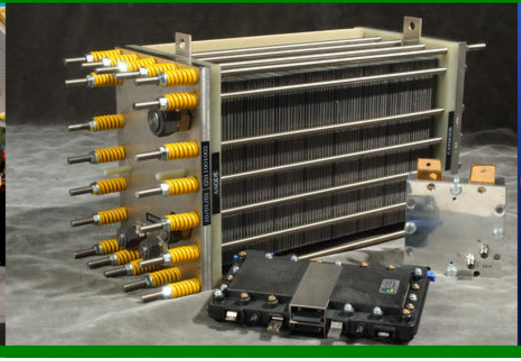
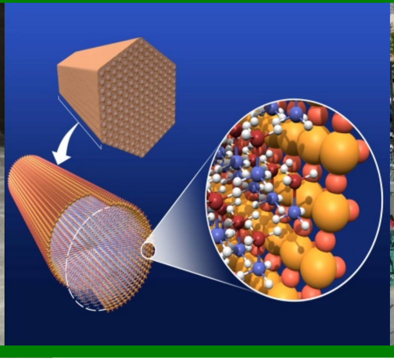





Fuel Cells Program Area
- Plenary Presentation-

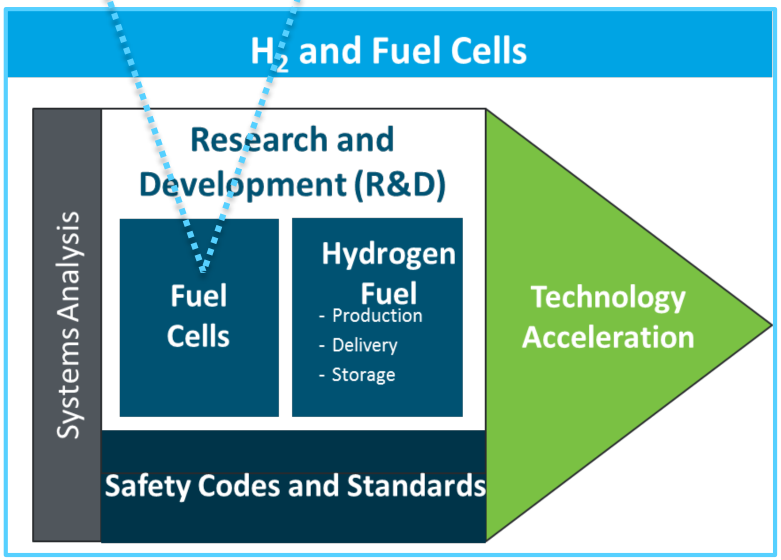
Dimitrios Papageorgopoulos
Fuel Cell Technologies Office

2017 Annual Merit Review and Peer Evaluation Meeting

June 5 - 9, 2017

Goal and Objectives

GOAL: Advance fuel cell technologies for transportation, stationary and early market applications



Fuel Cells MYRD&D Plan

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

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

2020 Targets by Application

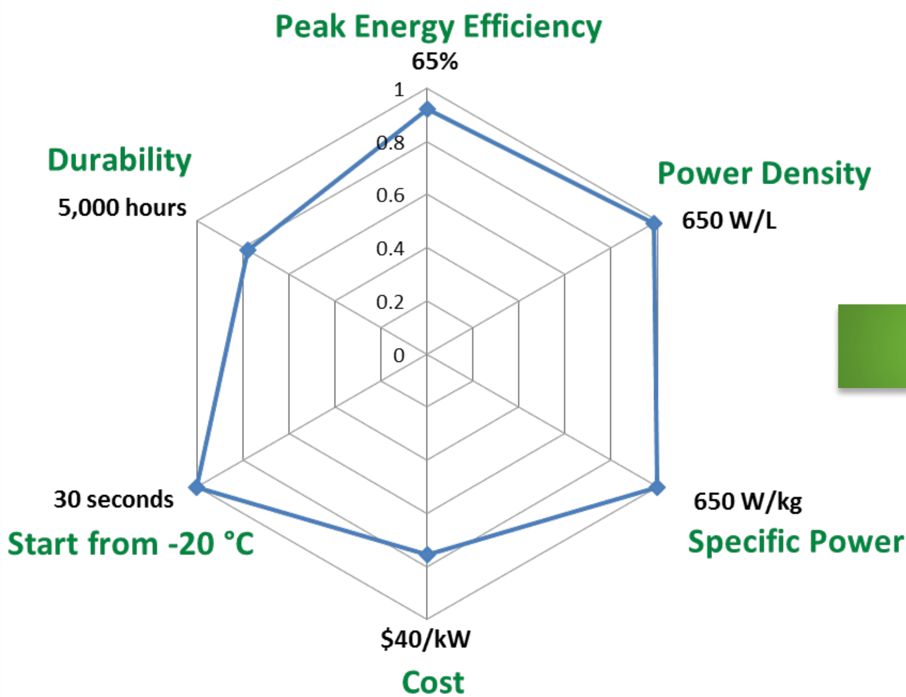
Fuel Cell Cost	$40/kW $30/kW*	$1,000/kW** $1,500/kW***
Durability	5,000 hrs 8,000 hrs*	80,000 hrs
Efficiency	65%	50% † 90% ‡

* Ultimate

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

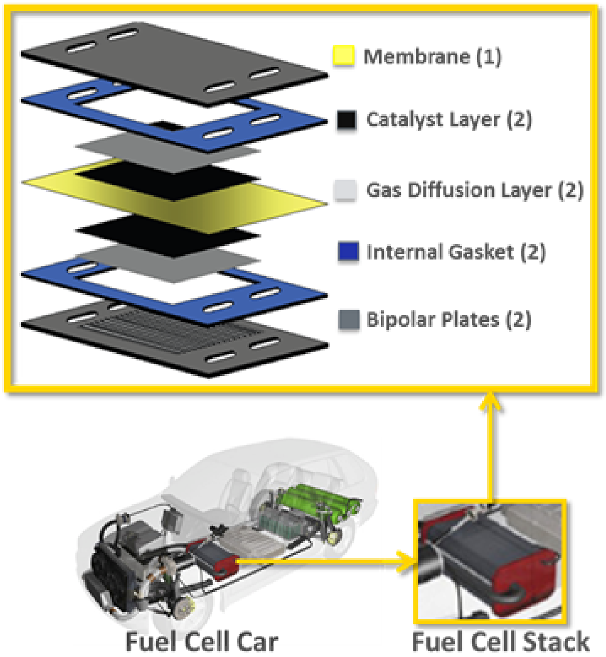
Challenges and Strategy

Durability and Cost are the primary challenges to fuel cell commercialization and must be met concurrently



Improvements in multiple components are required to meet the 2020 cost target

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



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

Challenges & Strategy

The Fuel Cells program supports applied early-stage R&D of fuel cells with goals of reducing cost and improving durability

