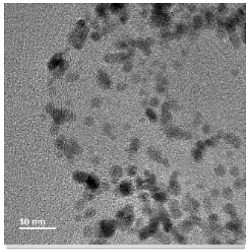


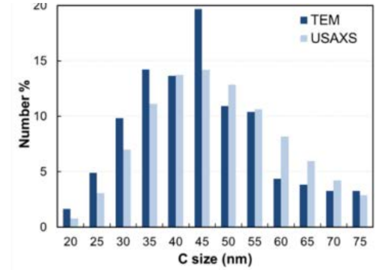
C particle size: TEM and USAXS





Pt particle size: TEM and USAXS

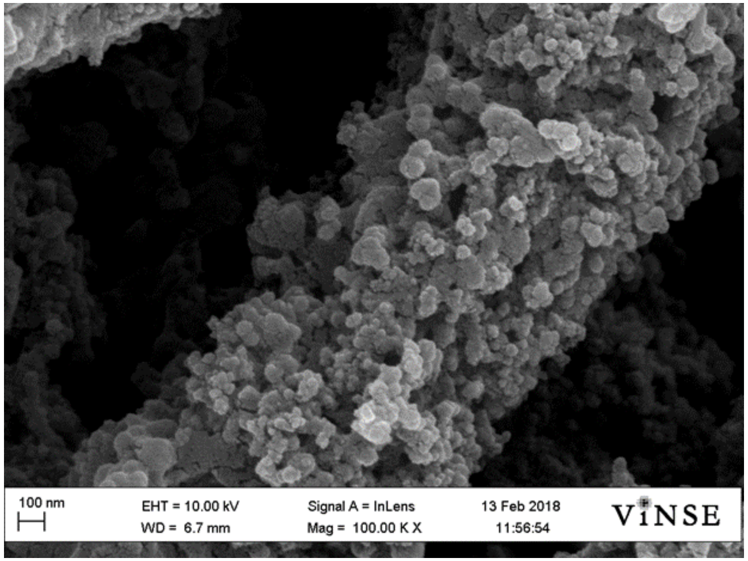




Accomplishment: Low-PGM Electrospun Catalyst Layers

Electrospun catalyst layers using PtCo catalyst with carrier ionomer improve low humidity performance

- **>3x** compared to project spray coating baseline at 40% RH
- Max power exceeds **1100 mW/cm²** at 0.1 mg_{Pt}/cm^2 cathode loading



MEA details: 80°C, 200 kPa (abs.)
Cathode: 0.1 mg_{Pt}/cm^2
Anode: 0.1 mg_{Pt}/cm^2 (Espun), J-M 0.4 mg_{Pt}/cm^2 (Spray)
Membrane: NR 211, **GDL**: SGL 29 BC

