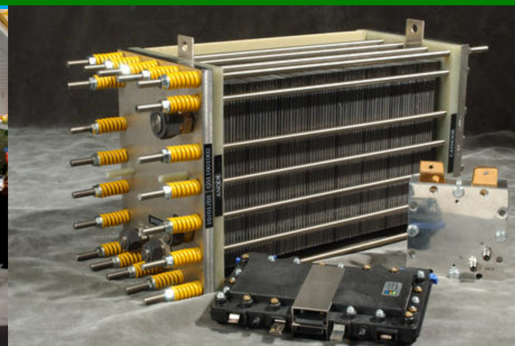
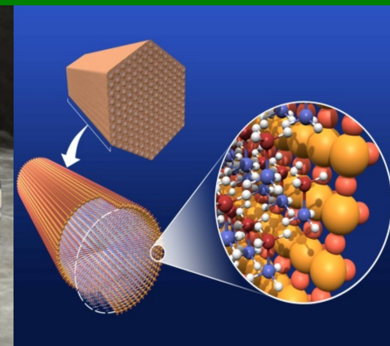






# Fuel Cells Program

# - Plenary Presentation-

*Dimitrios Papageorgopoulos*

***2015 Annual Merit Review and Peer Evaluation Meeting***

***June 8 - 12, 2015***

# Goals and Objectives



## Objectives

- By 2020, a 65% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation that can be mass produced at a cost of $40/kW
- By 2020, distributed generation and micro-CHP fuel cell systems (5 kW) operating on natural gas or LPG that achieve 45% electrical efficiency and 60,000 hours durability at an equipment cost of $1500/kW
- By 2020, medium-scale CHP fuel cell systems (100 kW–3 MW) with 50% electrical efficiency, 90% CHP efficiency, and 80,000 hours durability at an installed cost of $1,500/kW for operation on natural gas, and $2,100/kW when configured for operation on biogas
- Other specific objectives are in the Fuel Cell MYRD&D Plan


***Advance fuel cell technologies with a focus on transportation, as well as enabling stationary and early market applications***

# Challenges & Strategy

***Fuel Cells MYRD&D Plan under revision in 2015***

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

**BARRIERS**

Cost
Durability
Performance

→

**STRATEGY**

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

→

**Fuel Cell R&D**

↕

**Testing and Cost/Technical Assessments**

→

**FOCUS AREAS**

**Stack Components**
Catalysts
Electrodes
Electrolytes
MEAs and Cells
Gas diffusion media
Seals
Bipolar plates

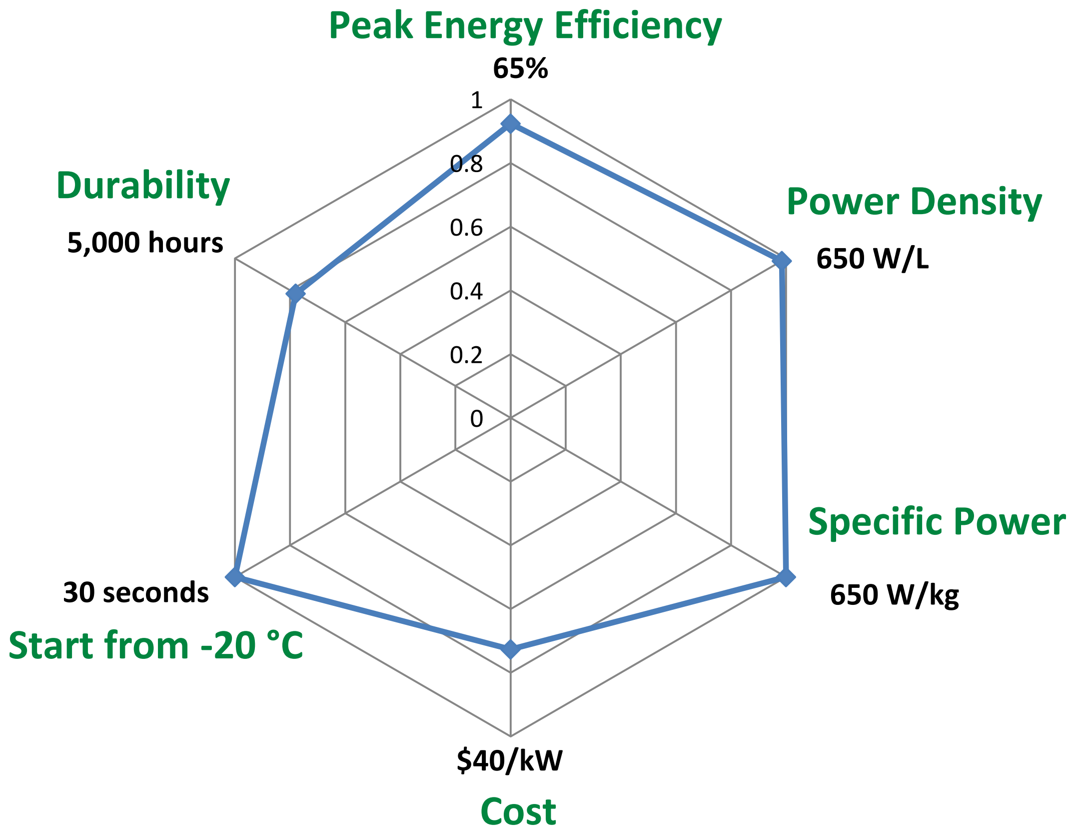
**Performance and Durability**
Mass transport
Durability
Impurities

**Systems and Balance of Plant (BOP)**
BOP components
Fuel processors
Stationary power
APUs
Early markets

***The Fuel Cells program supports R&D of fuel cells and fuel cell systems with goals of reducing cost and improving durability***

# Market-Driven Targets Ensure Competitive Strategy

*FC system cost targets allow competition with incumbent technology on a lifecycle cost basis*




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

*Automotive fuel cell cost targets: $40 / kW by 2020 and $ 30 / kW ultimate*

# Market-Driven Targets Ensure Competitive Strategy



**Technical Targets for Automotive Applications*:**
**80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen**

| Characteristic | Units | 2015 Status | 2020 Targets | Ultimate Targets |
|---|---|---|---|---|
| Peak energy efficiency | % | 60 | 65 | 70 |
| Power density | W / L | 640 | 650 | 850 |
| Specific power | W / kg | 659 | 650 | 650 |
| Cost | $ / kW$_{net}$ | 55 | 40 | 30 |
| Cold start-up time to 50% of rated power<br>@–20°C ambient temp<br>@+20°C ambient temp | <br>seconds<br>seconds | <br>20<br><10 | <br>30<br>5 | <br>30<br>5 |
| Start up and shut down energy<br>from -20°C ambient temp<br>from +20°C ambient temp | <br>MJ<br>MJ | <br>7.5<br>– | <br>5<br>1 | <br>5<br>1 |
| Durability in automotive drive cycle | hours | 3,900† | 5,000 | 5,000 |
| Startup/shutdown durability | cycles | – | 5,000 | 5,000 |
| Assisted start from low temperatures | °C | – | -40 | -40 |
| Unassisted start from low temperatures | °C | -30 | -30 | -30 |