BARRIERS

Cost
Durability
Performance

STRATEGY

Materials, components, 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

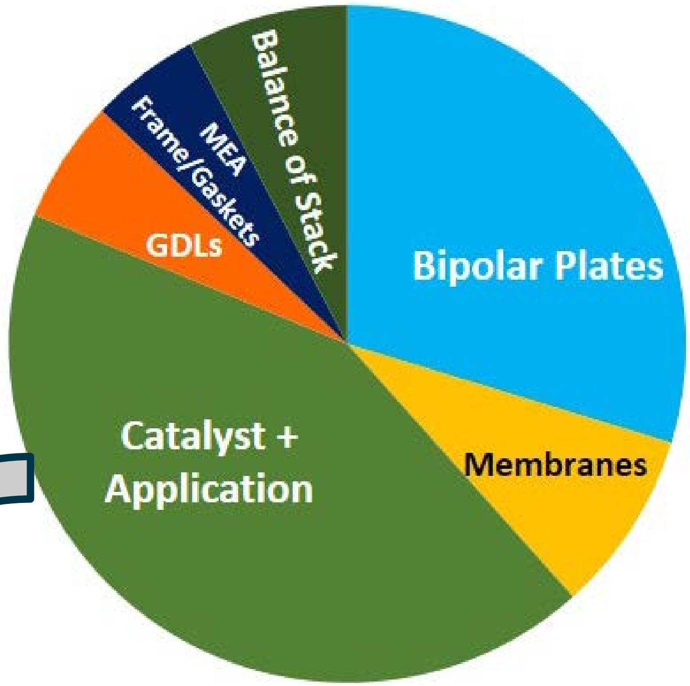
Performance and Durability

Mass transport
Durability
Impurities

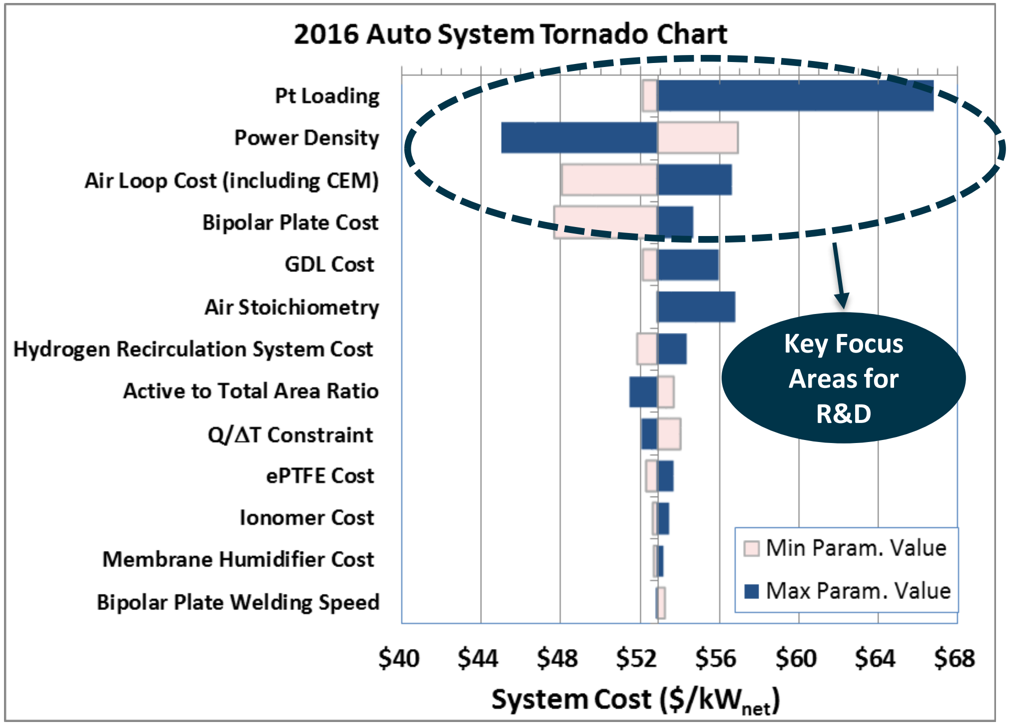
Balance of Plant Components (BOP)

Strategic Analysis Guides Fuel Cell R&D Focus Areas and Priorities

PEMFC Stack Cost Breakdown*



Sensitivity Analysis



***Catalyst cost** is projected to be the largest single component of the cost of a PEMFC manufactured at high volume.*

Strategy

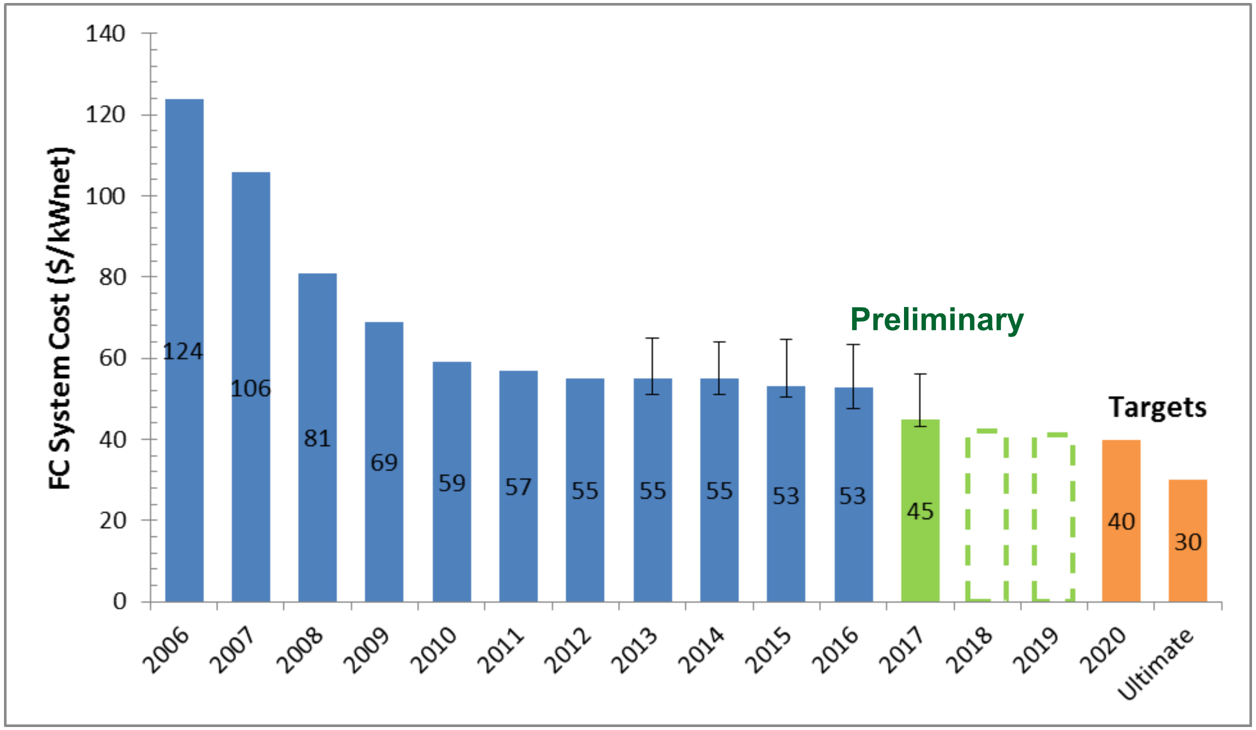
- ***Reduce PGM levels in catalysts***
- ***Improve MEA performance***

*@ 500,000 systems/year

Fuel Cell Cost Improvements

Fuel Cell Cost Status

- **$53/kW*** for 500,000 units/year
- **$59/kW*** for 100,000 units/year
- **$230/kW†** for currently commercialized technology at 1,000 units/year

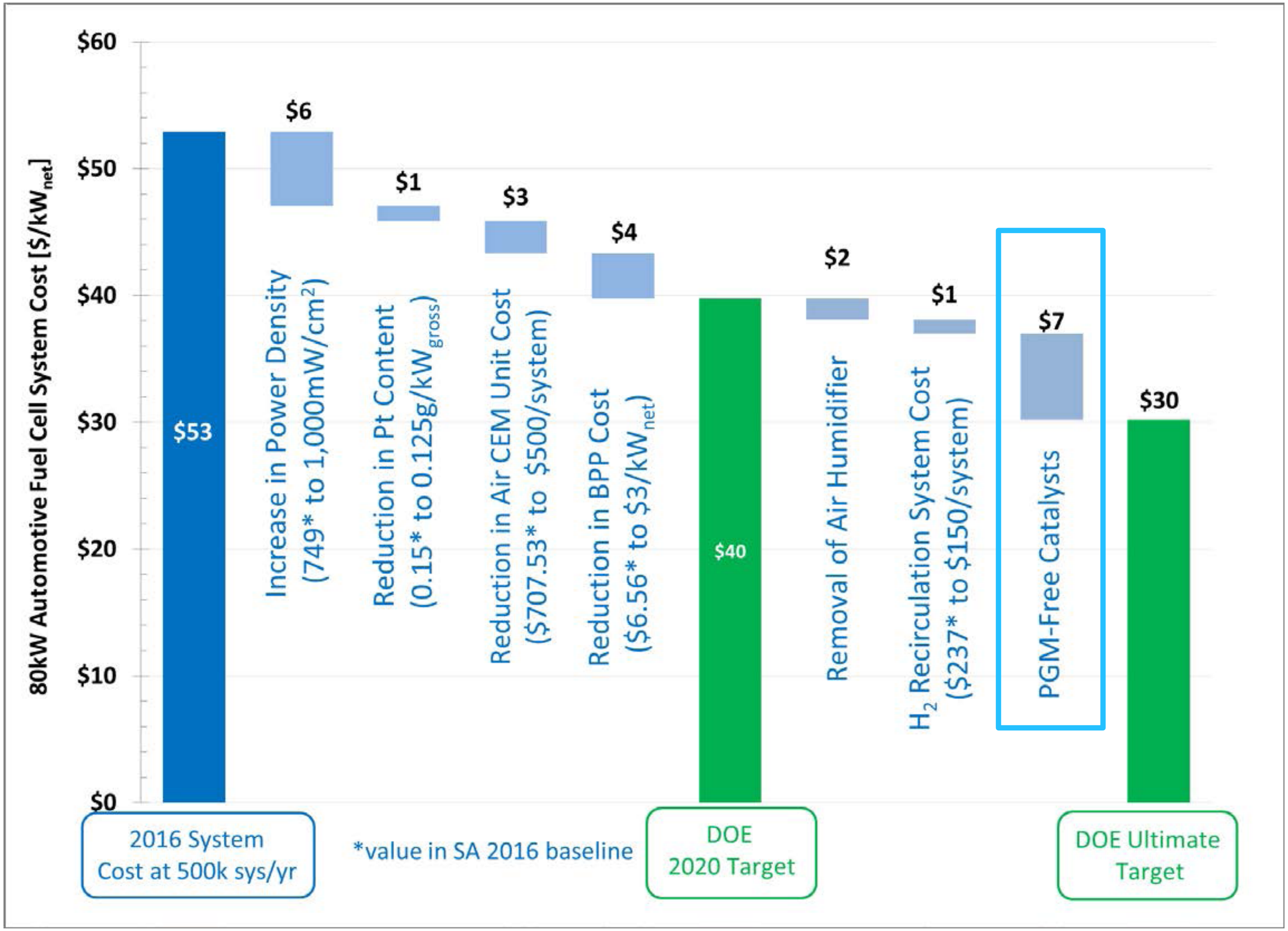


Preliminary values for 2017 fuel cell transportation system cost at volumes of 500,000 and 100,000 units/year are $45/kW and $50/kW, respectively.