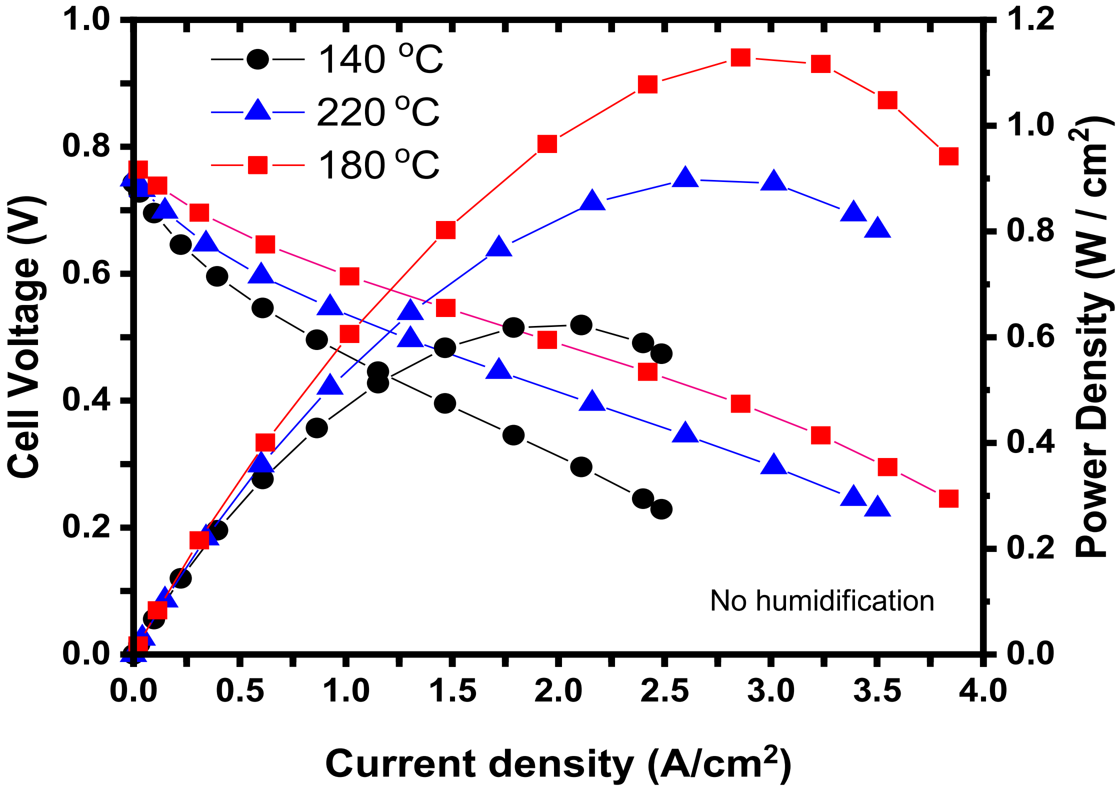
	100% RH			40% RH		
Sample	**Max Power (mW/cm²)**	**Power at 0.65 V (mW/cm²)**	**HFR (mΩ-cm²)**	**Max Power (mW/cm²)**	**Power at 0.65 V (mW/cm²)**	**HFR (mΩ-cm²)**
PtCo Spray	652	544	70	315	85	208
Gen-1 PtCo Espun	759	661	76	590	250	219
Gen-2 PtCo Espun	1132	998	56	967	488	120

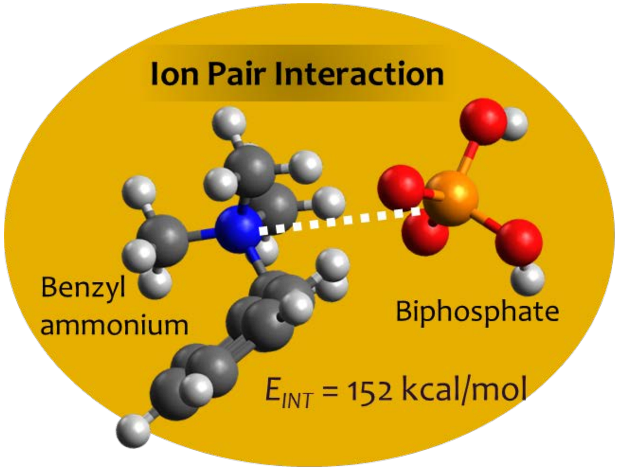
P. Pintauro, et al., Vanderbilt

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Accomplishment: Intermediate Temperature Fuel Cell Membranes

- **Peak power density exceeds 1100 mW/cm^2 at 180°C (H_2/O_2)**
- **> 20 × better water tolerance than established PBI system* to allow low-T operation**





MEA details: H_2/O_2, 285 kPa abs; **membrane**: PA-XL-BPN; **ionomer**: PA-QAPS; **Pt loading** 0.6 mg/cm^2 for both electrodes

*measured at P_{H2O} = 19.9 kPa, 80°C

Y. S. Kim, et al., LANL

Accomplishment: Direct Dimethyl Ether Fuel Cell

- **Close to 2x increase in anode specific activity compared to methanol**
- **Ten-fold decrease in crossover as compared to methanol**

Key Performance Indicator this period	Current DMFC	Status DDMEFC	Target DDMEFC
Total precious metal loading	5 mg_{PGM}/cm^2	4.5 mg_{PGM}/cm^2	3 mg_{PGM}/cm^2
Anode mass-specific activity	50 A/g measured at 0.5 V(*)	93.8 A/g measured at 0.5 V (PtRu)	75 A/g measured at 0.5 V
Maximum Power	160 mW/cm^2	135 mW/cm^2 (***)	270 mW/cm^2
Crossover	60-120 mA/cm^2 (**)	6 mA/cm^2	< DMFC

