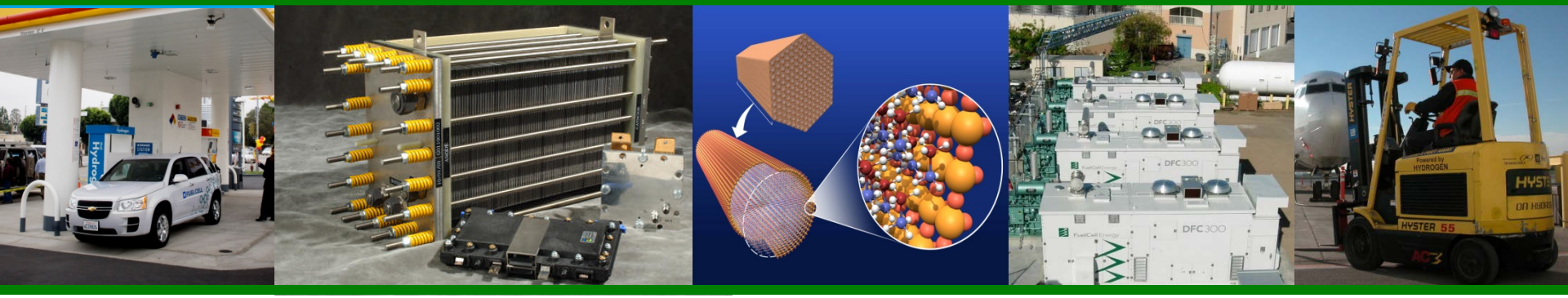
U.S. DEPARTMENT OF ENERGY



Fuel Cells

Dimitrios Papageorgopoulos

2013 Annual Merit Review and Peer Evaluation Meeting
May 13, 2013

Goals and Objectives

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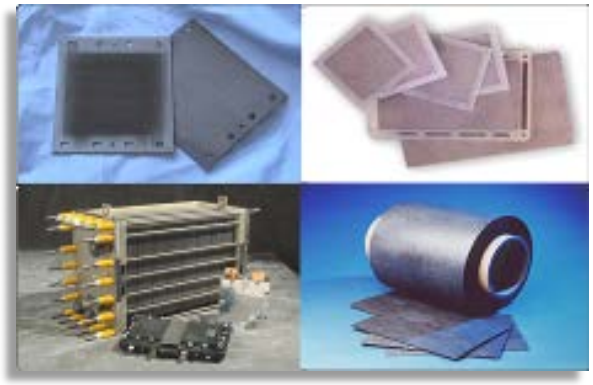
GOAL: Develop and demonstrate fuel cell power system technologies for stationary, portable, and transportation applications

Objectives

- By 2017, a 60% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation at a cost of $30/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.
- By 2020, APU fuel cell systems (1–10 kW) with a specific power of 45 W/kg and a power density of 40 W/L at a cost of $1000/kW.
- Other specific objectives are in the Fuel Cell MYRD&D Plan.



Challenges & Strategy

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The Fuel Cells program supports research and development of fuel cells and fuel cell systems with a primary focus on reducing cost and improving durability. Efforts are balanced to achieve a comprehensive approach to fuel cells for near-, mid-, and longer-term applications.

Fuel Cell MYRD&D Plan **:**
http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

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
Electrolytes
MEAs, Gas diffusion media, and Cells
Seals, Bipolar plates, and Interconnects

Operation and Performance
Mass transport
Durability
Impurities

Systems and Balance of Plant (BOP)
BOP components
Fuel processors
Stationary power
Portable power
APUs and Emerging markets

R&D portfolio is technology-neutral and includes different types of fuel cells.