** 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/16020_fuel_cell_system_cost_2016.pdf

Potential Cost Reduction Pathway



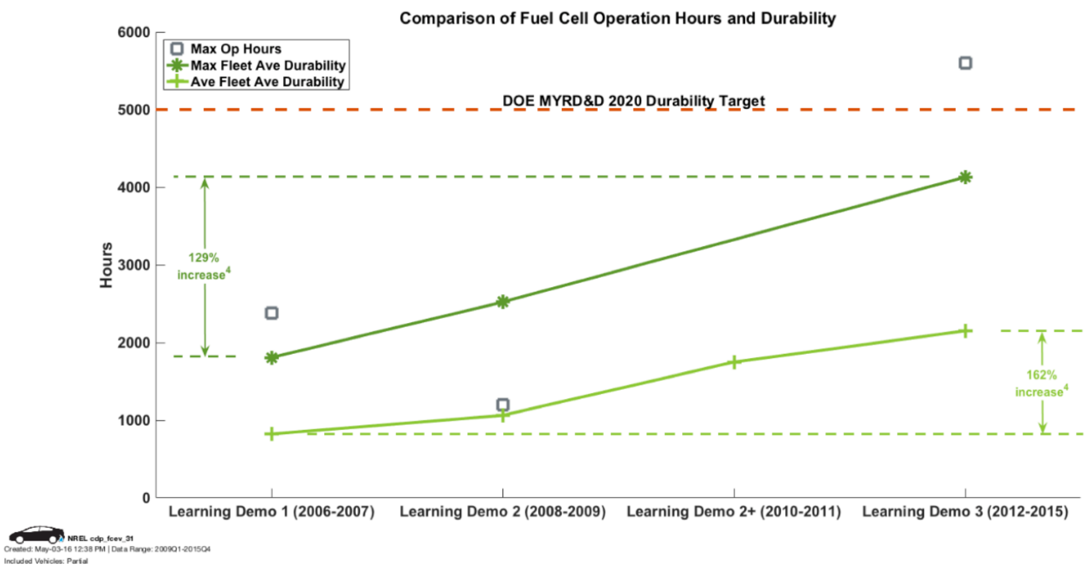
PGM-free catalysts are a key research goal for moving towards DOE's ultimate $30/kW target

On-Road Fuel Cell Stack Durability

CARS

4x increase in **durability**:

> 4,100 hours



Maximum projected durability to 10% voltage degradation of fuel cell systems increased from 950 hours in 2006 to over **4,100** hours in 2016

BUSES

Record **operation hours**:

> 23,800 hours

Surpassed the 2016 interim 18,000 hour target, nearing the 25,000 hour target

12 fuel cell systems have passed 15,000 operation hours, high operation hours is no longer confined to one bus

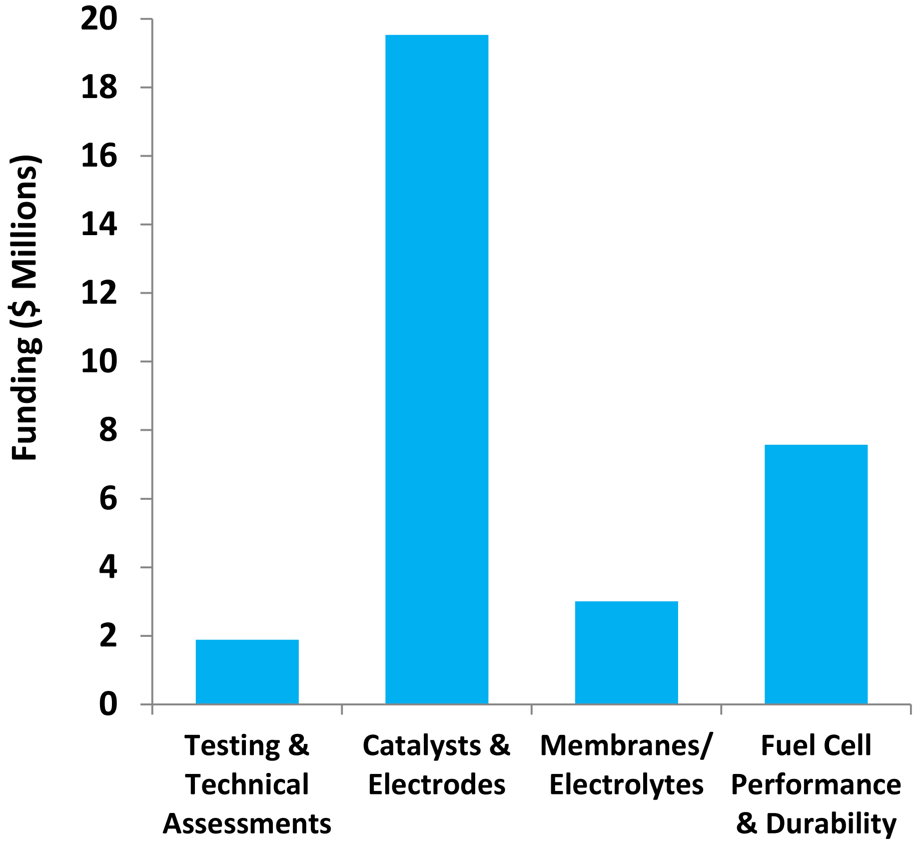
Further progress required to meet ultimate durability and cost targets concurrently

https://www.hydrogen.energy.gov/pdfs/16019_fuel_cell_stack_durability_2016.pdf

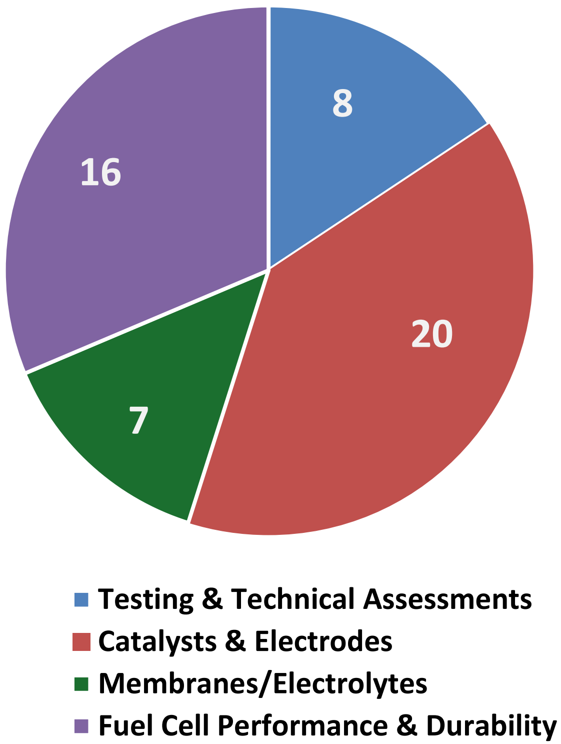
Fuel Cells Program Budget

FY 2017 Appropriation = $32.0 M

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



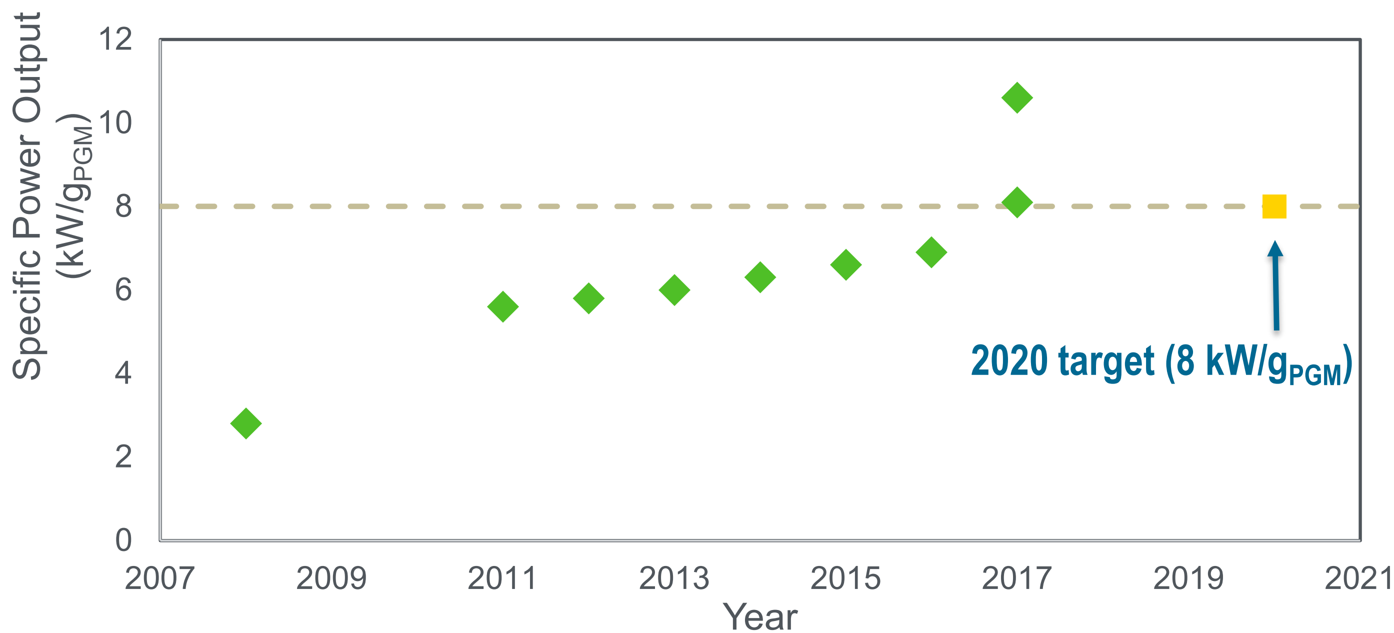
Number of Projects in Portfolio by Focus Area