†http://www.nrel.gov/hydrogen/images/cdp_fcev_21.jpg

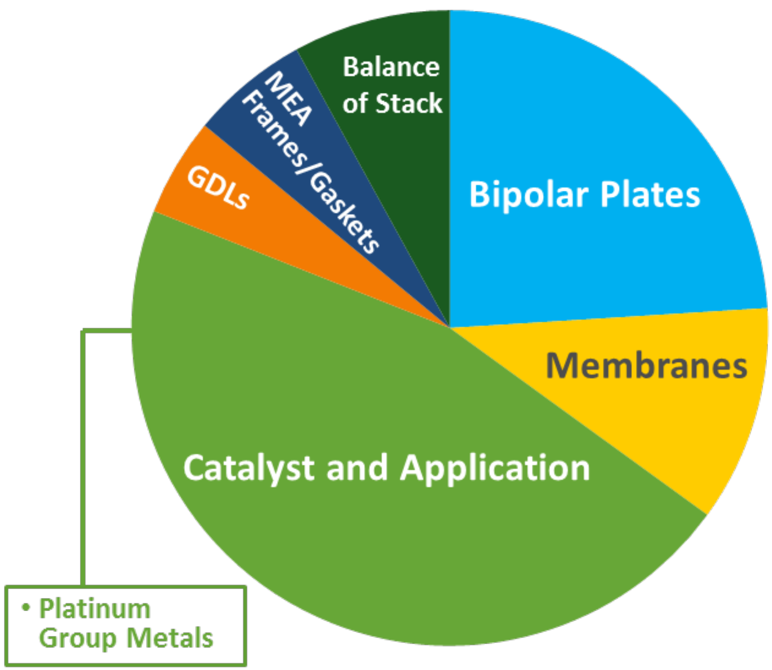
*** Preliminary***

***Updated technical targets to be released in 2015***

# Strategic Technical Analysis Guides Focus Areas for R&D and Priorities

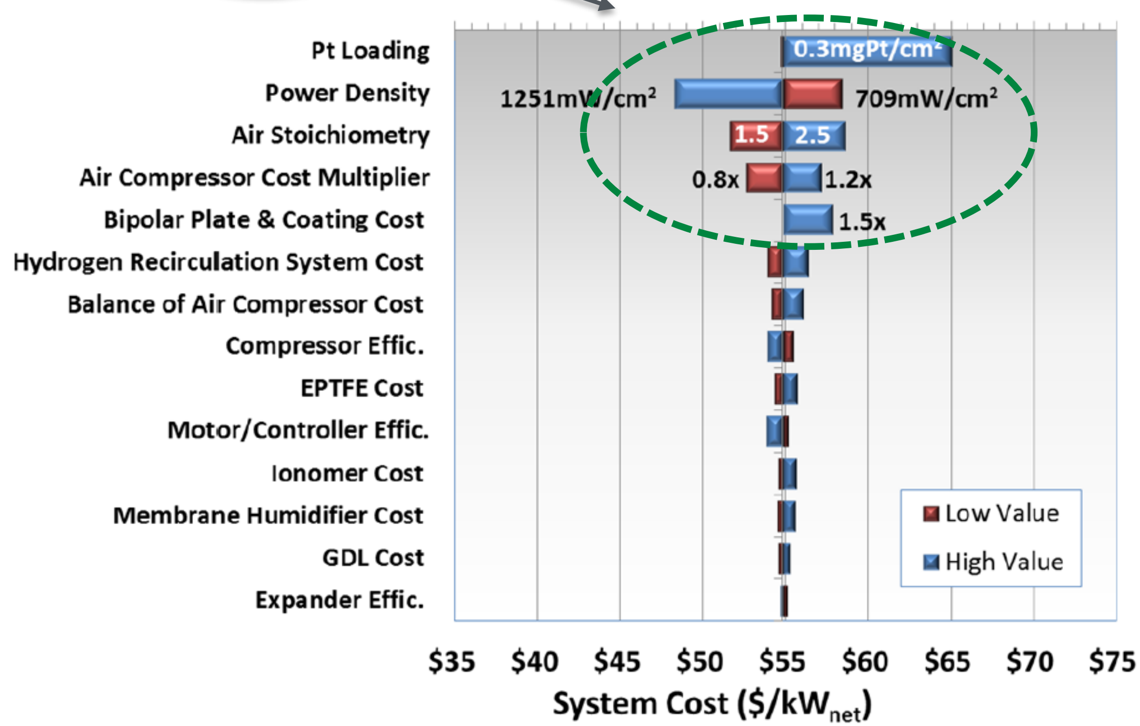
## PEMFC Stack Cost Breakdown

500,000 systems/year




Key Focus Areas for R&D

Sensitivity Analysis helps guide R&D



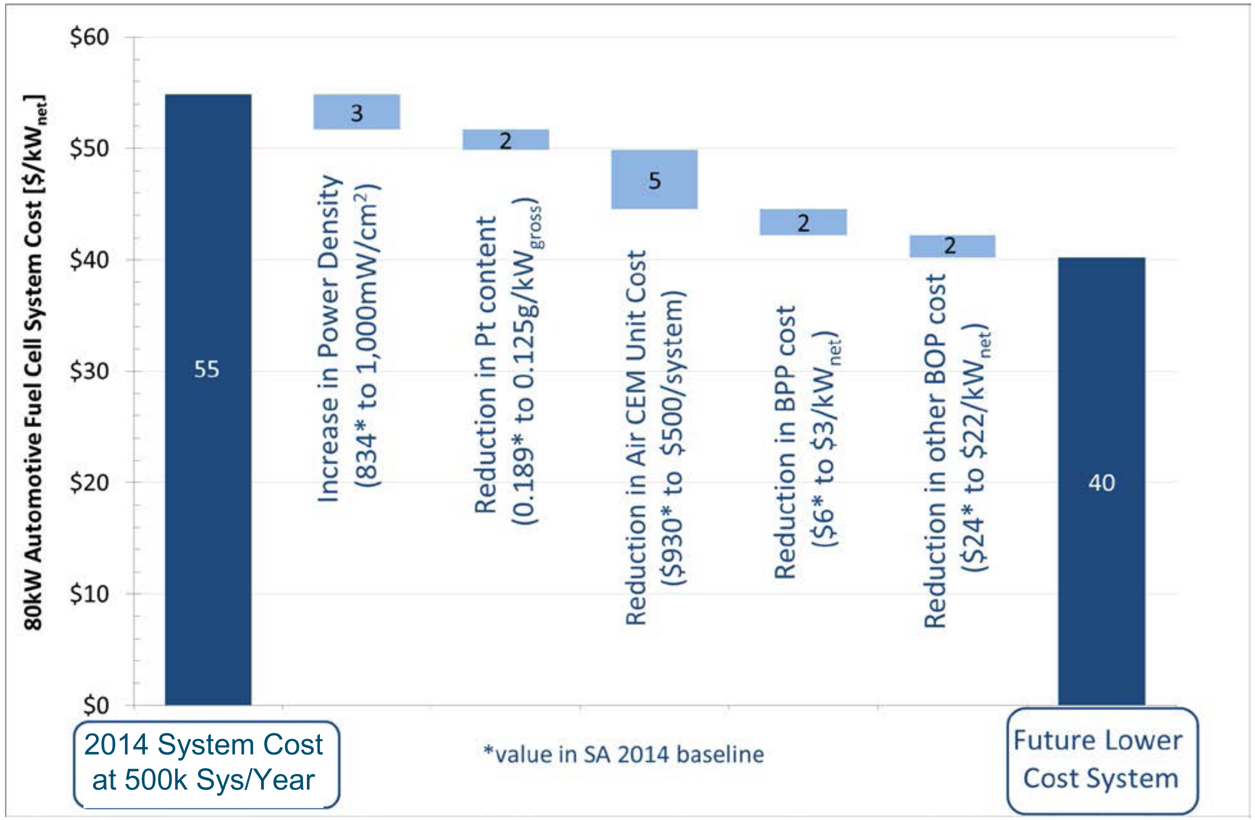

***Lowering PGM content and improving activity key to lowering cost***

# Strategic Technical Analysis Guides Focus Areas for R&D and Priorities



- *Improvements in multiple components are required to meet the 2020 cost target*
- *Advances in PEMFC materials and components could benefit a range of applications*

***Potential cost reduction based on DOE targets***



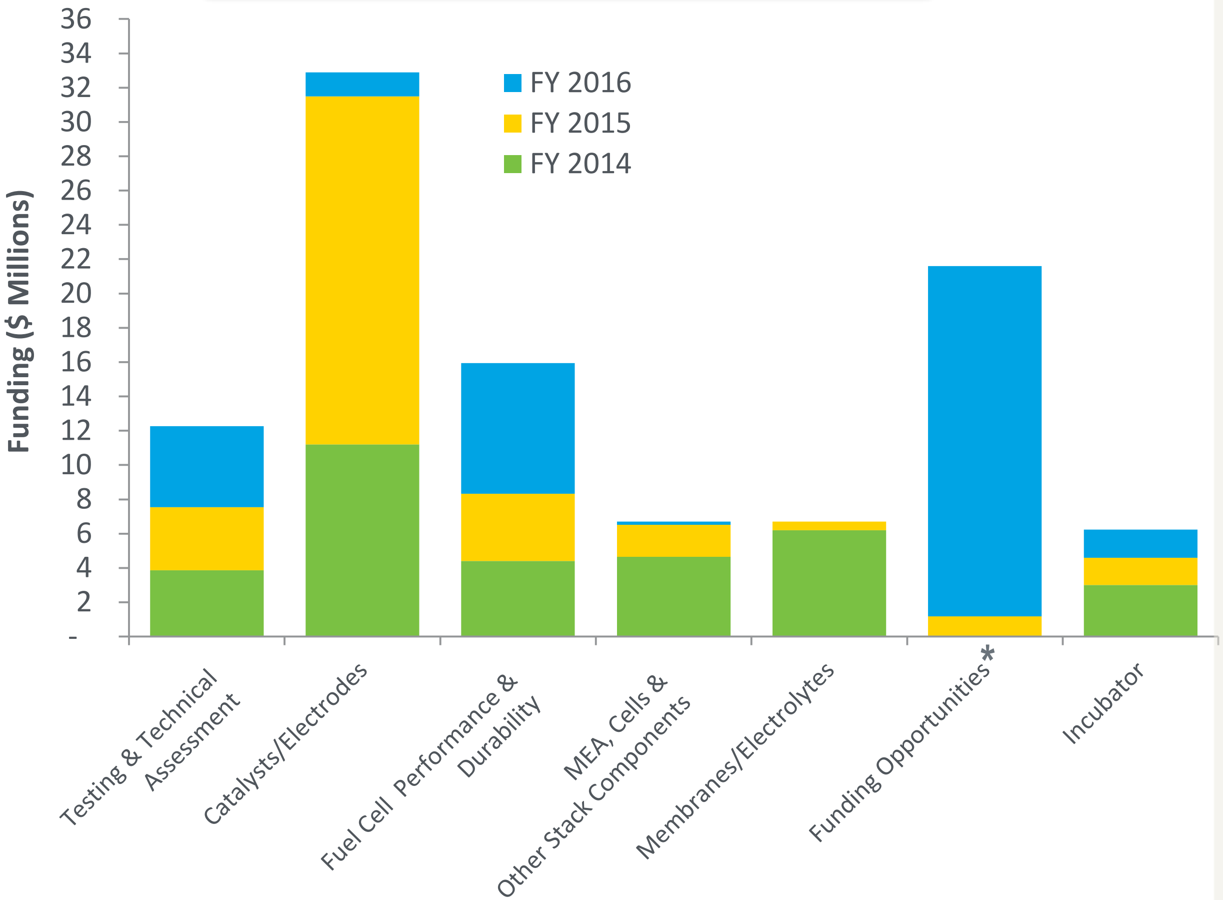

***Meeting guideline component level targets could pave path to $40 /kW***

# Fuel Cells Program Budget

**FY 2016 Request = $36.0M**

**FY 2015 Appropriation = $33.0M**

**FY 2014 Appropriation = $33.4M**




* Subject to appropriations
Full-upfront funding for non-lab financial assistance projects selected from FOAs