High-Impact Areas Addressed – PEMFCs for Automotive Applications

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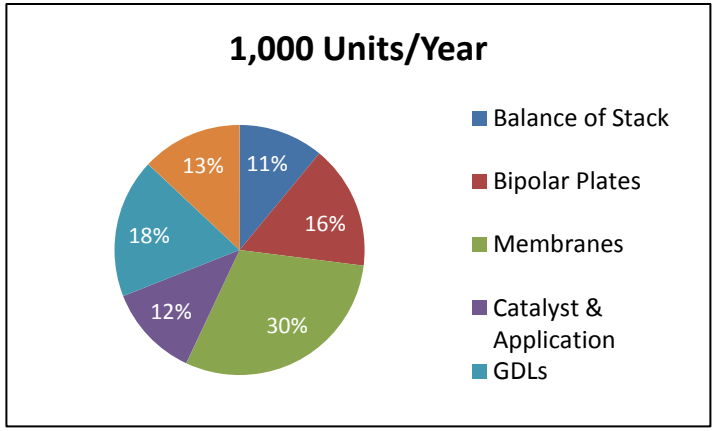
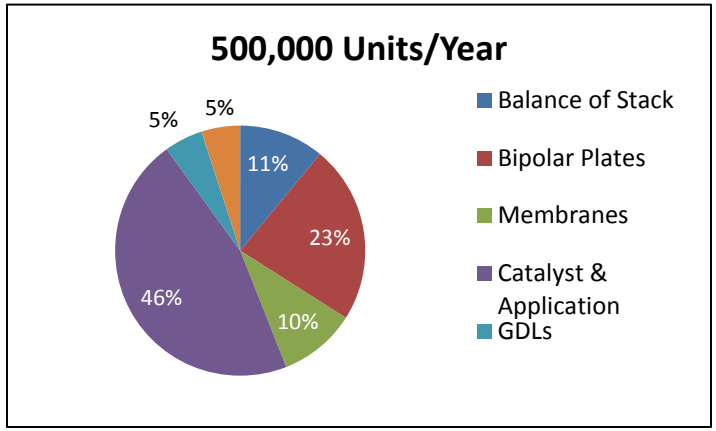
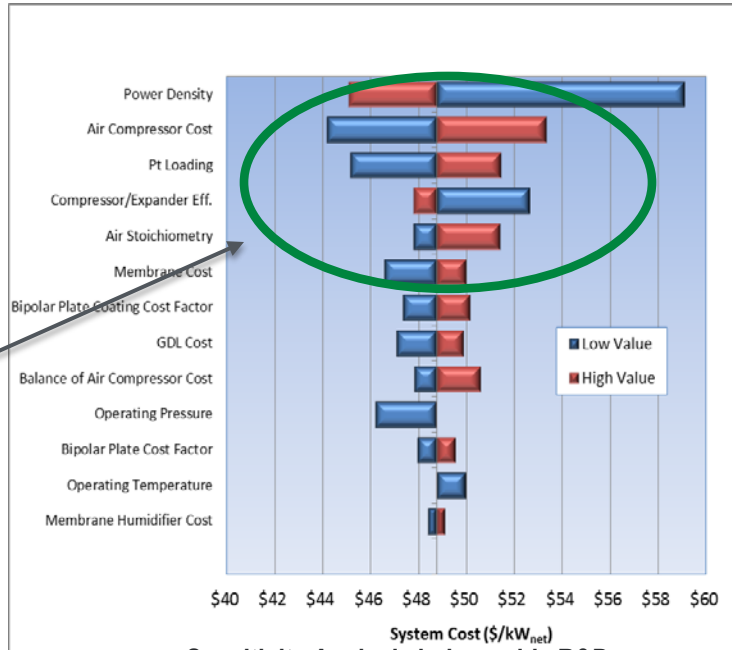
- Strategic technical analysis guides focus areas for R&D and priorities.
- Need to reduce cost to $30/kW and increase durability from 2,500 to 5,000 hours.
- Advances in PEMFC materials and components could benefit a range of applications

PEMFC Stack Cost Breakdown





Key Focus Areas for R&D



Sensitivity Analysis helps guide R&D

Membrane cost is projected to be the largest single component of the cost of a PEMFC manufactured at low volume; the electrocatalyst cost at high volume

Strategies to Address Challenges – Catalyst Examples

- Lower PGM Content
- Pt Alloys
- Novel Support Structures
- Non-PGM catalysts

High-Impact Areas Addressed – Fuel Cell Durability

U.S. DEPARTMENT OF ENERGY

Durability is a major barrier to fuel cell commercialization. The Program emphasizes the identification of degradation mechanisms and approaches for mitigating the effects.