Full-upfront funding for non-lab financial assistance projects selected from FOAs

Catalyst Focused R&D Portfolio Achieves Targets

2.8 kW/g_{PGM} (2008) → 10.6 kW/g_{PGM} (2017)*

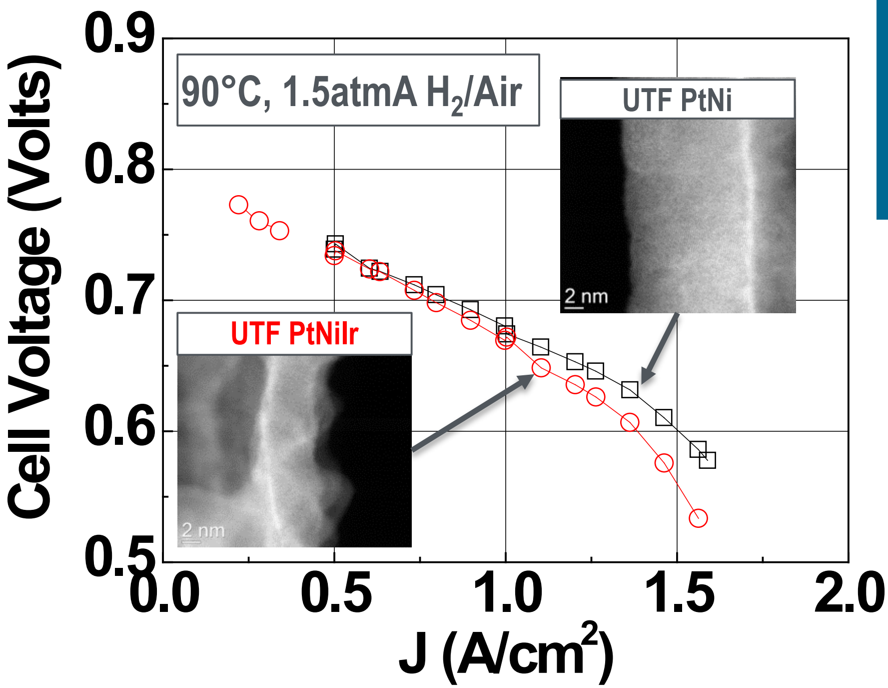


Further progress required to meet durability and cost targets concurrently

**Demonstrated in MEA @ 150 kPa (abs) meeting heat rejection requirement*

Improved the catalyst specific power of fuel cells to 10.6 kW/g_{PGM}, a more than 3x improvement to the 2008 baseline of 2.8 kW/g_{PGM} and exceeding the 2020 target of 8.0 kW/g_{PGM}

Accomplishments: UTF PtNi Catalysts



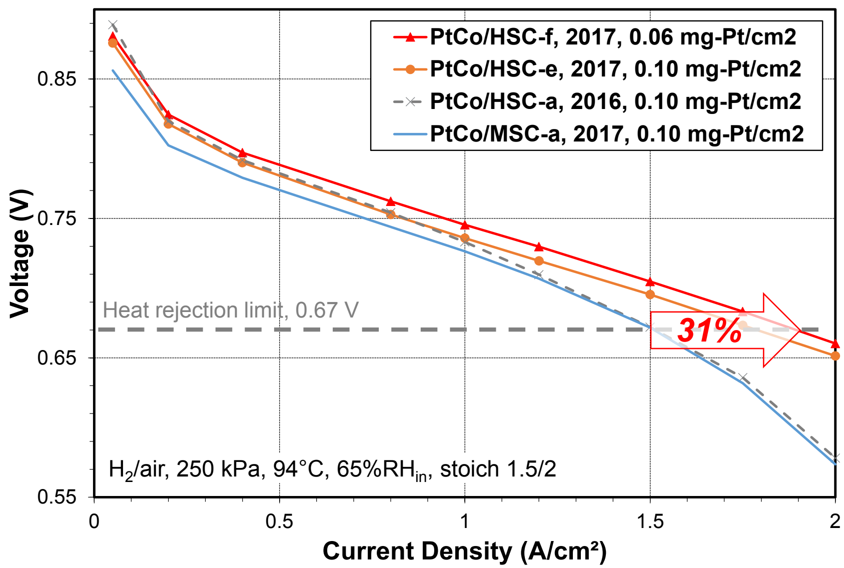
Ultra-thin film (UTF) PtNi catalyst 8.1 kW/g_{PGM}, exceeding 2020 DOE target

- Total Pt loading 0.077 g_{Pt}/cm^2
- Nearly meets targets for mass activity (0.37 A/mg_{PGM}) and activity loss during AST (43%)
- UTF PtNiIr meets mass activity and H_2/Air durability targets

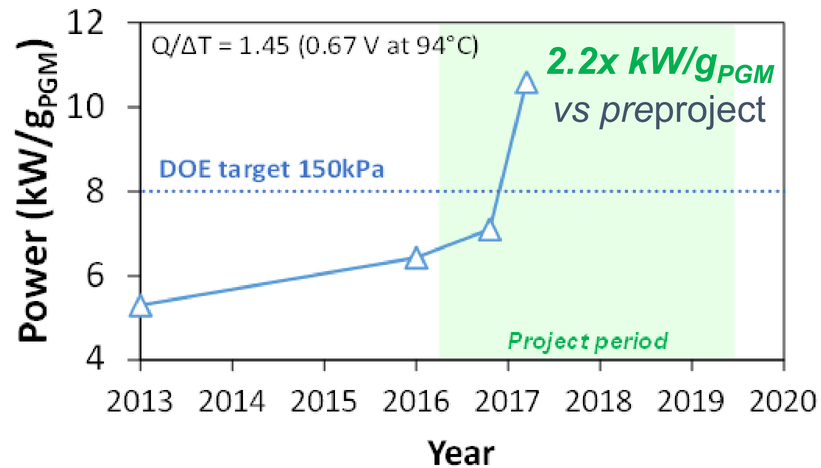
	Total PGM Loading (mg/cm^2)	Spec. Power @ Q/ΔT=1.45 (kW/g_{PGM})	Rated Power @ Q/ΔT=1.45 (W/cm^2)	1/4 Power (A/cm^2 @ 0.80V)	ORR Mass Activity (A/mg_{PGM})	Electrocatalyst AST Durability (NSTF Cathode Only): Mass Act. Loss (%)	Electrocatalyst AST Durability (NSTF Cathode Only): ΔV @ 0.8A/cm^2 (mV)
DOE 2020 Target	0.125	8.0	1.000	0.300	0.44	40	30
2017 (Jan.) UTF PtNi	0.077	8.1	0.626	NA	0.37	43	50
2017 (Mar.) UTF PtNiIr	< 0.089	>6.6	0.584	< 0.200	0.44	45	23

A. Steinbach et al., 3M

Accomplishments: PtCo Catalysts Supported on High Surface Area Carbons

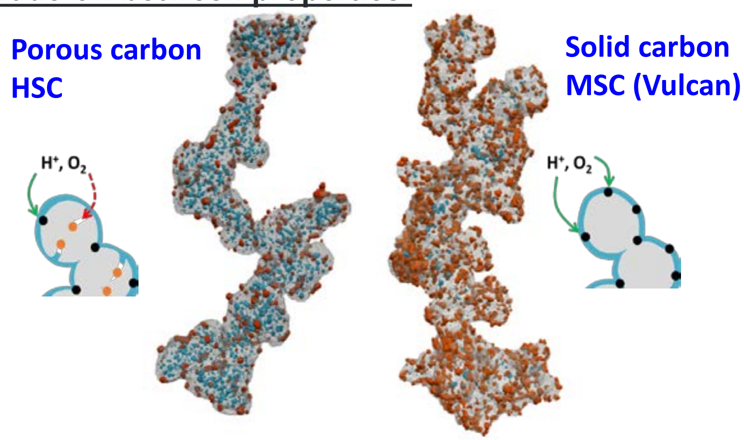


Highest catalyst specific power demonstrated to date: 10.6 kW/g_{PGM}



- Total Pt loading 0.088 mg_{PGM}/cm^2
- PtCo/HSC-f catalyst exceeds targets for specific power, PGM loading
- Power density 0.93 W/cm^2; needs improvement in other MEA components
- AST testing not yet performed
- Mass activity 0.7 A/mg_{PGM}

TEM tomography shows Pt NP location, Trade-off between properties:



- ✓ High Pt dispersion
- ✓ High ORR activity
- ✓ Easy to make good alloy

- ✓ Good O_2/proton transport
- ✓ Better stability

A. Kongkanand et al., GM

ElectroCat (Electrocatalysis Consortium)

Goal

ElectroCat Electrocatalysis Consortium → Energy Materials Network U.S. Department of Energy

Accelerate the deployment of fuel cell systems by **eliminating the use of platinum group metal-free (PGM-free) catalysts**

Mission

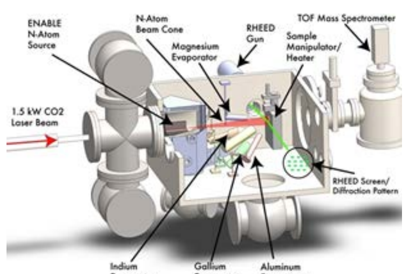
Develop and implement PGM-free catalysts by:

- **streamlining access** to unique synthesis and characterization tools across national labs
- **developing missing strategic capabilities**
- **curating a public database** of information

Core Lab Team

Argonne National Laboratory · Los Alamos National Laboratory · NREL National Renewable Energy Laboratory · Oak Ridge National Laboratory