(*) By comparison, LT direct DME FC obtained 25 A/g measured at 0.5 V with PtRu.
(**) 60 mA/cm^2 with 0.5 M MeOH, 80 ^oC, Nafion® 117; 120 mA/cm^2 with 1.0M MeOH.
(***) 2.23mg/cm^2 PtRu anode, 2.3mg/cm^2 Pt-alloy cathode

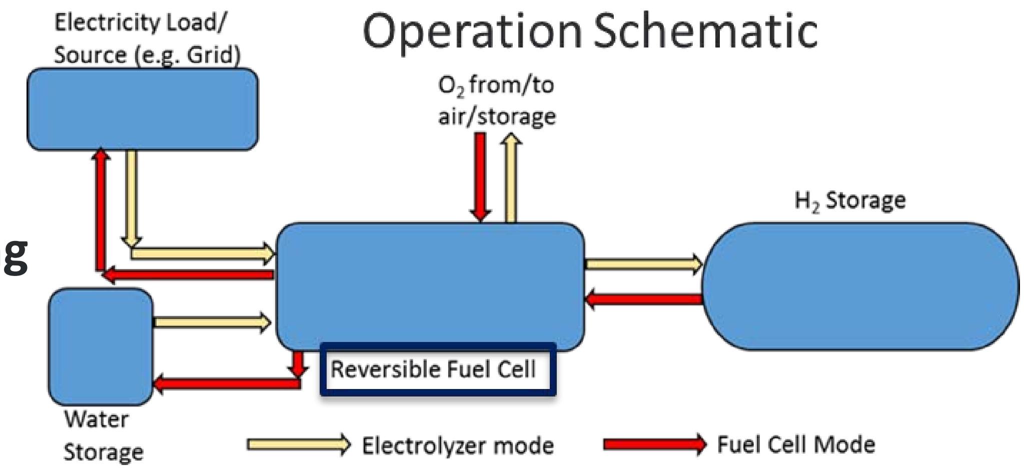
E. De Castro, et al., Advent

Reversible Fuel Cells (RFCs)

Research Priorities Include:

- **Bifunctional catalysts**
- **Advanced membranes**
- **Electrode optimization including effective water management**
- **Corrosion protection schemes**

Reversible Fuel Cell Operation Schematic



Viability and cost-competitiveness of RFCs require foundational R&D to improve roundtrip efficiency and meet long-term targets less than $1250/kW capital cost and cycle life of 5,000 cycles

https://www.energy.gov/sites/prod/files/2017/03/f34/quadrennial-technology-review-2015_1.pdf. (Chapter 3, Table 3.C.2)

R&D to focus on innovative concepts for reversible fuel cells to provide easily dispatchable power and flexibility to address resiliency and grid/microgrid needs

Summary of Current Activities

- **Applied Early-Stage R&D** addresses cost reduction, performance and durability enhancement of materials and stack components, including catalysts and membranes

- **ElectroCat** coordinates with newly awarded FOA projects to expedite the development of PGM-free catalysts and electrodes

- **FC-PAD**, including industry/university partners, continues to expand the knowledge base to advance fuel cell performance and durability

Summary of Upcoming Activities & Milestones

- **Fuel cells** to enable **energy storage** and **resiliency***
- **Innovative R&D projects** through FY18 FOA and FY19 Lab Call
- **Lab-led membrane R&D project working group** to coordinate efforts and leverage activities with other agencies
- **Technical milestones:**
  - Demonstrate **25 mA cm^{-2}** at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (**4Q 2018**)
  - Demonstrate **29 mA cm^{-2}** at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (**4Q 2019**)

**Under 'Beyond Batteries' crosscut effort (FY 2019 Budget Request)*

Collaborations

Vehicle Technologies Office (VTO) Small Business Innovation Research (SBIR)

Energy Materials Network
U.S. Department of Energy

Energy Materials Network

DOE-EERE Fuel Cells Program

INDUSTRY

U.S. DRIVE Partnership: Fuel Cell Tech Team

Technology Validation

National Collaborations (inter- and intra-agency efforts)

DOE - FE	DOE - BES	DOE – ARPA-E	NSF	DOT/FTA	DOD	DOC/NIST	DOT/FRA
SOFC Program	Catalysts and Membranes	IONICS& INTEGRATE	ElectroCat	Fuel Cell Buses	DOD/DOE MOU	Neutron Imaging	H_2/FC-Rail

Applied R&D is coordinated among a range of organizations

Fuel Cell Program Contacts

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Questions?