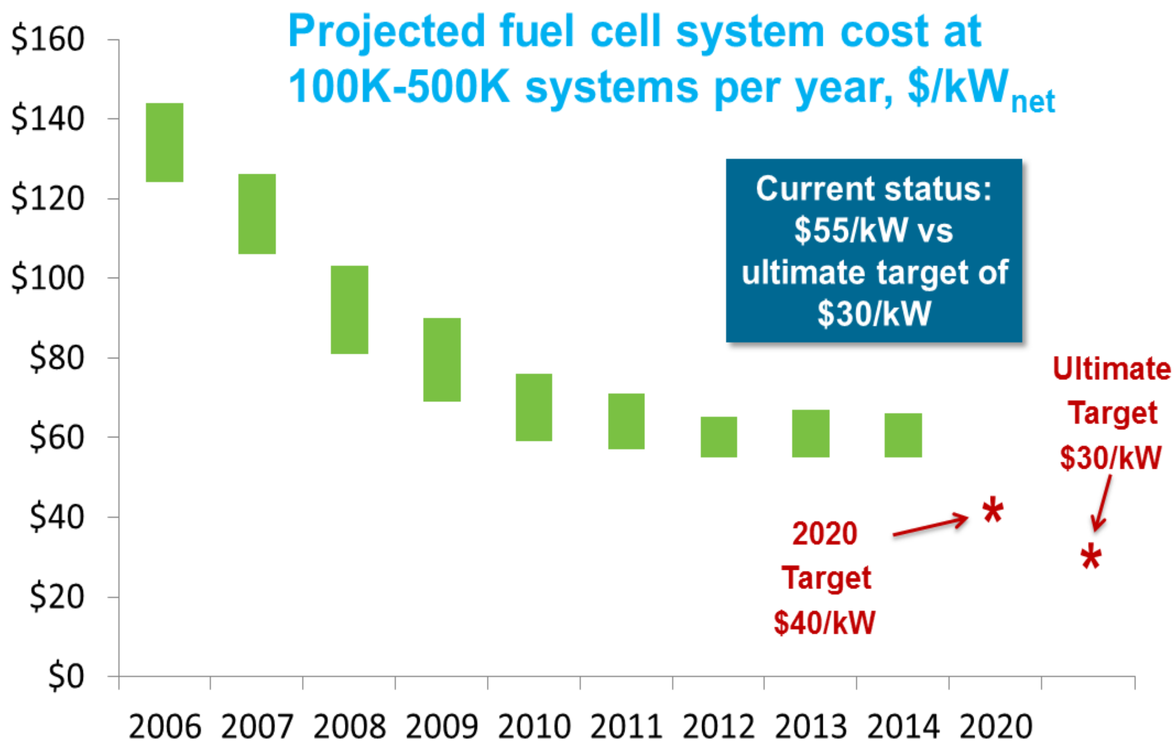
## EMPHASIS

- Increase activity and utilization of low-PGM catalysts and develop non-PGM catalysts for long-term applications
- Develop membranes with enhanced performance and stability at reduced cost
- Improve PEM MEAs through integration of state-of-the-art MEA components
- Address transport and degradation issues
- Maintain core activities for stationary applications

# Fuel Cell Cost

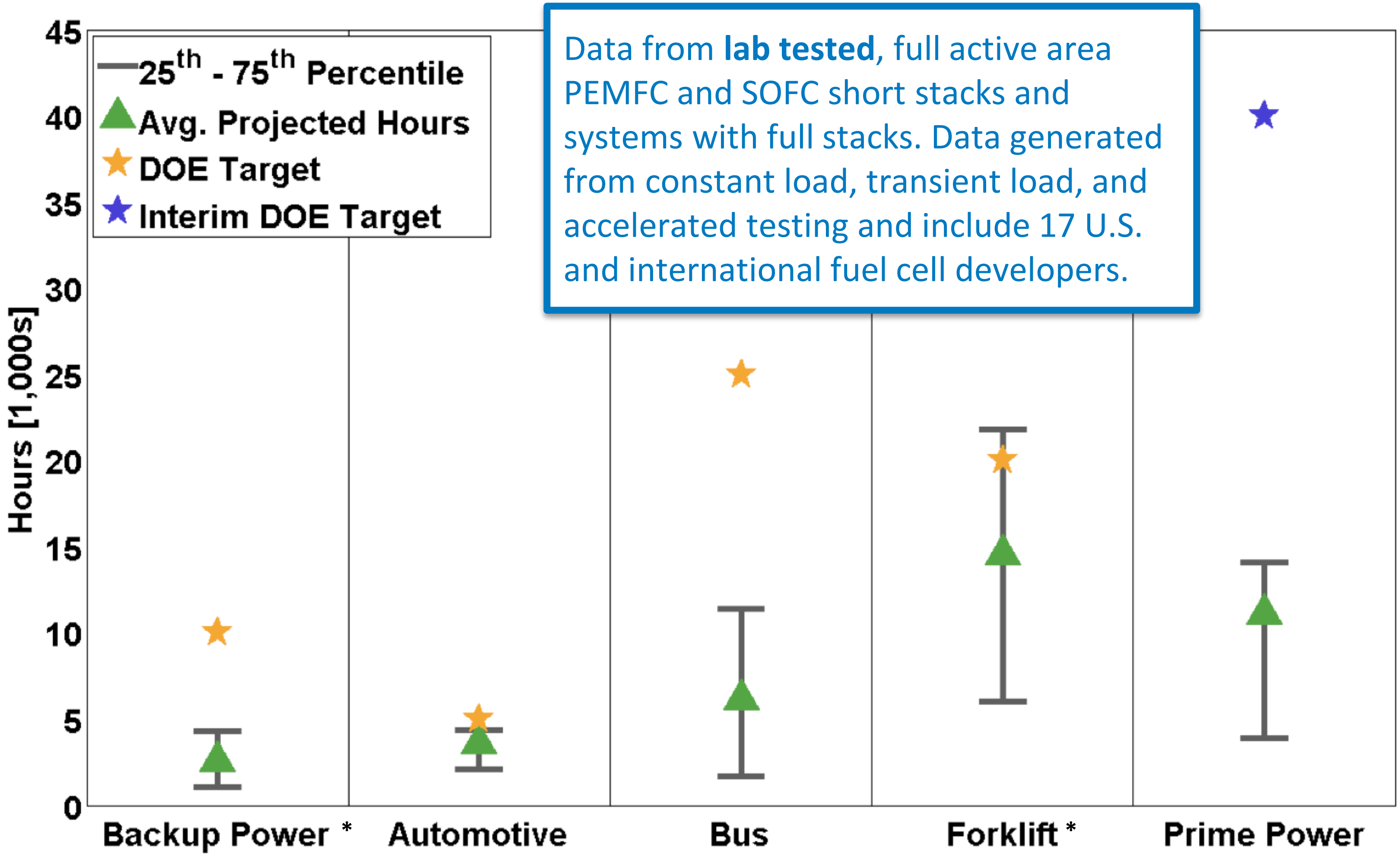
## Cost Estimates:

- **$55/kW*** (next-gen lab technology scaled up to 500,000 sys/year)
  - ✓ More than *30% reduction since 2008*
  - ✓ *More than 50% reduction since 2006*
- **$280/kW†** (current technology at 20,000 sys/year)
  - ✓ *Expected cost for initial FCEV commercialization*




* SA, bottom-up analysis of model system manufacturing cost
† ORNL, top-down analysis based on OEM input

# Fuel Cell Durability Assessment: Voltage Degradation Results by Application




Data from **lab tested**, full active area PEMFC and SOFC short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing and include 17 U.S. and international fuel cell developers.

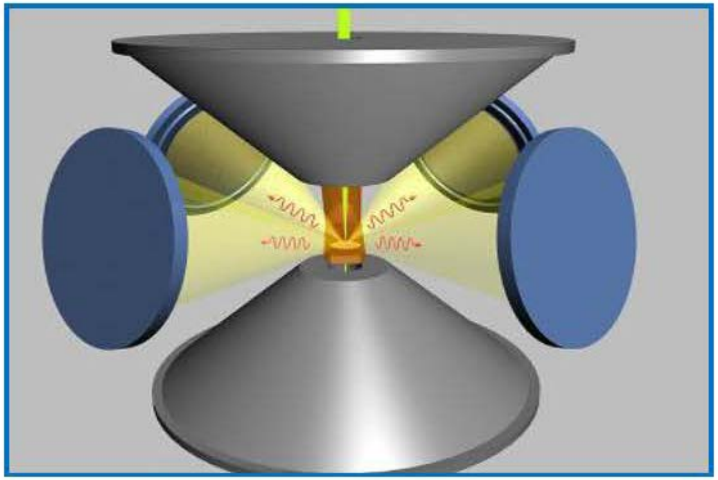
*10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes.*