High-throughput materials discovery, characterization, and testing



Design and synthesis of PGM-free catalysts and electrodes

www.electrocat.org

Accomplishments To-Date and Next Steps

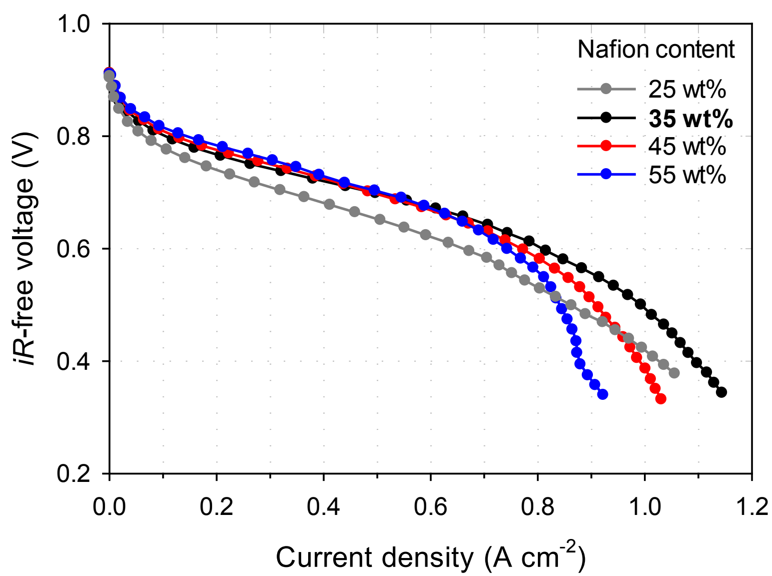
- Established key tech transfer agreement templates, data management plan, capability set, and national laboratory team
- Initiated technical work, achieving significant progress in **(a)** catalyst development, **(b)** active-site characterization, and **(c)** high-throughput PGM-free catalyst modeling and synthesis
- **Next:** Plan and host advanced computational modeling workshop (*tentative*)
- **Next:** Add partners through FY17 FOA

ElectroCat Technical Accomplishments

Performance Improvement

- Improved PGM-free H_2-air as-measured performance **by 25%** versus 2016 status by using Zn as a pore-forming component in the (CM+PANI)-Fe-C catalyst synthesis and by optimizing electrode ionomer content

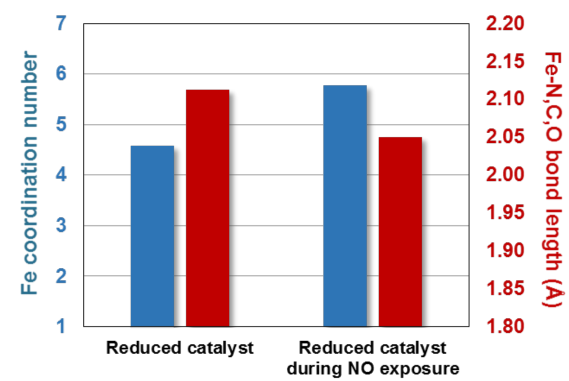
Anode: 0.3 mg_{Pt} cm^{-2} Pt/C H_2, 200 sccm, 1.0 bar H_2 partial pressure; **Cathode:** *ca.* 4.8 mg cm^{-2} catalyst loading, air, 200 sccm, 1.0 bar air partial pressure; **Membrane:** Nafion®, 211; **Cell:** 5 cm^2, 80 °C

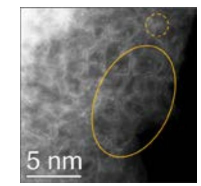


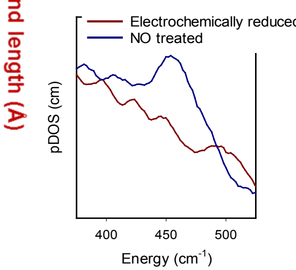
- Increased ORR activity for atomically-dispersed Fe-N-C catalyst **by 20 mV** at $E_{½}$

Characterization

- Obtained **direct microscopic and spectroscopic evidence** of a majority of **Fe sites being on the surface** and **atomically dispersed in (AD)Fe-N-C**

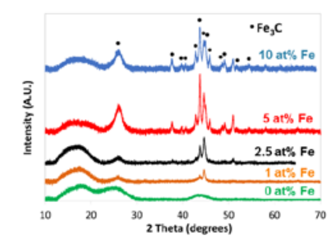






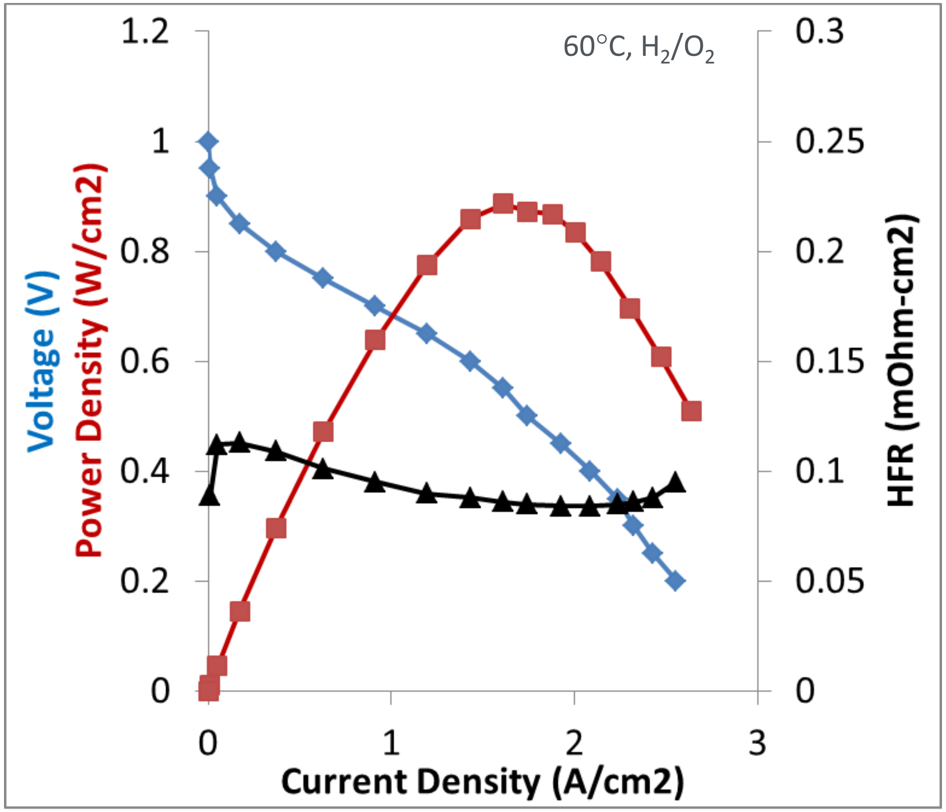
High-Throughput (HT)

- Used **HT software to calculate durability descriptor** for PGM-free cathode catalysts
- Used **HT robotic system to synthesize and characterize** 40 variations of (AD)Fe-N-C



ElectroCat
Electrocatalysis Consortium

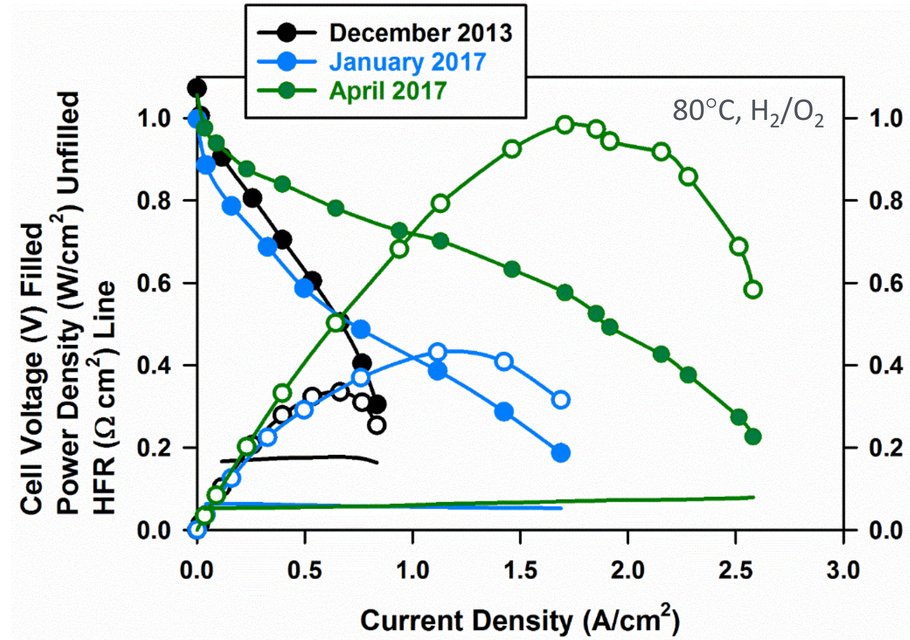
Accomplishments: Alkaline Membrane Fuel Cells



Membrane: Gen 2 Perfluoro AEM
Ionomer: HC grafted onto ETFE
Anode: PtRu/Vu 0.67 mg_{Pt}/cm^2
Cathode: Pt/Vu 0.4 mg_{Pt}/cm^2

Perfluoro-Based Membrane

B. Pivovar et al., NREL



Membrane: poly(terphenyl alkylene)
Ionomer: Polyfluorene-based (HC)
Anode: Pt_2-Ru_1/C 0.5 mg_{Pt}/cm^2
Cathode: Pt/C 0.6 mg_{Pt}/cm^2