System/stack durability assessment

Data from OEMs aggregated and reported as a composite data product at NREL

NREL's Hydrogen Secure Data Center

Market-driven targets set for a range of applications

System	Property	Status	Target
80-kW_e Automotive	Operating lifetime	2,500 h	5,000 h
Bus	Power plant lifetime	12,000 h	25,000 h
1–10 kW_e micro-CHP	Degradation rate	<2%/1000 h	0.3%/1000 h
1–10 kW_e micro-CHP	Operating lifetime	12,000 h	60,000 h
100 kW–3 MW CHP	Operating lifetime	40,000–80,000 h	80,000 h
Portable Power (<2 W)	Operating lifetime	1500 h	5000 h
Portable Power (10–50 W)	Operating lifetime	1500 h	5000 h
Portable Power (100–250 W)	Operating lifetime	2000 h	5000 h
APU (1 to 10 kW_e)	Degradation rate	2.6%/1000 h (2010)	1%/1000 h
APU (1 to 10 kW_e)	Operating lifetime	3000 h (2010)	20,000 h

FCT Durability Working Group

Meets twice a year to exchange information, create synergies, and collaboratively develop both an understanding of and tools for studying fuel cell degradation. Its members include PIs and supporting personnel from DOE-funded durability projects.

Impurities

The effects of air impurities and system contaminants, on durability are also investigated and quantified, with efforts leading to the development of mitigation strategies

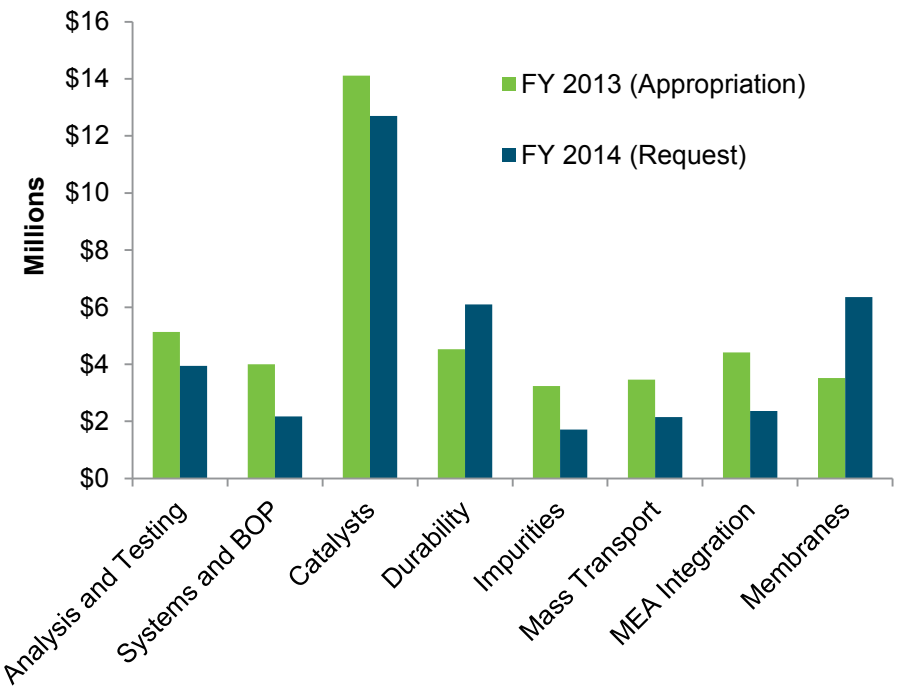
Fuel Cell R&D - Plans

U.S. DEPARTMENT OF ENERGY

Maintains critical fuel cell R&D to improve the durability, reduce cost, and improve the performance of fuel cell systems for stationary, transportation, and portable power. Key goal: Increase PEM fuel cell power output per gram of PGM catalyst from 2.8 kW/g (in 2008) to 8.0 kW/g by 2017.