** Preliminary DOE Targets*

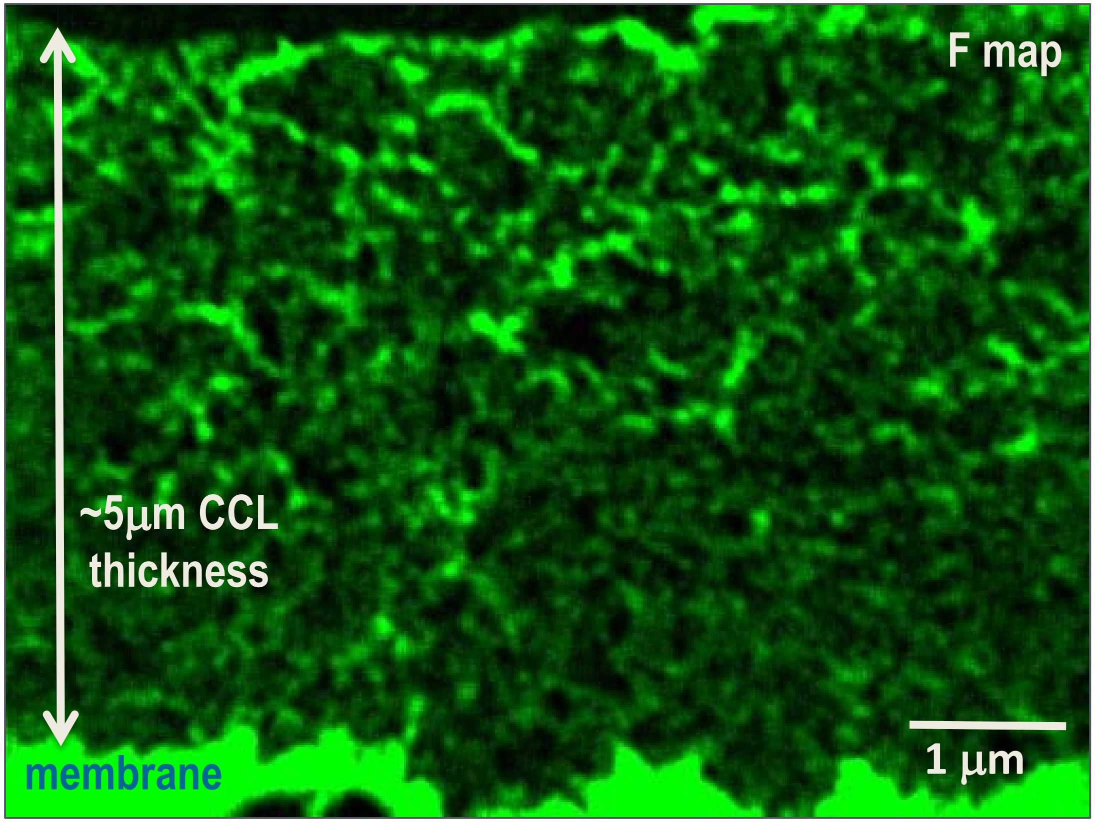
***J. Kurtz et al., NREL***

# Enabling Capability: Visualizing Ionomer Distributions

Large solid angle detector systems enable high X-ray collection efficiencies with a 10-fold decrease in collection times



Four individual 30 $mm^2$ detectors arranged symmetrically within the pole gap close to sample – 120 $mm^2$ total active area




Ionomer distribution (Fluorine X-ray map) across full thickness of 5mm cathode catalyst layer (CCL) can be imaged

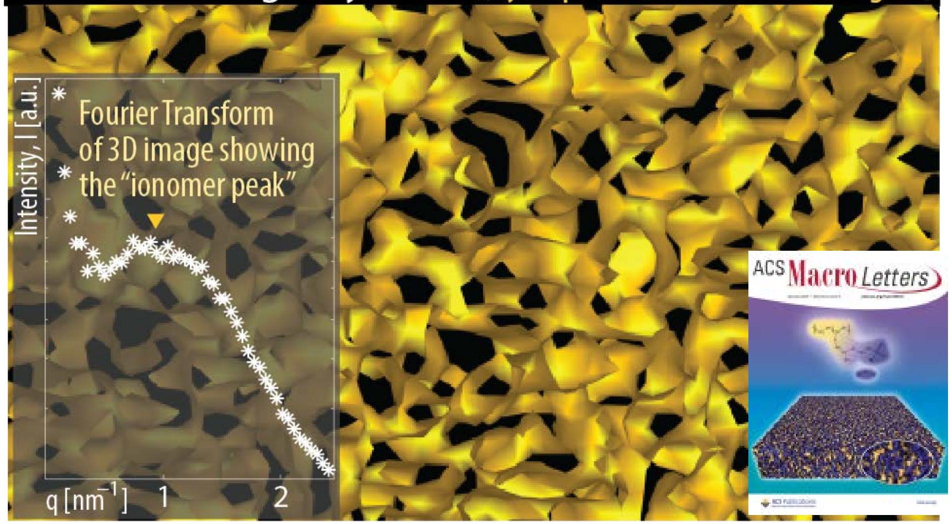
***K. More et al., ORNL***

***Ionomer distributions as a function of solvent, carbon support, Pt-loading, etc. are being quantified via high spatial-resolution EDS mapping***

# Enabling Capability: Direct Imaging of 3D Morphology of Nafion®

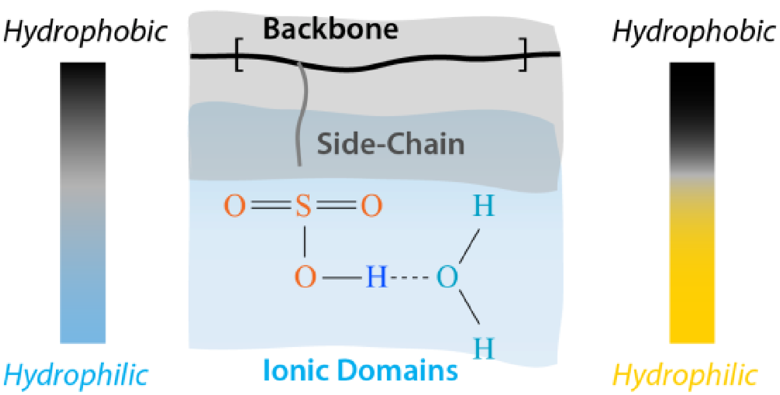
- Complex, dynamic ionomer morphology controls transport properties
- 3D images enable advanced computation of transport in the membrane, including:
  - Transport at interfaces and thin films
  - Multi-ion and contaminant response
  - Effect of environmental conditions

**3D nanoscale morphology of as-cast hydrated Nafion obtained through cryo-TEM (hydrophilic domains shown in gold)**




F.I. Allen, L.R. Comolli, A. Kusoglu, M.A. Modestino, A.M. Minor, A.Z. Weber, *ACS Macro Letters*, 4 (2015) 1-5 | DOI: 10.1021/mz500606

***Phase-Separation with Hydration***

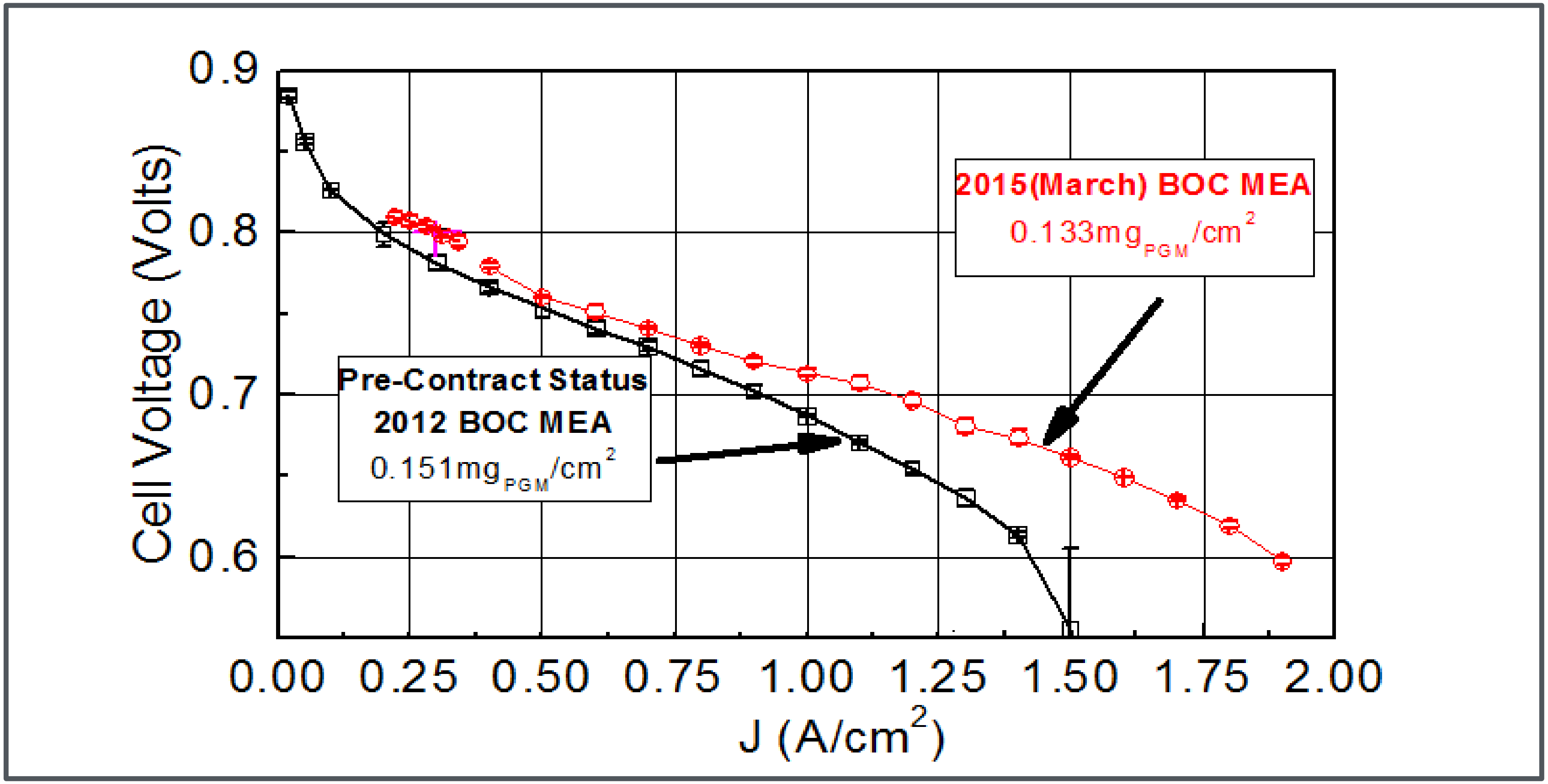



- Cryo TEM tomography of hydrated Nafion reveals a connected locally-flat network