Hydrocarbon-Based Membrane

Y.S. Kim et al., LANL

Early tests show encouraging stability of both membrane materials
Need better understanding of electrode performance and degradation issues

NREL and LANL demonstrate AEMFCs with significantly improved performance

FC-PAD: Consortium to Advance Fuel Cell Performance and Durability

Approach

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

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

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

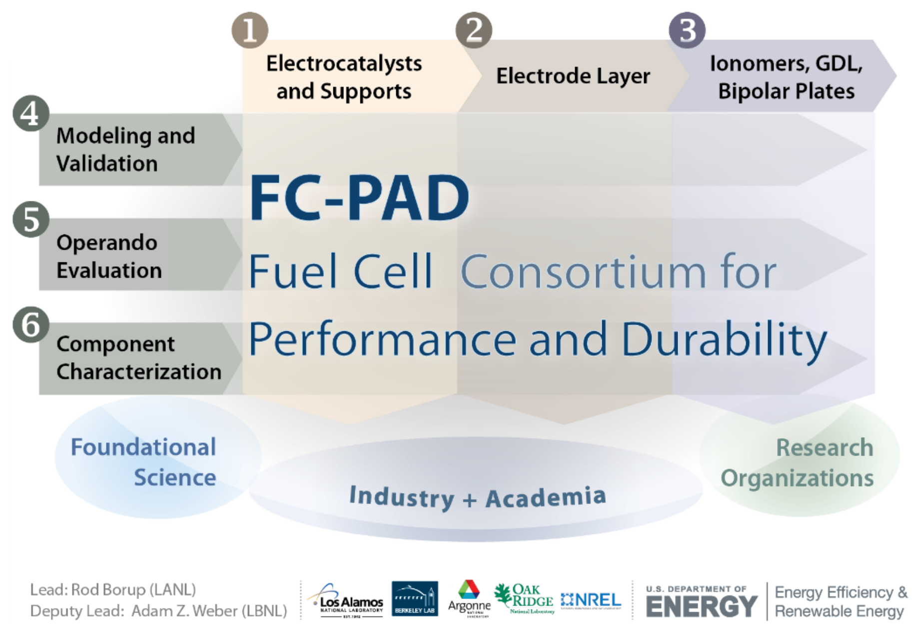
Core Consortium Team

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

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

3M, GM, United Technologies Research Center, Vanderbilt

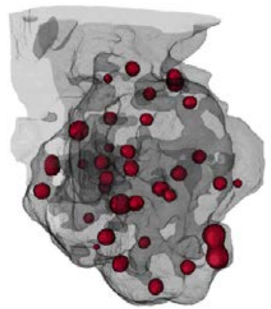
Structured across six component and cross-cutting thrusts

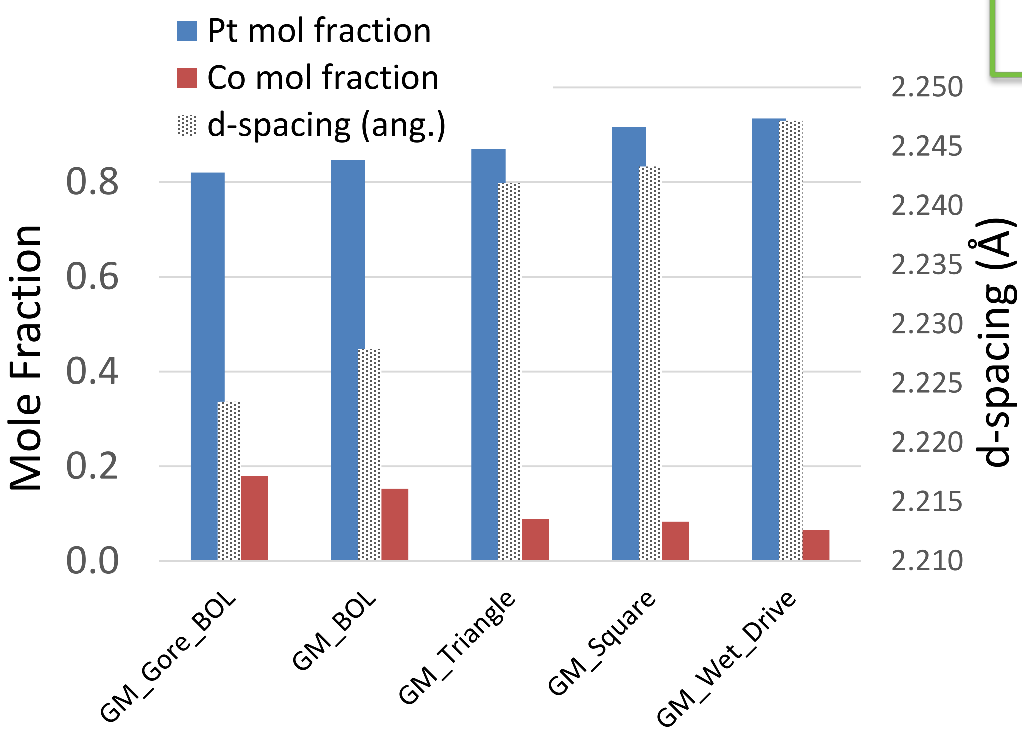


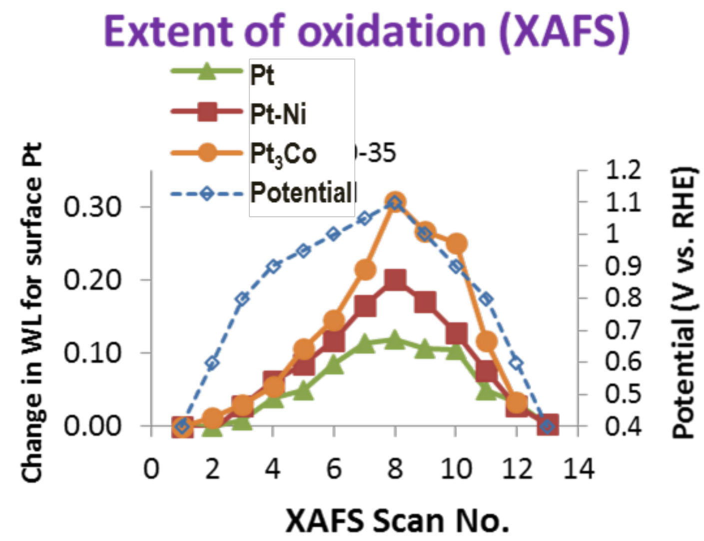
www.fcpad.org

FC-PAD: Enhanced Understanding of Pt Alloy Catalysts

Understanding performance and durability of low-PGM catalysts with different morphologies







- **77% of PtCo particles are *inside* HSAC support**
- **Porous particles show *lower Pt* but *higher Co* dissolution leading to accelerated performance loss**
- **Higher surface oxidation for alloys versus Pt-only, leads to poorer durability**
- **PtCo catalysts become more "Pt-like" during ASTs and potential-cycling operation**

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

RDE Testing Protocol and Best Practices Disseminated

Standard test protocol and best practices will assist the scientific community by enabling procedural consistency and less variability

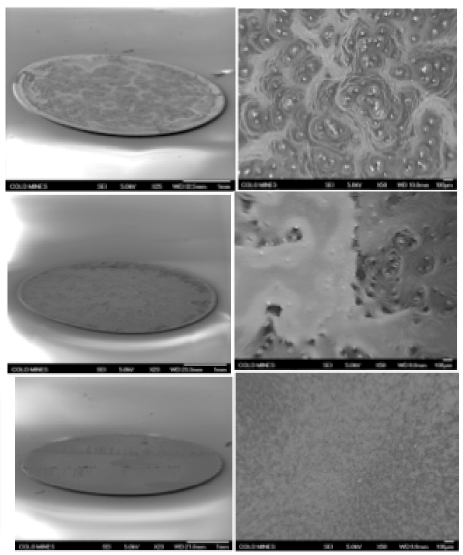
Test protocol and best practices validated at NREL and ANL

3 film deposition/drying methods evaluated

SAD (stationary air-dry)

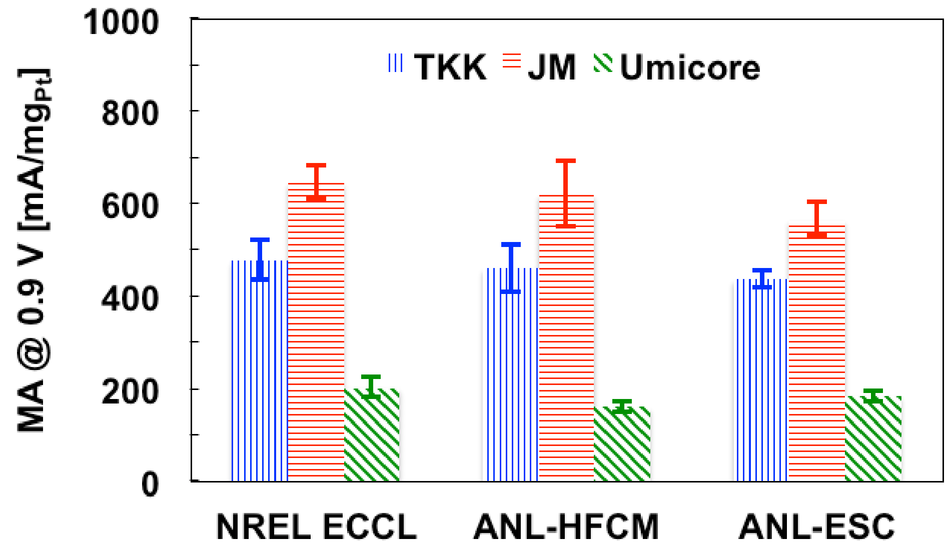
RAD (rotational air-dry)