FY 2013 Appropriation = $42.4M

FY 2014 Request = $37.5M



*Subject to appropriations, project go/no go decisions and competitive selections. Exact amounts will be determined based on R&D progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements (FOAs).

EMPHASIS

- Focus on approaches that will increase activity and utilization of current PGM and PGM-alloy catalysts, as well as non-PGM catalyst approaches for long-term applications.
- Develop ion-exchange membrane electrolytes with enhanced performance and stability at reduced cost.
- Improve PEM-MEAs through integration of state-of-the-art MEA components.
- Develop transport models and in-situ and ex-situ experiments to provide data for model validation.
- Identify degradation mechanisms and develop approaches to mitigate their effects.
- Maintain core activities on components, sub-systems and systems specifically tailored for stationary and portable power applications (e.g. SOFC).

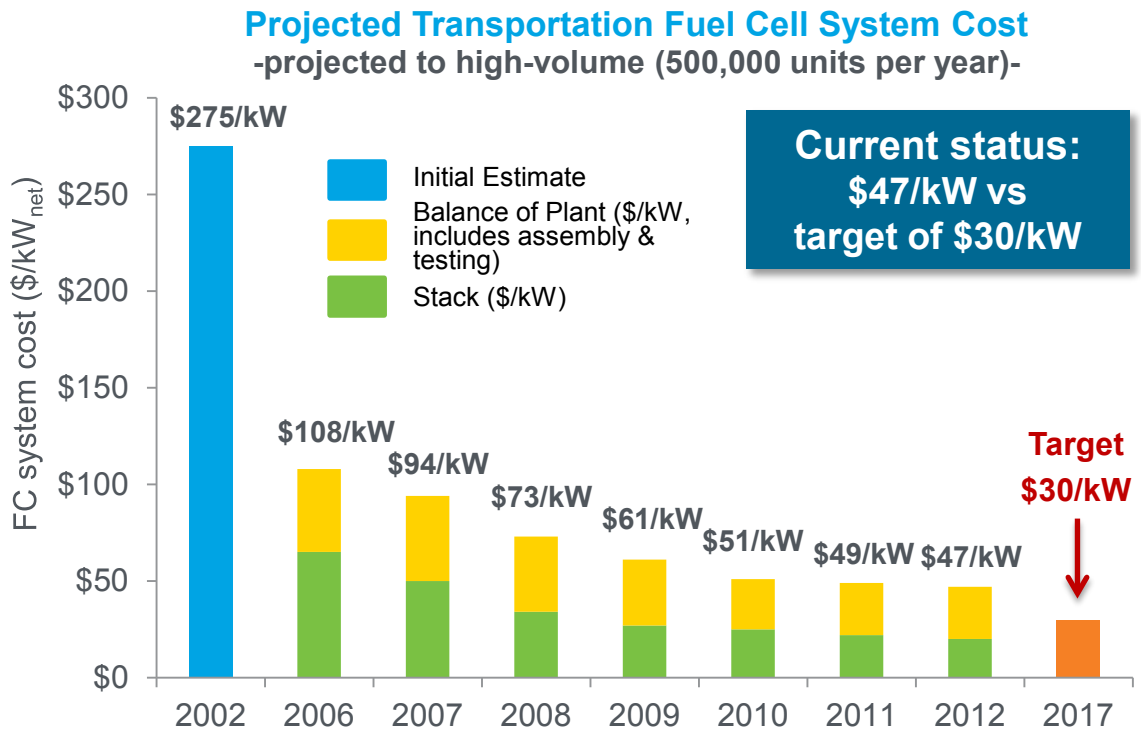
Progress – Fuel Cell R&D

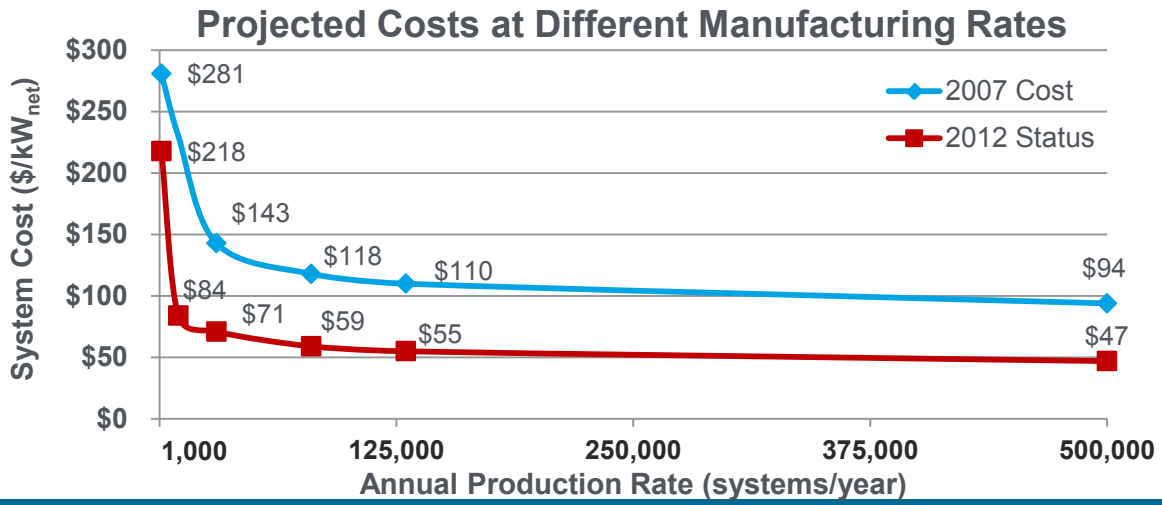
U.S. DEPARTMENT OF ENERGY

Projected high-volume cost of fuel cells has been reduced to $47/kW (2012)*

- ***More than 35% reduction since 2008***
- ***More than 80% reduction since 2002***

***Based on projection to high-volume manufacturing (500,000 units/year).** The projected cost status is based on an analysis of state-of-the-art components that have been developed and demonstrated through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.*