***A. Weber et al., LBNL***

***3D images enable advanced computation of transport properties***

# Accomplishments: MEA Integration



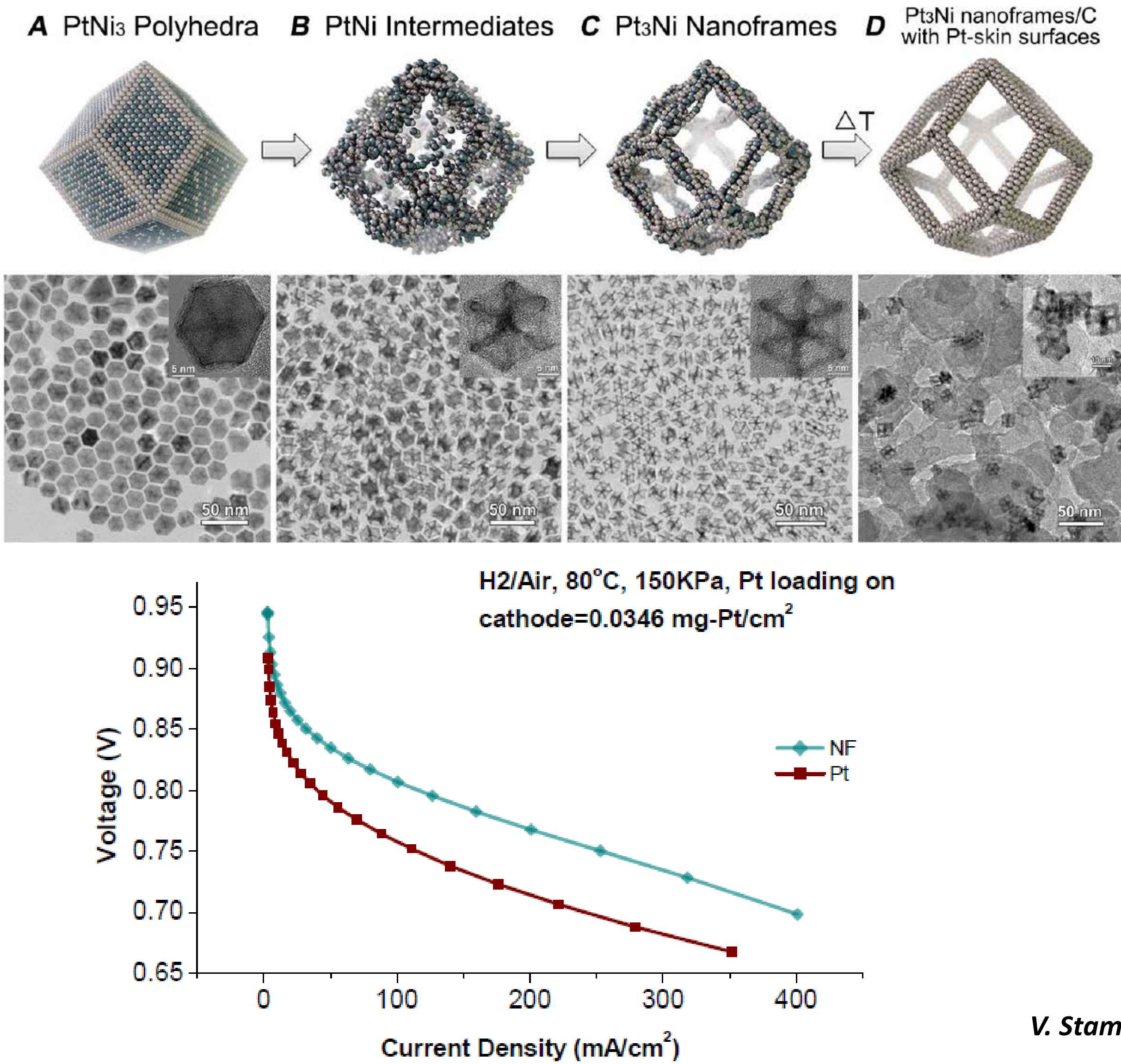

Improved MEAs produce **6.5 kW/g$_{PGM}$** under conditions that satisfy Q/ΔT target (2008 baseline 2.8 kW/g$_{PGM}$; 2014 status 6.2 kW/g$_{PGM}$)

- Further work required to meet performance, durability, and robustness targets simultaneously

***A. Steinbach et al., 3M***

***MEA integration R&D leads to improved performance and decreased PGM content***

# Accomplishments: Nanosegregated Catalysts




- PtNi nanoframe catalysts synthesized through a novel spontaneous corrosion and annealing procedure
- Low-loaded MEA testing shows 3X mass activity enhancement relative to Pt/C, but further work needed to increase loading and optimize MEA integration

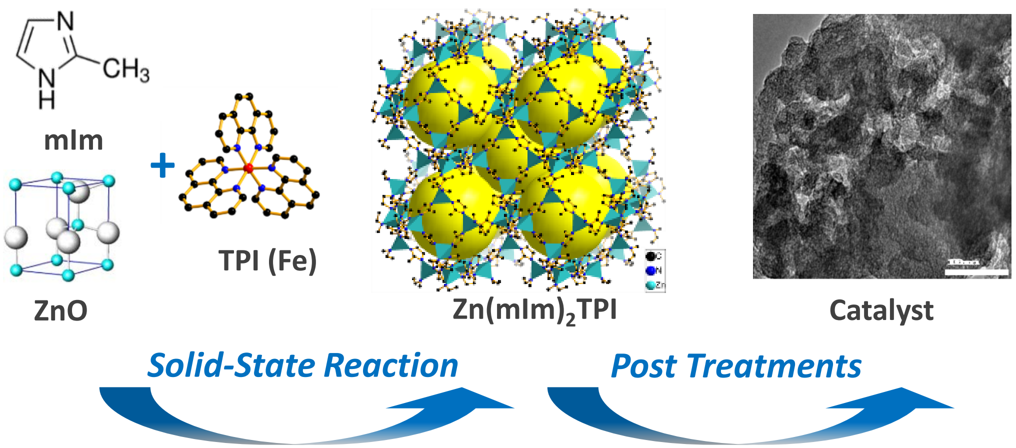
*V. Stamenkovic, P. Yang and coworkers, ANL & LBNL*

***Nanoframe catalysts have 3X mass activity of Pt/C in low-loaded MEA***

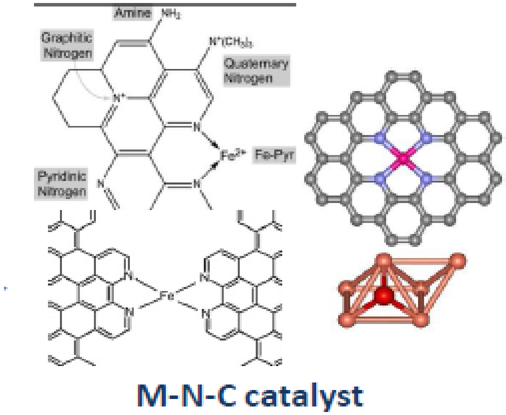
# Accomplishments: Non-PGM Catalysts



*Zeolitic Imidazolate Framework Catalyst (ANL)*



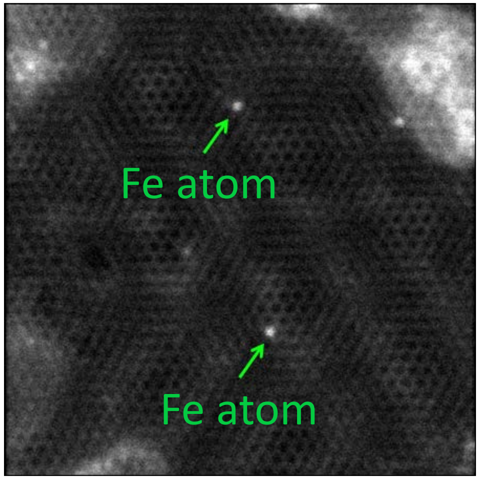

*Fe-Metal Organic Framework Catalyst (NEU/UNM)*




Progress toward achieving non-PGM catalyst and MEA targets:

- 0.9 $V_{IR\text{-}free}$, 100% RH $O_2$, 1.5 bar: **14-24 mA/cm$^2$**
  - 2014 status: 9-15 mA/cm$^2$
  - Target: 44 mA/cm$^2$ @0.9 $V_{IR\text{-}free}$
- 0.8 V, 100% RH air, 1.5 bar: **90-110 mA/cm$^2$**
  - 2014 status: 25-75 mA/cm$^2$
  - Target: 300 mA/cm$^2$ @0.8 V

*Cyanamide-Polyaniline-Fe-C Catalyst (LANL)*

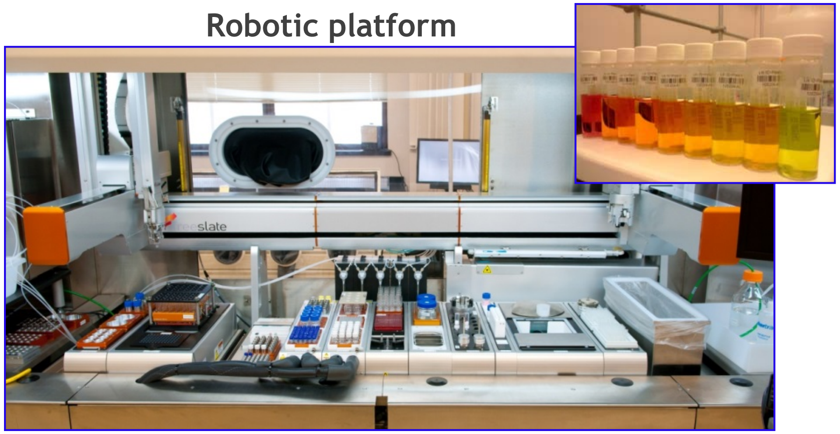



***D.J. Liu et al., ANL; P. Zelenay et al., LANL; S. Mukerjee et al., NEU***

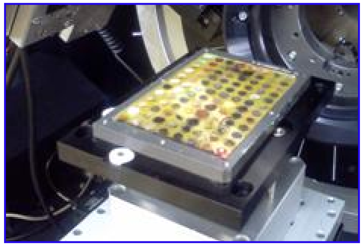
***Improved non-PGM catalysts developed at ANL, LANL, and NEU/UNM***