Back Up Slides

R&D Benefits Various Fuel Cell Market Sectors

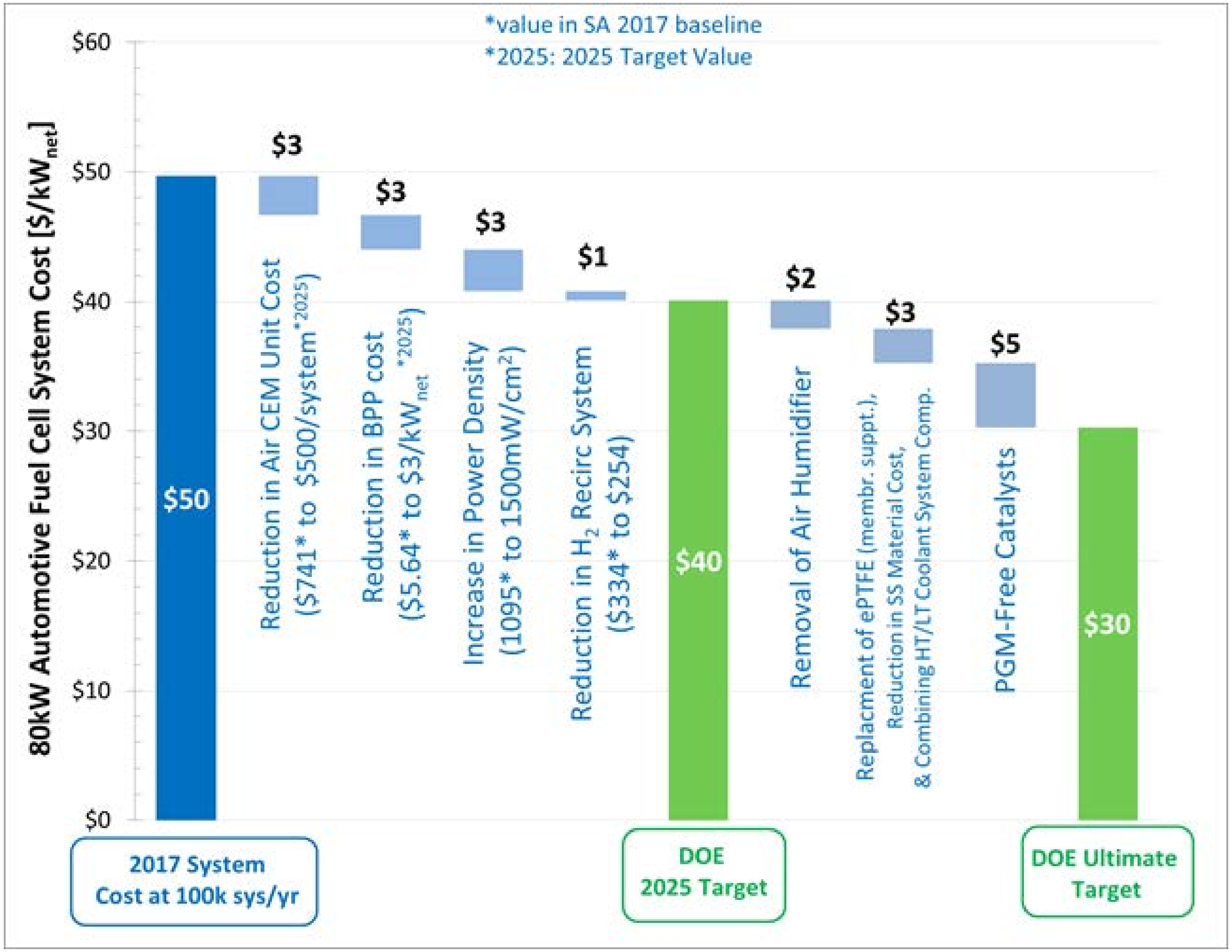
■ Federal RD&D
■ Commercialization and Ongoing Industry Improvements