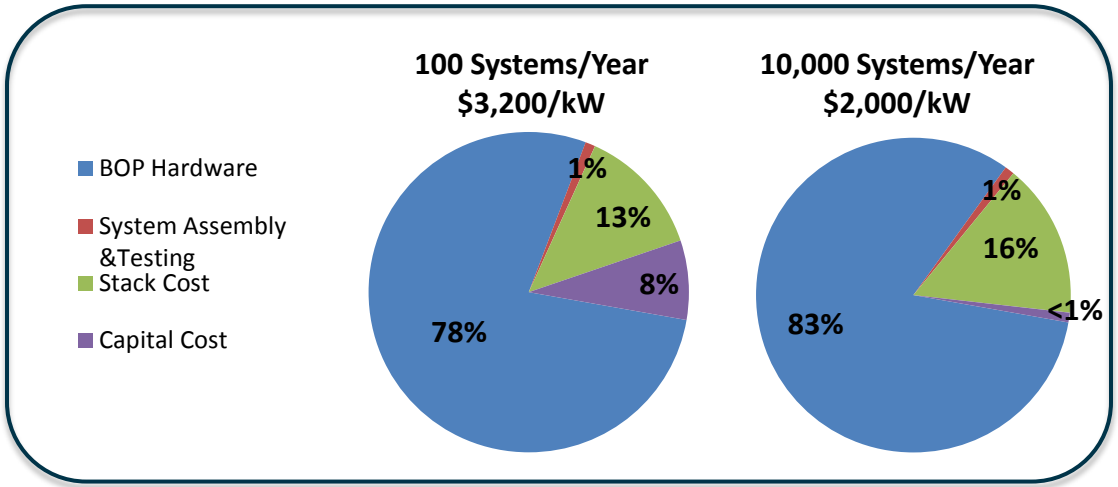


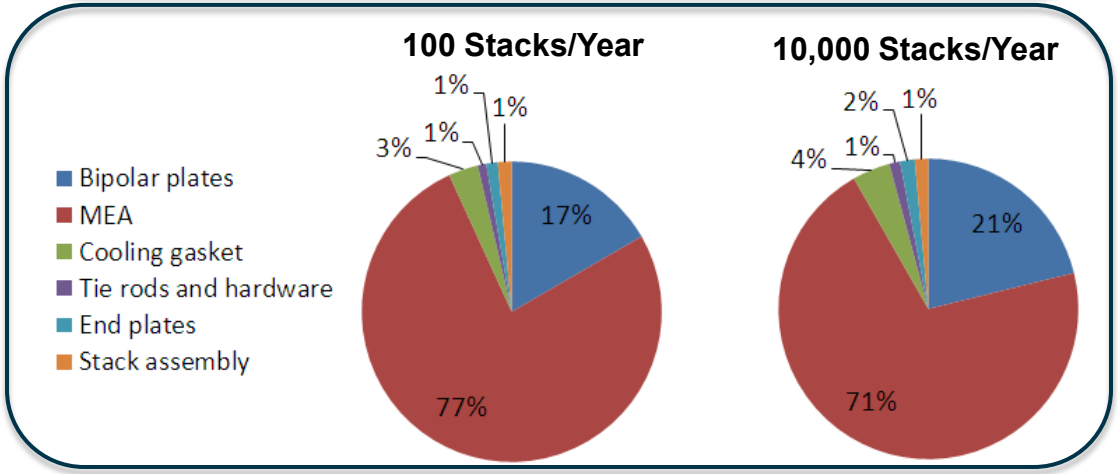
Progress: Emerging Market Cost Analysis

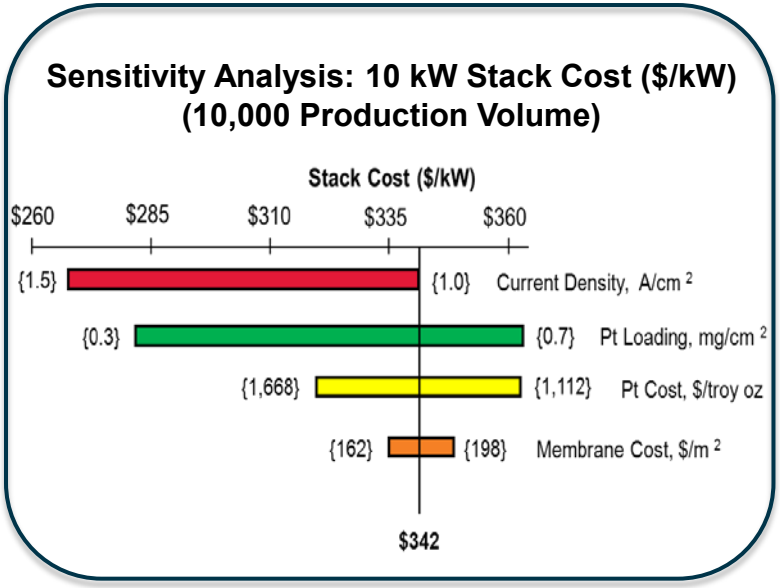
U.S. DEPARTMENT OF ENERGY

Cost analyses in development for material handling applications

10 kW material handling systems







- MHE systems @ 10 and 25 kW
- Annual volume of 100; 1,000; and 10,000 systems
- Modeling using DFMA® software based on Battelle internal knowledge and discussion with industry partners
- Future year analysis will examine 1 and 5 kW systems