# Accomplishments: High-Throughput Approaches

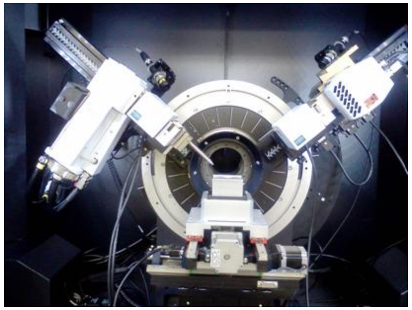
Robotic platform



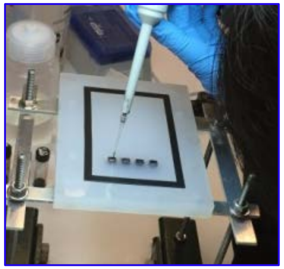
HT pyrolysis
(45 variations)



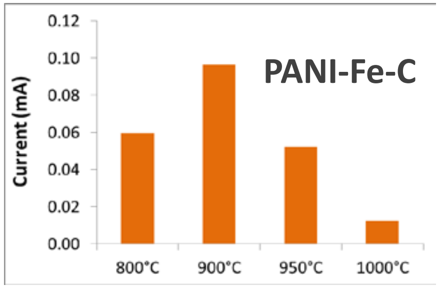
HT X-ray powder diffraction

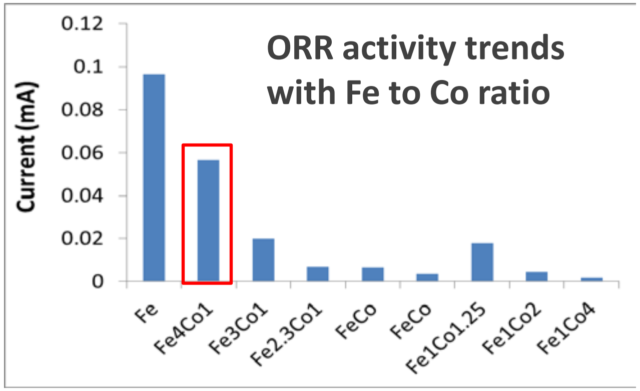


HT acid washing



Channel flow double electrode cell



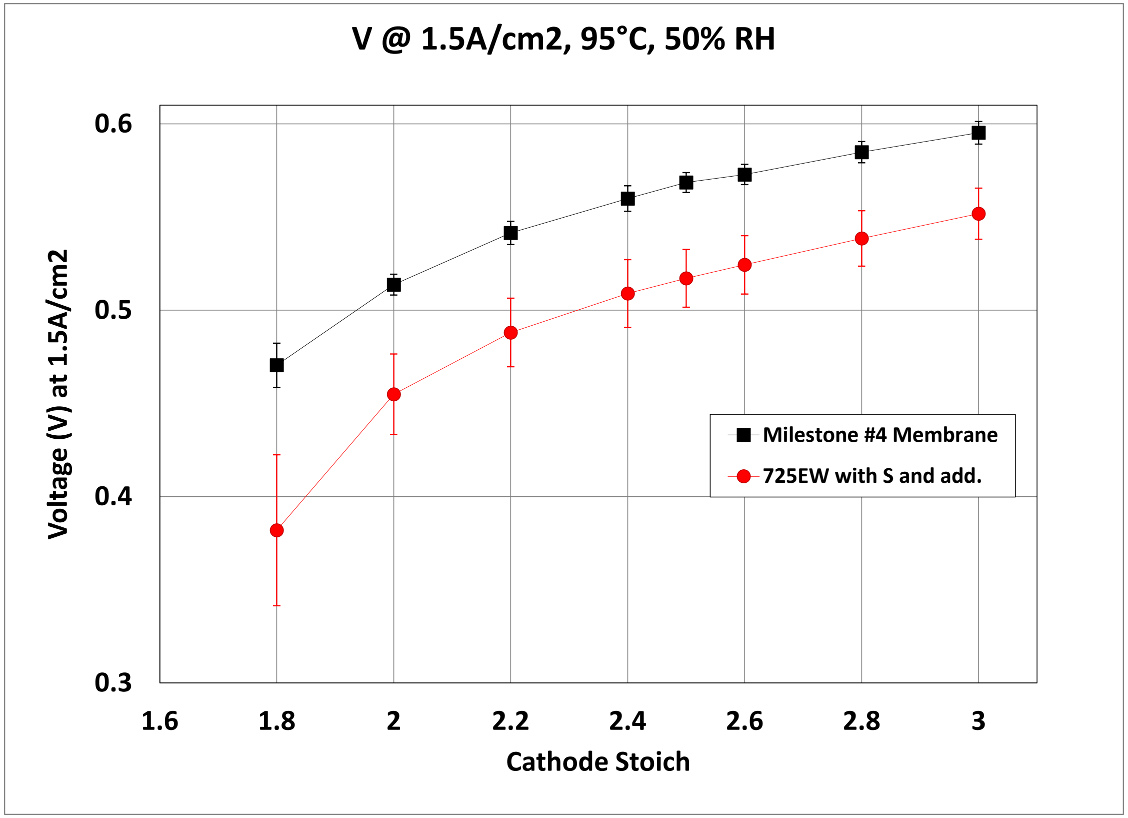



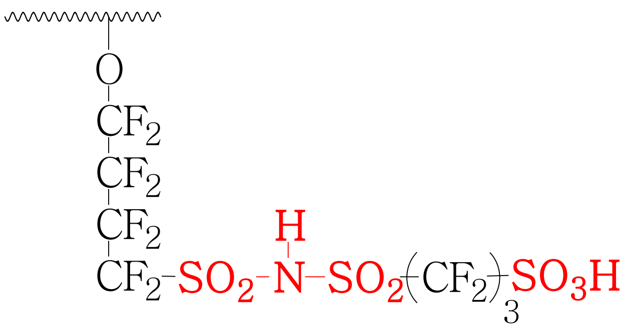

- Argonne's HT process produces PANI-Fe-C powder with same phase composition as large single batch synthesized at LANL
- HT screening of ORR activity showed same activity trends as large single batches
- Identified a new PANI-$Fe_xCo_y$ composition with higher ORR activity than previously best in the binary class: **PANI-$Fe_4Co$ pyrolyzed at 800°C**

*D. Myers et al., ANL*

***Developed methods for high-throughput (HT) synthesis and characterization of PANI-$Fe_xCo_y$***

# Accomplishments: New Membranes




*Perfluoro Imide Acid (PFIA)*

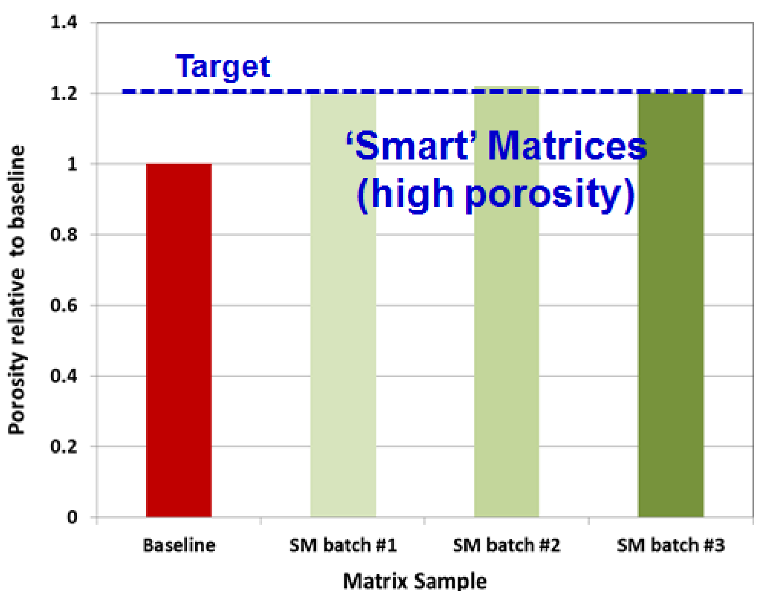
A PFIA-based MEA has simultaneously demonstrated:

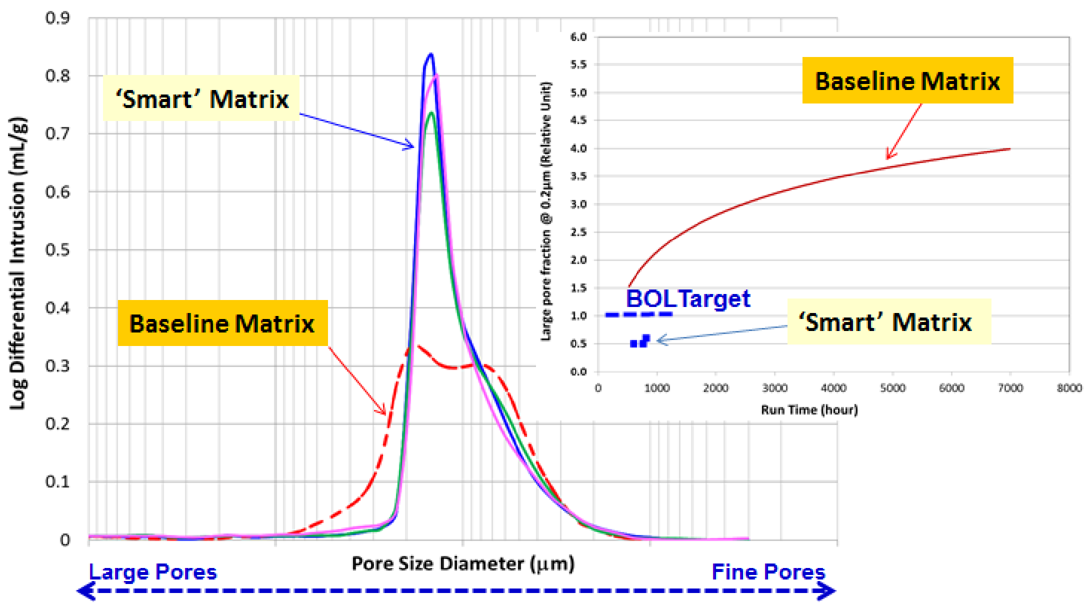
- ~50 mV higher performance than 725 EW PFSA MEA at 95°C, 50% RH
- Average chemical stability (OCV test): 740 h (target: 500 h)
- Mechanical stability (RH cycling): >23,700 cycles (target: 20,000 cycles)

***M. Yandrasits et al., 3M***

***MEAs with PFIA membranes pass durability tests, outperform PFSA MEAs***

# Accomplishments: Molten Carbonate Fuel Cells




New "Smart Matrix" project targets technology advancement toward meeting stationary fuel cell durability of 80,000 hours. The project has

- increased MCFC matrix BOL porosity by 20%
- decreased fraction of pores over 0.2 µm by 30%
- identified and characterized coarsening mechanisms to improve durability

*C. Yuh et al., FuelCell Energy*

***Improved electrolyte matrix for higher performance and better durability***

# FC-PAD: Consortium for Fuel Cell Performance And Durability

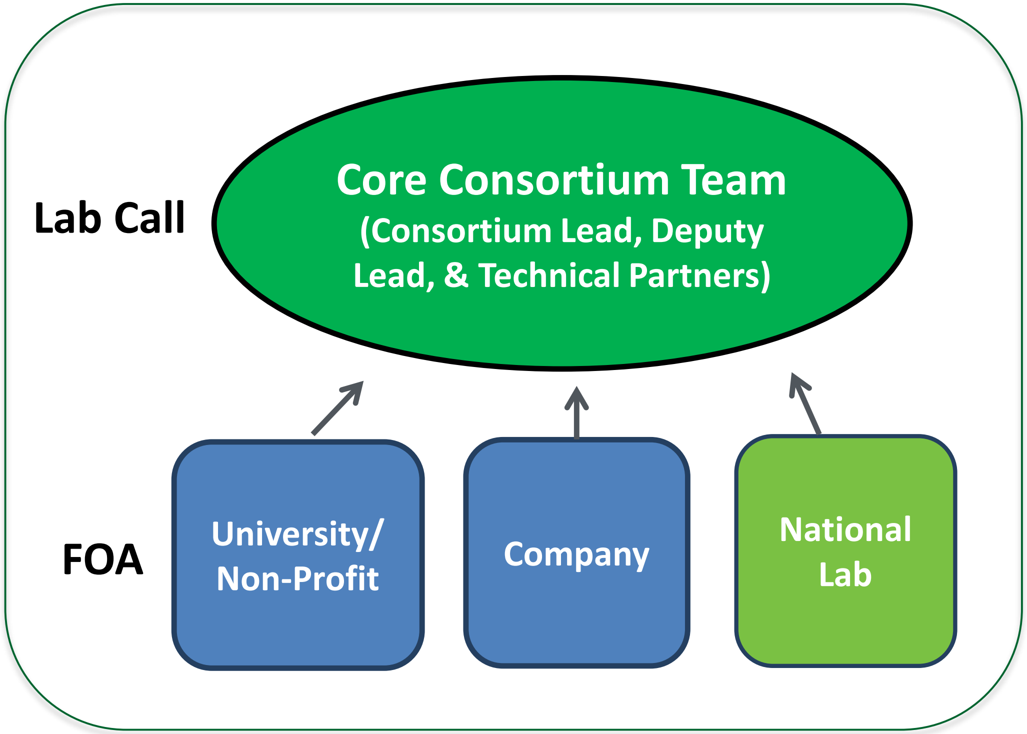
**Approach:**

- Couple national lab capabilities with future FOAs for an influx of innovative ideas and research

**Technical Objectives:**

- Address transport issues to improve MEA performance
- Identify degradation mechanisms and develop mitigation strategies
- Develop new materials* and structures for enhanced performance and durability

** excluding catalysts and membranes*

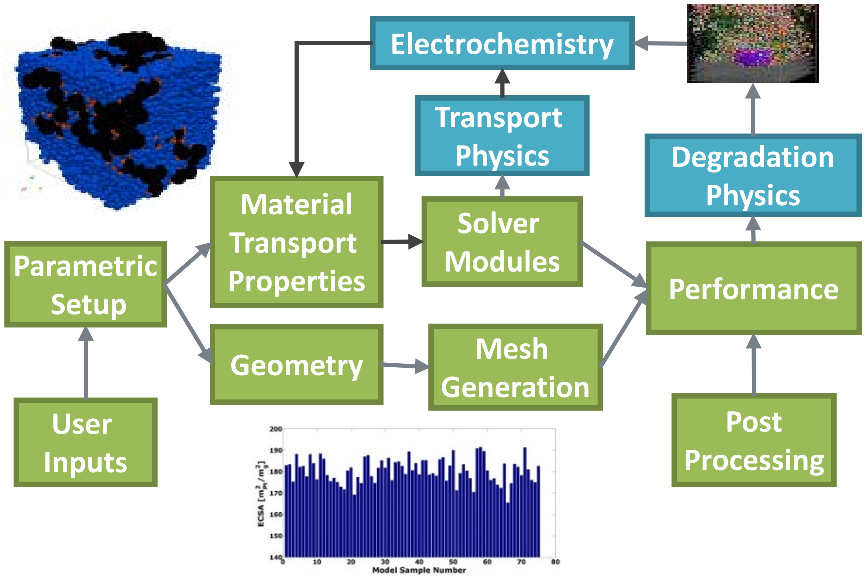



***Consortium will foster sustained capabilities and collaborations***

***Creating a high-functioning team with core activities and projects to advance fuel cell performance and durability***

# FC-APOLLO Tutorial






# FC-APOLLO

***F**uel*
***C**ell*
***A**pplication*
***P**ackage for*
***O**pen-source*
***L**ong-**L**ife*
***O**peration*

- Open-source application package for simulation of performance and durability of PEMFCs.
- The software suite includes physics encompassing beginning of life performance and subsequent material degradation due to Pt dissolution and carbon corrosion.

**Source code available via Source Forge at:**
www.sourceforge.net/projects/fcapollo

*This tutorial will cover the development background, the implemented physics and reaction kinetics, the open source release, methods for access and use, and a general demonstration of the model.*

***D. Harvey, et al., Ballard***

***Wednesday, June 10, 4:15 – 6:00pm, Gateway Salon J&K***

# Fuel Cells Incubator Selections



***Facilitated Direct Liquid Fuel Cells with High Temperature Membrane Electrode Assemblies***
Advent Technologies, Inc. (East Hartford, CT) with LANL

***Advanced Catalysts and MEAs for Reversible Alkaline Membrane Fuel Cells***
Giner, Inc. (Newton, MA) with University of Buffalo-SUNY and NREL

***Development of non-PGM Catalysts for Hydrogen Oxidation Reaction in Alkaline Media***
University of New Mexico (Albuquerque, NM) with IRD Fuel Cells, Pajarito Powder, and LANL

***Highly Stable Anion-Exchange Membranes for High-Voltage Redox-Flow Batteries***
University of Delaware (Newark, DE) with NREL

***Innovative Non PGM Catalysts for CHP Relevant Proton Exchange Membrane Fuel Cells***
Northeastern University (Boston, MA) with Fuel Cell Energy, Pajarito Powder, and University of New Mexico

***High-risk / high-reward projects complementing FCTO RD&D in: direct DME fuel cells, high-T PEMFCs, non-PGM catalysts, AMFCs, reversible fuel cells, redox flow batteries***

# Request for Information

## Gas Clean-Up for Fuel Cell Applications Workshop Report

### Workshop Findings:

- Fuel cleanup is a barrier
- Fuel gas clean-up costs can be reduced through a combination of development efforts
- Opportunities to use APG onsite with fuel cells identified

**RFI Comments Due 7/24/2015**

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

**EERE 104: Request for Information (RFI)**
Version 1 • Last Updated July 2013

**Gas Clean-Up for Fuel Cell Applications Workshop Report**
**DE-FOA-0001331**

**DATE**: May 18, 2015

**SUBJECT**: Request for Information (RFI)

**DESCRIPTION**: Request for Information on *Gas Clean-Up for Fuel Cell Applications* Workshop Report

**BACKGROUND**: The U.S. Department of Energy's (DOE) Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy (EERE) seeks to advance the development and deployment of fuel cells for power generation in a variety of applications. In support of this goal, EERE funds a broad range of fuel cell research, development, and demonstration activities.