Sector	Market	Fuel Cell Application	Cost & Durability Status[1]	Cost & Durability Targets (2025)
Stationary Power	Backup Power Systems	Backup power (direct hydrogen)	$6,000/kW 8,000 h	$1,000/kW 10,000 h
Stationary Power	Primary Power Systems (Including combined-heat-and-power)	Medium scale CHP (natural gas)	$1,200-4,500/kW 40,000-80,000 h	$1,000/kW 80,000 h
Transportation	Auxiliary Power Units for Transportation	APUs (diesel, 1-10 kW system)	$2,100/kW 3,000 h	$1,000/kW 20,000 h
Transportation	Transit Buses	Buses	$893,000[2] 25,000 h[3]	$600,000 25,000 h
Transportation	Fuel Cell Vehicles – Government & Fleets Fuel Cell Vehicles – Widespread Commercialization	Automotive	$50/kW[4] $45/kW[5] 4,100 h (on-road)[6]	$40/kW ($30/kW ultimate) 5,000 h (8,000 h ultimate)
Portable Power	Portable Power	Portable power (100-250 W)	$15/W 2,000 h	$5/W 5,000 h

[1] Unless otherwise stated , from Fuel Cells MYRD&D Plan, *http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22*
[2] Projected to a production volume 400 units/year. *https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_sa_2016_pemfc_transportation_cost_analysis.pdf*
[3] https://www.nrel.gov/docs/fy18osti/70075.pdf
[4] Projected to a production volume of 100,000 units/year. https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf
[5] Projected to a production volume of 500,000 units/year. https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf
[6] https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf

Near Term → Mid Term → Long Term

Potential Cost Reduction Strategy

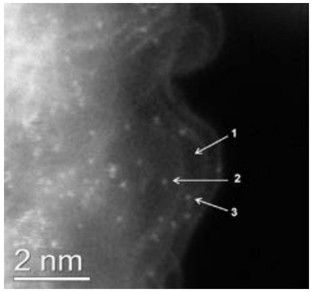


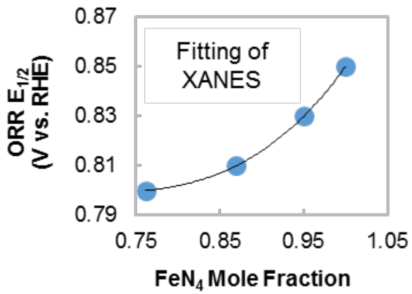
PGM-free catalysts and advancements in key components are key research goals for meeting DOE's ultimate $30/kW target

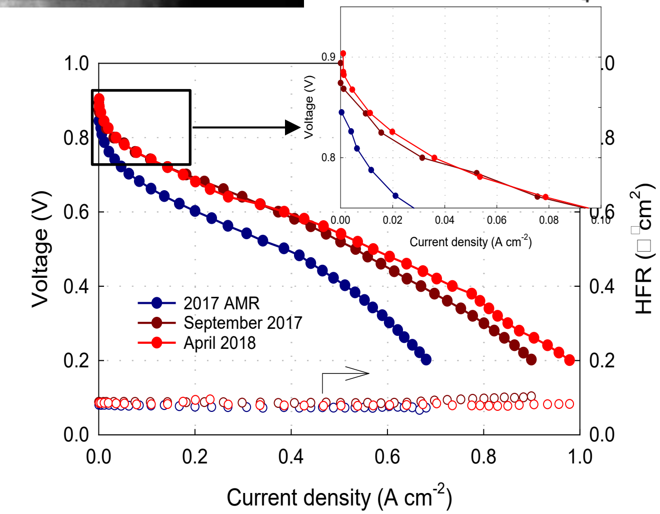
Accomplishments: ElectroCat

Four-fold H_2-air performance increase for ZIF-derived catalyst

- ZIF-based Fe-N-C catalyst with no Fe-rich nanoparticles detected
- Fe present in N-coordinated FeN_x sites
- H_2-air fuel cell performance at 0.80 V, from **9 mA cm^{-2}** to **36 mA cm^{-2}** since 2017 AMR