SIPAD (stationary IPA dry)



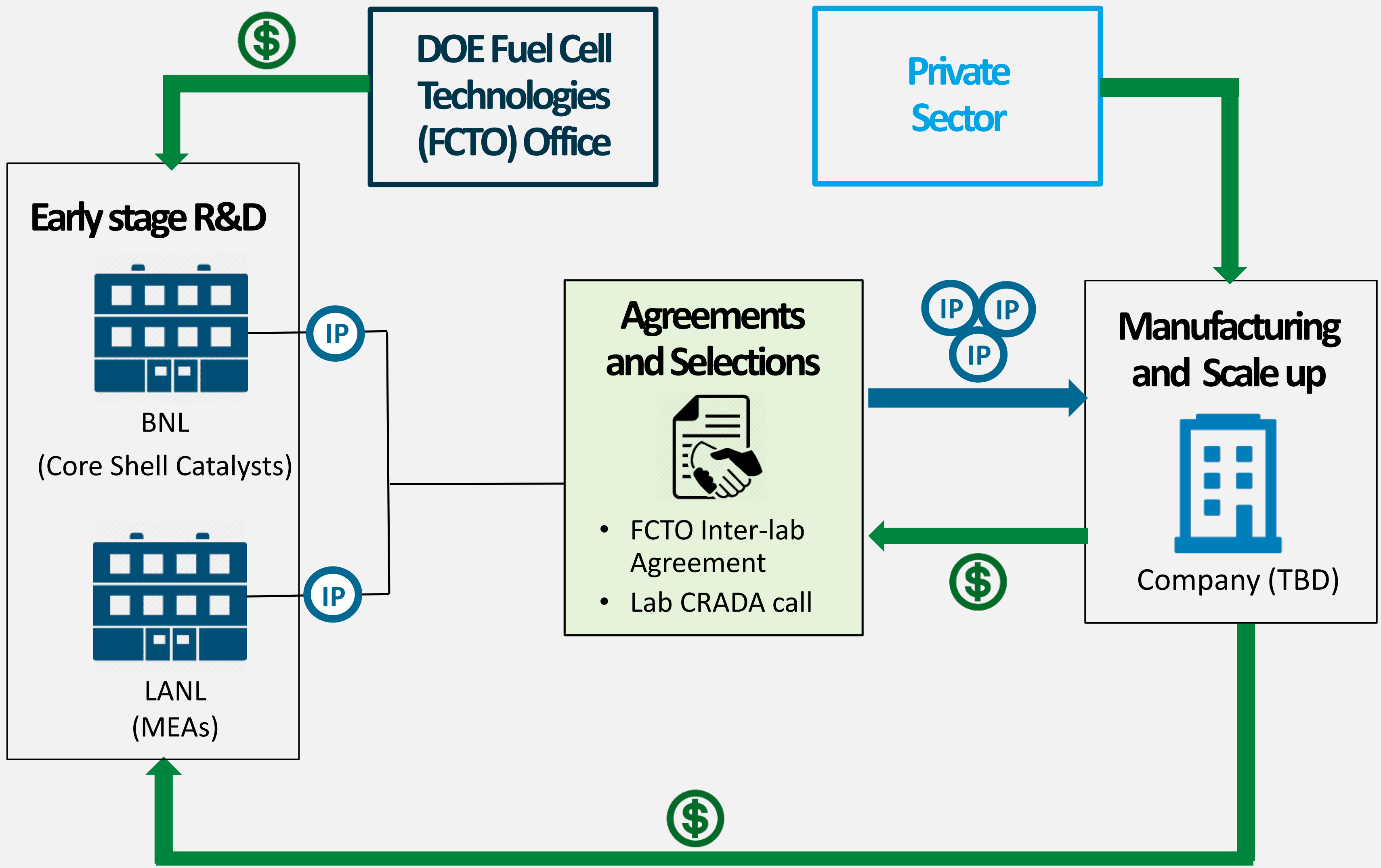
Nafion-based Rotational Air Drying (N-RAD) most reliable method for routine screening

Pt/C mass activity (mA/mg_{Pt}) inter-lab comparison (N-RAD technique)



Kocha, Shyam S., Kazuma Shinozaki, Jason W. Zack, Deborah J. Myers, Nancy N. Kariuki, Tammi Nowicki, Vojislav Stamenkovic, Yijin Kang, Dongguo Li, and Dimitrios Papageorgopoulos. *"Best Practices and Testing Protocols for Benchmarking ORR Activities of Fuel Cell Electrocatalysts Using Rotating Disk Electrode."* ***Electrocatalysis (2017): 1-9. doi:10.1007/s12678-017-0378-6***

L'Innovator Pilot Bundles BNL & LANL IP



Summary of Activities and Upcoming Events/Milestones

- **Applied early-stage R&D** addresses cost reduction, performance and durability enhancement of stack components including catalysts, membranes and MEAs
- **ElectroCat** established with core capabilities to expedite the development of PGM-free catalysts and electrodes.
- **FC-PAD** Consortium added industry/university partners to advance fuel cell performance and durability

Upcoming Events/Milestones

- **Tentative workshop:** Advanced computational modeling for catalyst R&D (ElectroCat)
- **Technical milestones:**
  - Demonstrate 20 mA cm^{-2} at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (4Q 2017)
  - Demonstrate 25 mA cm^{-2} at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (4Q 2018)

Bipolar Plates Workshop

- R&D Needs for Bipolar Plates for PEM Fuel Cell Technologies Workshop held on February 14, 2017, in Southfield, Michigan.
- Presentations, agenda, and summary of workshop available online https://energy.gov/eere/fuelcells/downloads/research-and-development-needs-bipolar-plates-pem-fuel-cell-technologies

Agenda for Bipolar Plates Workshop

USCAR – 1000 Town Center Drive, Suite 300 - Southfield, Michigan 48075

Feb. 14th 2017

8:00 – 8:30	Registration	
8:30 – 8:45	Opening Remarks and Workshop Overview	Bahman Habibzadeh - DOE
8:45 – 9:00	Bipolar Plate Cost and Issues at High Production Rate	Brian James - SA
9:00 – 9:15	GM Perspective on Bipolar Plate Status and Needs	Balsu Lakshmanan - GM
9:15 – 9:30	R&D for Automotive PEM Fuel Cell System – Bipolar Plates	Shinichi Hirano - Ford
9:30 – 9:45	BREAK	
9:45 – 10:00	Graphite-Based Bipolar Plates for PEM Motive Fuel Cell Applications	Julian Norley - GrafTech
10:00 – 10:15	Corrosion Resistant Coating of Metal Bipolar Plates for PEM Fuel Cells	CH Wang – TreadStone
10:15 – 11:45	BREAKOUT SESSION (Materials and Coatings)	
11:45 – 12:15	Recap	
12:15 – 1:15	LUNCH BREAK	
1:15 – 1:30	Modeling Performance and Stability of Bipolar Plates	Rajesh Ahluwalia - ANL
1:30 – 1:45	Bipolar Plate Durability Testing	Rod Borup - LANL
1:45 – 2:00	Forming and Manufacturing Issues in Automotive Bipolar Plate Production	Simon Farrington - AFCC
2:00 – 2:15	Approaches to Provide a Metallic Bipolar Plate Module to the Industry	Raimund Stroebel - Dana
2:15 – 2:30	BREAK	
2:30 – 4:00	BREAKOUT SESSIONS (Manufacturing and Modeling/Testing)	
4:00 – 4:30	Recap and Concluding Remarks	

Balance of Plant (BOP) Workshop

- FCTO and Office of Fossil Energy held a Balance of Plant Workshop on March 31, 2017, in Elyria, Ohio, in collaboration with the Ohio Fuel Cell Corridor as part of the Ohio Fuel Cell Symposium.
- Presentations, agenda, and summary of workshop available online https://energy.gov/eere/fuelcells/downloads/2017-ohio-fuel-cell-symposium-and-balance-plant-workshop

PARTNERS IN PROGRESS

2017 Ohio Fuel Cell Symposium

A Unique Collaborative Effort of all Fuel Cell Technologies Represented at One Event!

MARCH 30-31, 2017

John A. Spitzer Conference Center
Lorain County Community College
1005 N. Abbe Rd, Elyria, OH 44035

REGISTER AT www.fuelcellcorridor.com

MARCH 30th AGENDA

10:00 am—1:30 pm	OFCC Board of Directors Meeting (closed)
1:30 pm—2:30 pm	Set-up for Exhibitors and Supply Chain Exchange
2:30 pm—5:00 pm	Supply Chain Exchange (by invitation)
5:00 pm—8:00 pm	Networking Reception and Exhibit Hall Unveiling (Symposium attendees)

MARCH 31st AGENDA

The U.S. Dept. of Energy (DOE) Fuel Cell Technologies Office (FCTO) and the Office of Fossil Energy (FE), in collaboration with the Ohio Fuel Cell Coalition (OFCC), present a workshop on Fuel Cell Systems Balance of Plant (BOP) Components. This workshop will identify integrator needs and supply chain gaps for both Stationary and Transportation applications, as well as explore common ground for manufacturing and strengthening the supply chain.