The Gas Clean-up for Fuel Cell Applications Workshop was held at Argonne National Laboratory on March 6-7, 2014, and featured 43 participants from industry (fuel cell, process solution providers, and material suppliers), government agencies, advocacy groups, universities, and national laboratories with expertise in the relevant fields. The objective of the workshop was to identify and prioritize:

- The impurities that have the greatest impact on the complexity and performance of a fuel cell plant;
- The Research and Development (R&D) strategies that can alleviate the cost for onsite removal of impurities;
- The R&D strategies that will simplify a plant and reduce product cost (heat, power, hydrogen); and
- The fuel processors and gas clean-up systems that facilitate modularity and fuel flexibility for a range of fuel cell technologies.

The main activities of the workshop were arranged in three sessions to (i) discuss the impurities, (ii) discuss the clean-up technologies, and (iii) discuss the R&D needed to advance the clean-up technologies.

**PURPOSE**: The purpose of this RFI is to obtain feedback and opinions from industry, academia, research laboratories, government agencies, and other stakeholders on the report findings from the *Gas Clean-up for Fuel Cell Applications Workshop* held at Argonne National Laboratory in 2014. The report can be found on the Exchange website at https://eere-exchange.energy.gov/.

Key conclusions of the workshop include:

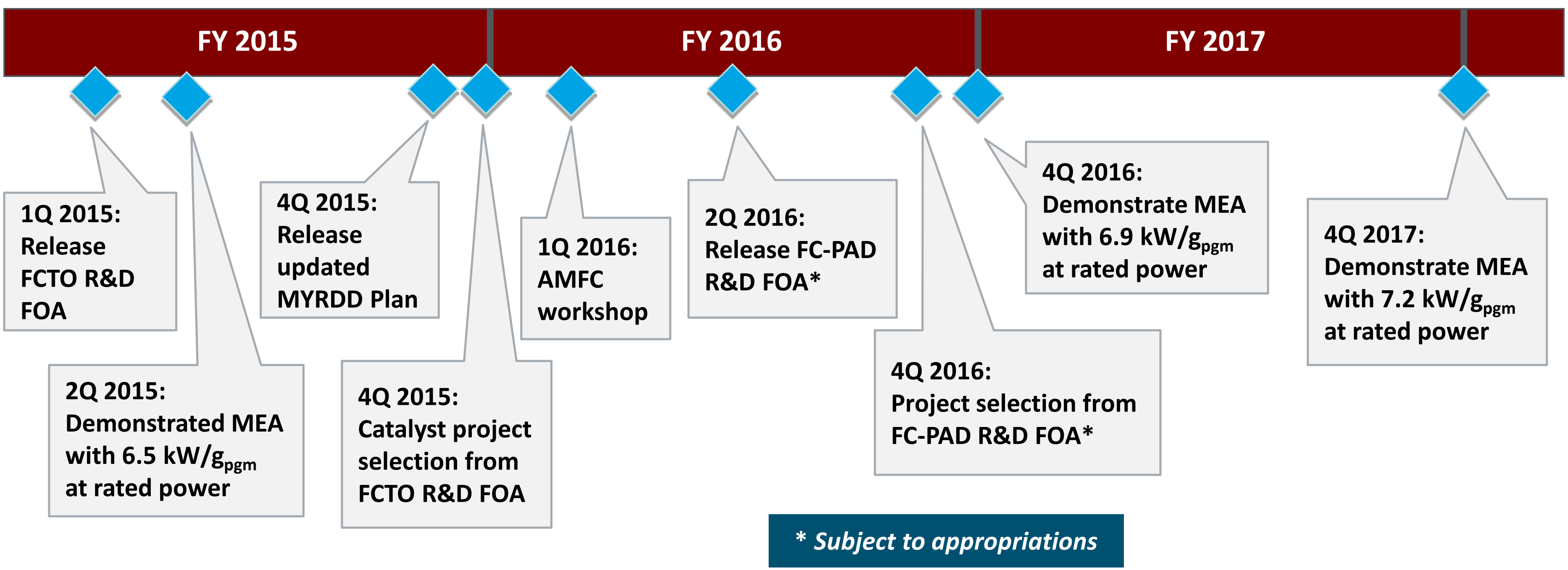
- The sensitivity of the fuel processor and fuel cells to the impurities present in fuels of interest imposes a clean-up cost that adds to the burden of fuel cell systems in stationary

*This is a Request for Information (RFI) only. EERE will not pay for information provided under this RFI and no project will be supported as a result of this RFI. This RFI is not accepting applications for financial assistance or financial incentives. EERE may or may not issue a Funding Opportunity Announcement (FOA) based on consideration of the input received from this RFI.*

# Summary of Activities and Upcoming Milestones



- Projects addressed cost reduction and performance and durability enhancement of stack components including catalysts, membranes and MEAs
- Potential new low-PGM catalyst projects to strengthen R&D portfolio
- FC-PAD: Consortium approach to advance fuel cell performance and durability
- Materials Genome Initiative approach will expedite advanced materials and functional interface development focusing on non-PGM catalyst containing MEAs through improved modeling, high-throughput screening, and advanced characterization



# Collaborations



## INTERNATIONAL ACTIVITIES

- International Energy Agency – Hydrogen Implementing Agreement

## DOE-EERE Fuel Cells Program

- Vehicle Technologies Office
- Small Business Innovative Research (SBIR)
- 44 projects

## INDUSTRY

- U.S. DRIVE Partnership: Fuel Cell Tech Team
- Codes & Standards Organizations

## TECHNOLOGY VALIDATION

## National Collaborations (inter- and intra-agency efforts)

**DOE - FE**
SOFC Program

**DOE - BES**
Catalysts and Membranes

**DOE – ARPA-E**
Reliable Electricity Based Electrochemical Systems (REBELS)

**DOT/FTA**
Fuel Cell Buses

**DOD**
DOD/DOE MOU

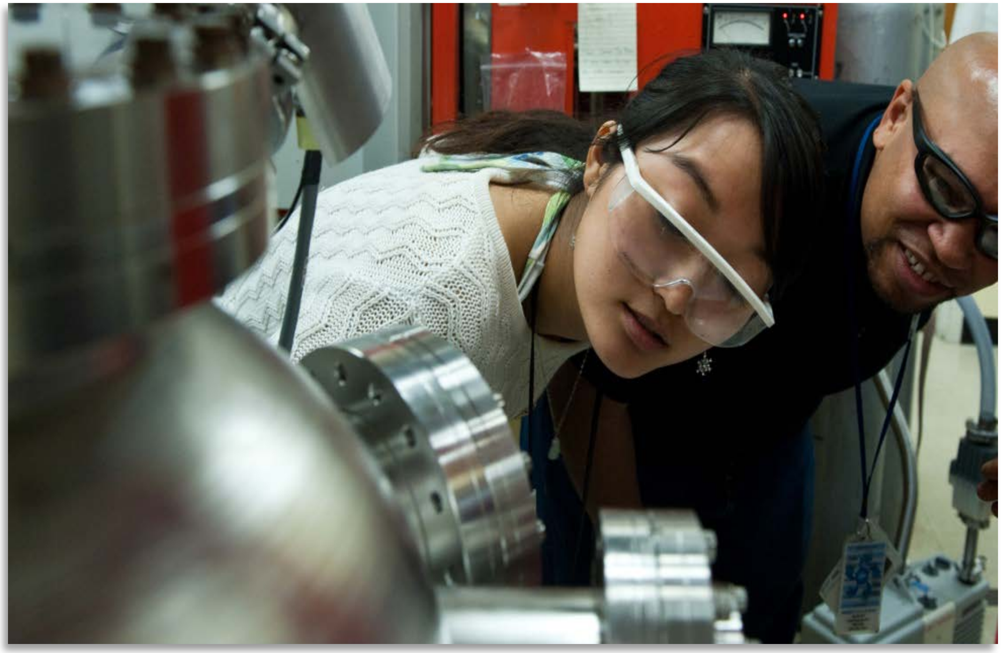
**DOC/NIST**
Neutron Imaging

***Applied R&D is coordinated among national and international organizations***

## Fuel Cell Fellowship Opportunity

Science and Technology Policy Fellowship for Scientists and Engineers

- Ph.D. is required, experience preferred
- 2-Year Fellowship
- Located in Washington, D.C.
- Health benefits and relocation expenses included



***Opportunity EERE-RPP-FCT-1804***

***https://www.zintellect.com/Posting/Details/1078***

# Fuel Cells Program Contacts



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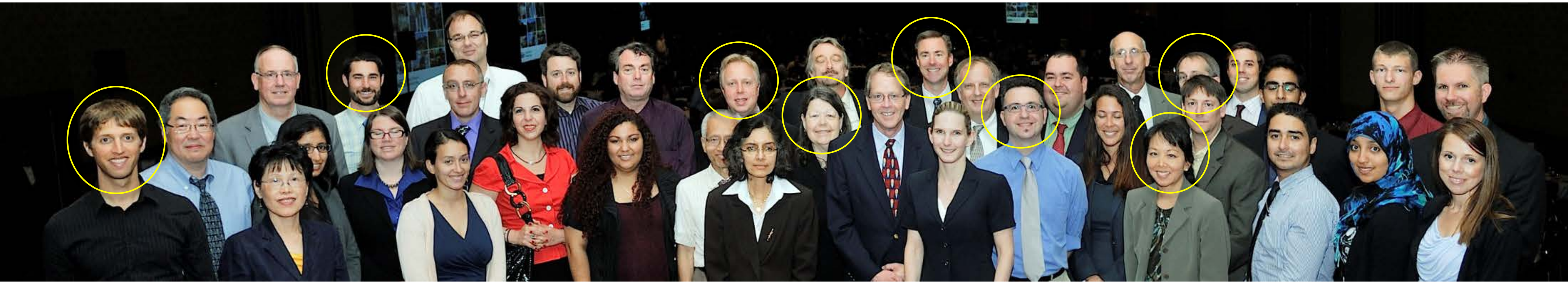

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