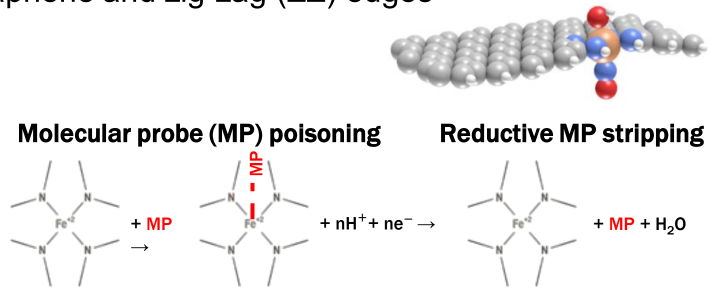






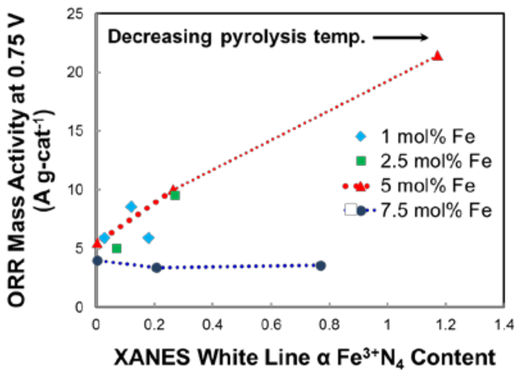
Molecular probe for quantifying active sites

- NO adsorbs on surface Fe sites from a nitrite solution
- Count surface Fe sites by reductive stripping scan
- Developed library of adsorption energy of probes/poisons to Fe-N_x site structures hosted in graphene and zig-zag (ZZ) edges



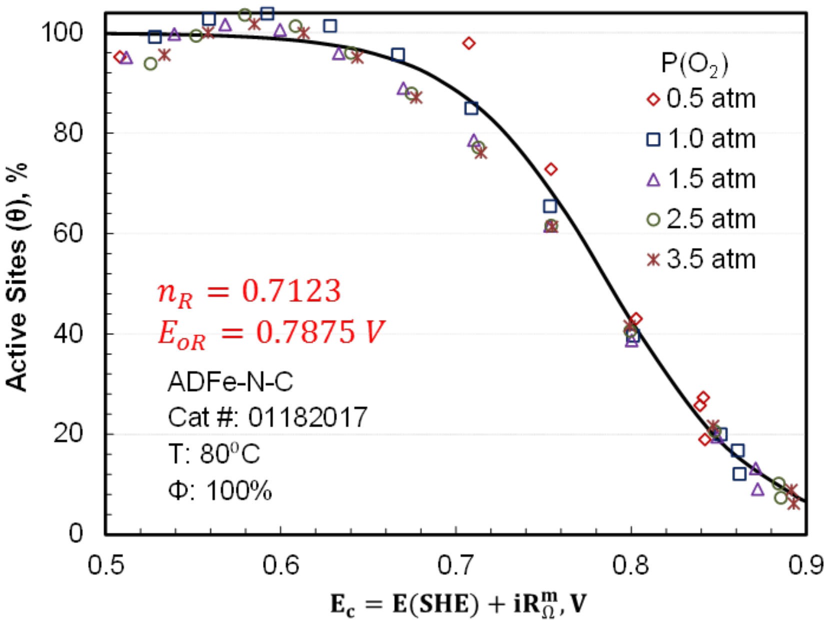
Active site identification and high-throughput catalyst discovery

- ORR activity of intermediate Fe-content catalyst correlates with FeN_4 content
- Catalyst identified with **5X ORR activity** versus baseline composition



Accomplishments: HT Synthesis & Characterization

Potential dependence of ORR kinetics



ORR kinetics in MEA correlated with potential dependence of active site availability

ElectroCat
Electrocatalysis Consortium

Molecular probe for quantifying active sites

- Fe sites counted by reductive stripping scan to remove NO_{ads}

  3x10¹² sites/cm² (0.5 site per surface Fe atom)
- Developed library of probes adsorption energy on Fe-N_x sites in bulk graphene and at edges