Mahadevan et al., Battelle

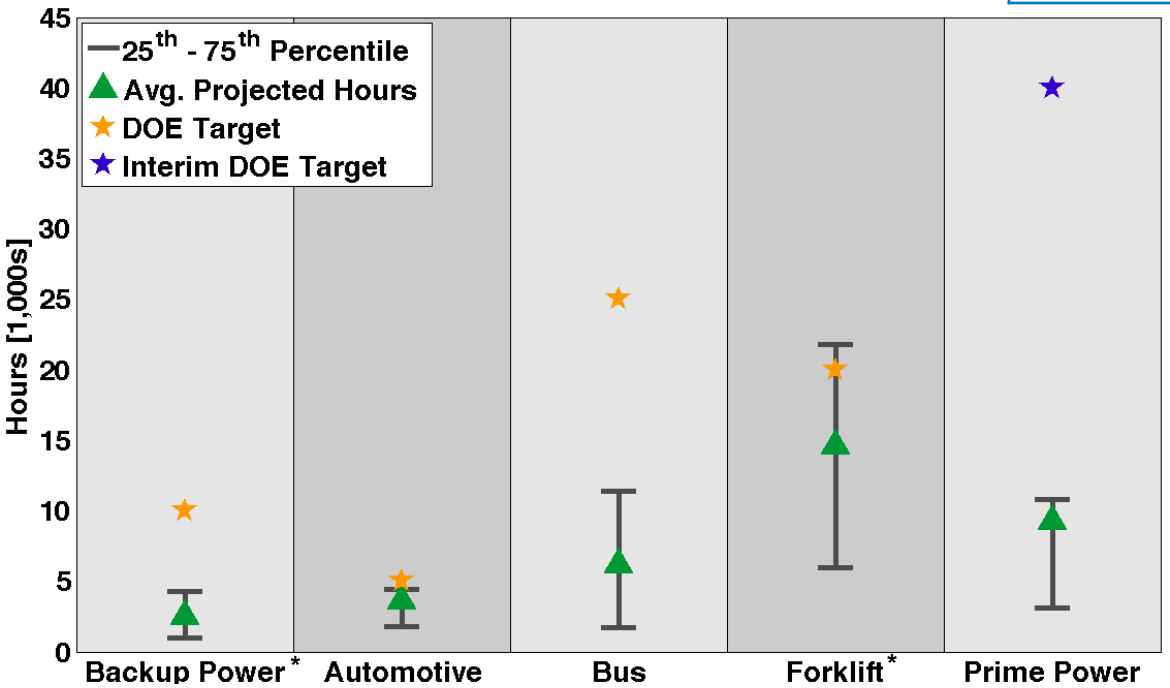
Progress – Durability Assessment

U.S. DEPARTMENT OF ENERGY

Aggregated results provide a benchmark in time of state-of-the-art fuel cell durability.

NREL is analyzing and aggregating durability results by application, providing a benchmark of state-of-the-art fuel cell durability (time to 10% voltage degradation). Results include 98 data sets from 15 fuel cell developers.

Application	Avg Projected Time to 10% Voltage Drop	Avg Operation Hours
Backup Power	2,500	1,100
Automotive	3,600	2,200
Bus	6,200	3,800
Forklift	14,600	4,400
Prime Power	9,300	5,600



J. Kurtz, et al., NREL

** DOE Targets Under Review*

PEMFC, DMFC, & SOFC data from lab-tested, full active area short stacks and systems with full stacks. Data generated from constant load, transient load, and accelerated testing.