TIME	TOPIC/PRESENTER
7:45 am—8:30 am	**Registration and Continental Breakfast**
8:30 am—8:45 am	**Symposium Opening Remarks and Meeting Objectives** — Pat Valente, OFCC **Introduction/Remarks** — Dr. Marcia Ballinger, President, Lorain County Comm. College
8:45 am—9:00 am	**Welcome and FCTO Fuel Cell Systems BoP Technology Perspective**— Dr. Sunita Satyapal, Director, Fuel Cell Technologies Office (FCTO)
9:00 am—9:15 am	**FE/NETL SOFC BoP Technology Perspective** — Regis Conrad, Fossil Energy
9:15 am—9:35 am	**Manufacturing Cost Analyses of Fuel Cell Systems for Stationary Applications** Vince Contini, Battelle
9:35 am—10:35 am 20 min. company intro 25 min. panel discussion 15 min. Q & A	**Panel 1—Integrator Needs/Supply Chain Gaps** (Solid Oxide, Molten Carbonate, Phosphoric Acid) Moderator: Dr. Jeffry Stevenson, Laboratory Fellow, Pacific Northwest National Lab Panelists: Cris DeBellis—LG Fuel Cell Systems, Randy Petri—FuelCell Energy, Benson Lee—Technology Management Inc., and Dr. Stelu Deaconu—Redox Power Systems
10:35 am—11:00 am	**Senator Sherrod Brown Video—then break between sessions**
11:00 am—11:45 am 15 min. company intro 15 min. panel discussion 15 min. Q & A	**Panel 2—PEM Integrator Needs/Supply Chain Gaps** Moderator: Dr. Nancy Garland, Fuel Cell Technologies Office (FCTO) Panelists: Tim Terrill—Plug Power, Peter Bach—Ballard, Harol Koyama—H2 PowerTech
11:45 am—12:15 pm	**NASA Glenn: Hydrogen Infrastructure and Power**—Ian Jakupca
12:15 pm—1:15 pm LUNCH	**Analysis of Supply Chain Opportunities for Fuel Cell Buses** Andrew Thomas (Cleveland State University) **Best Practices in Hydrogen Fueling and Maintenance Facilities for Transit Agencies**—Steve Sokolsky, CALSTART **Remarks** from the legislative office of Congresswoman Marcy Kaptur
1:15 pm—1:30 pm	**Fuel Cell Industries and Veteran Outreach**—Dr. Bruce Weigl (LCCC)
1:30 pm—2:30 pm 20 min. company intro 25 min. panel discussion 15 min. Q & A	**Panel 3—BOP Suppliers** Moderator: Dr. Rodger McKain, LG Fuel Cell Systems Panelists: William Whittenberger—Johnson Matthey, Paul Cassidy—AVL, Dr. Yuto Takagi —Saint-Gobain Innovative Materials, Kathy Heidebrecht—VAIREX Air Systems
2:30 pm—3:00 pm	**Wrap-up, survey, and conclusion of event**

Power Electronics Workshop Update

Power Electronics Workshop

- Organized by NIST, FCTO, AMO
- Goal of the workshop was to identify major power electronics needs for enabling large-scale deployment of fuel cell and water electrolyzer systems

NIST | Search NIST | NIST MENU

NIST - DOC High-Megawatt Converter Workshop

High-Megawatt - January 2007 - Converter Workshop

High-Megawatt - April 2008 - Power Converter Technology R&D Roadmap Workshop

High Megawatt - March 2009 - Workshop on Future Large CO2 Compression Systems

High Megawatt - December 2009 Workshop on Challenges to Growth of Grid Connected Electronics

High Megawatt - June 2011 Workshop on Challenges to Growth of Grid Connected

2016 Workshop on Next Generation Power Electronics for Enabling Large-Scale Deployment of Hydrogen and Fuel Cell Technologies

NIST, Gaithersburg, MD

Page will be updated frequently

(December 19, 2016)

Proceedings Summary

Agenda

Goals

Key Questions

Presentations

Overview of DOE Fuel Cell (FC), Water Electrolyzer (WE), and Wide-Bandgap (WBG) Power Electronics Programs

1. Allen Hefner
2. Reuben Sarkar
3. Mark Ruth

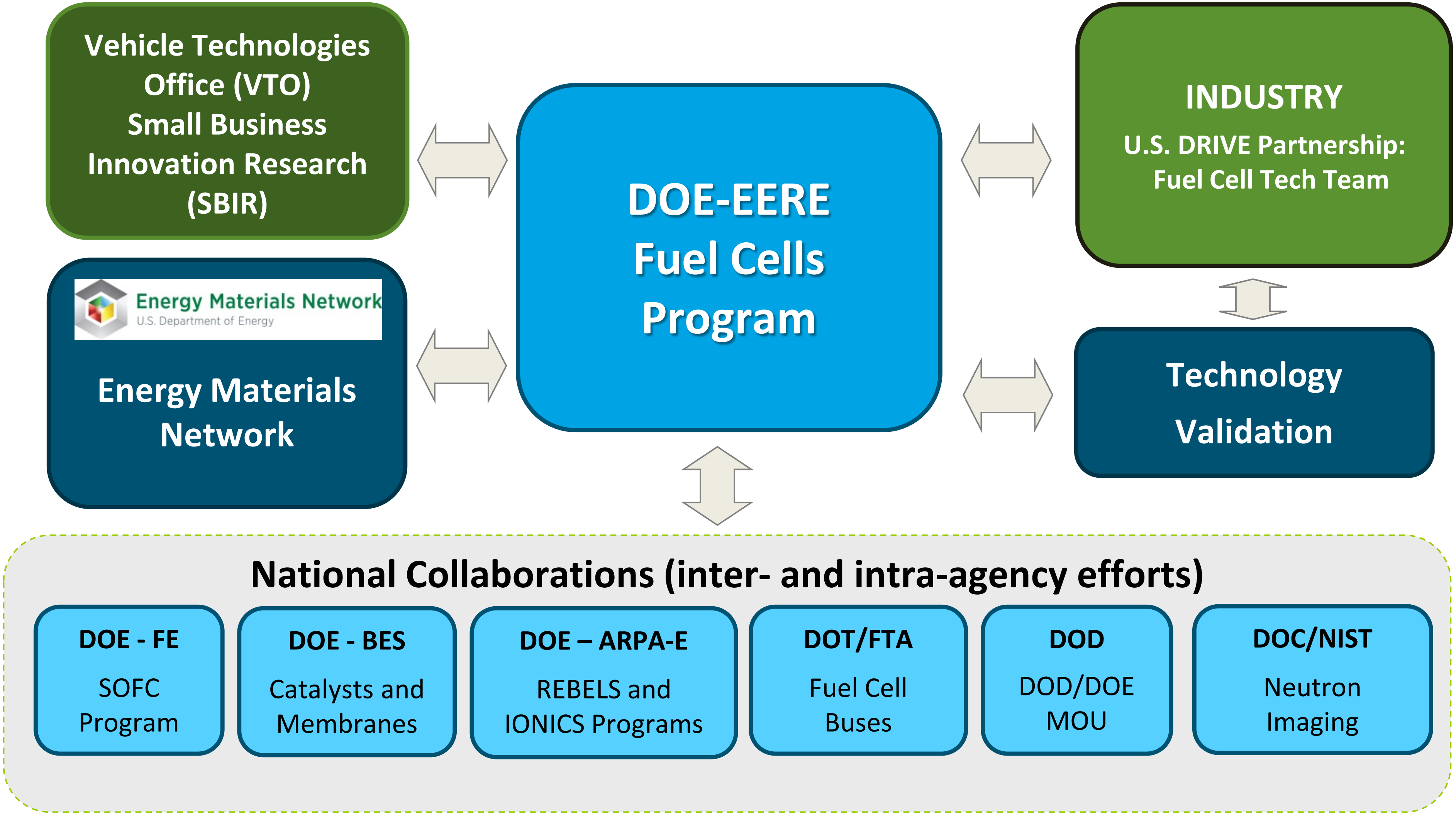
Panel 1: Fuel Cell Systems Requirements – Dimitrios Papageorgopoulos

1. Ralph Teichmann
2. David Reale
3. Randy Petri
4. 30-minute discussion period

Panel 2: Water Electrolysis (WE) Systems Requirements – David Peterson

1. Kevin Harrison
2. Monjid Hamdan

Collaborations



Applied R&D is coordinated among a range of organizations

Fuel Cells Program Contacts

Dimitrios Papageorgopoulos
Fuel Cells Program Manager
202-586-5463
dimitrios.papageorgopoulos@ee.doe.gov

Donna Lee Ho
202-586-8000
donna.ho@ee.doe.gov

Nancy Garland
202-586-5673
nancy.garland@ee.doe.gov

Greg Kleen
720-356-1672
greg.kleen@ee.doe.gov

Adria Wilson
202-586-5782
adria.wilson@ee.doe.gov

David Peterson
720-356-1747
david.peterson@ee.doe.gov

Simon Thompson (Fellow)
202-586-1758
simon.thompson@ee.doe.gov

John Kopasz and Tom Benjamin
(Argonne National Laboratory)
Shaun Onorato and Chris Werth)
(Allegheny Science & Technology)
Eric Parker (Keylogic)
Bahman Habibzadeh (on detail from BTO)

http://energy.gov/eere/fuelcells/fuel-cell-technologies-office