Please send inquires to Fuelcelldatacenter@ee.doe.gov

Progress: De-alloyed Catalysts

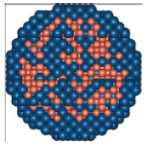
U.S. DEPARTMENT OF ENERGY

Low-PGM de-alloyed catalysts meet mass activity and durability targets

M is one or more non-precious metals

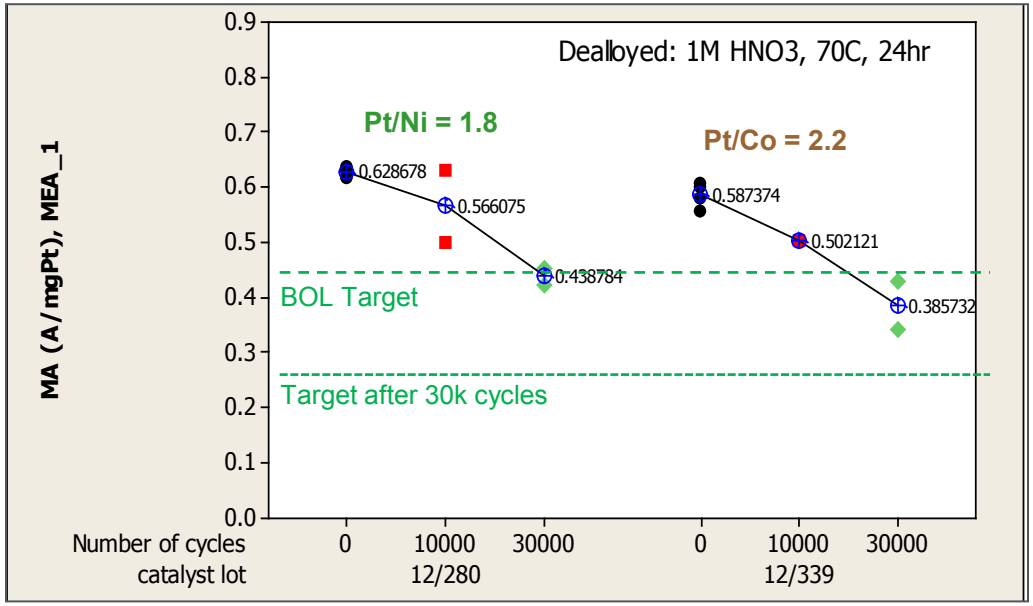
precursor dealloying catalyst

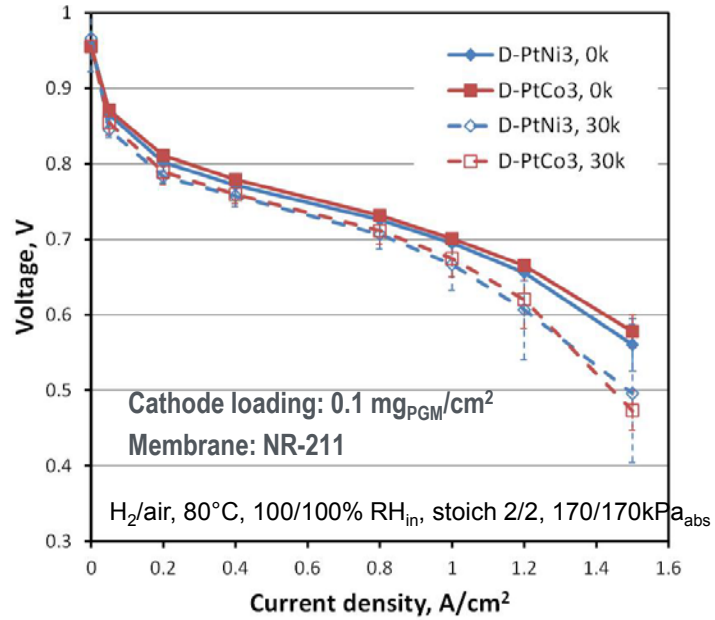
PtM_3/C ----------> $Pt_{1.5\text{-}3}M/C$



Cross section, Pt in blue

Lattice compression of surface Pt layer





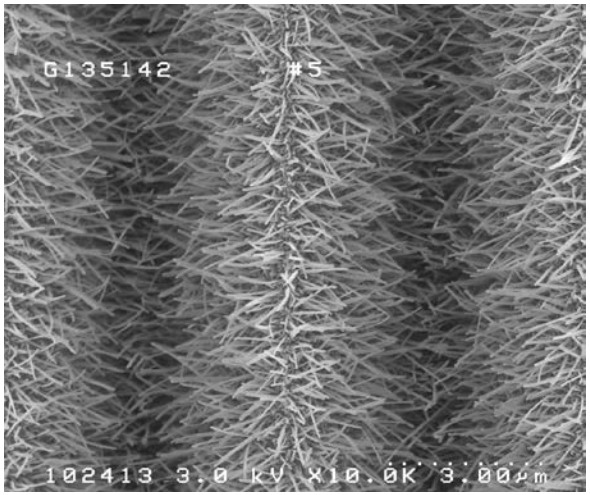
- Dealloying of $PtNi_3$ and $PtCo_3$ large-batch precursors yields catalysts that meet initial mass activity and mass activity after voltage cycling targets
- Catalysts based on $PtNi_3$ and $PtCo_3$ have also achieved 0.56 V @ 1.5 A/cm^2 milestone
- Further work needed to maintain performance at 1.5 A/cm^2 after voltage cycling

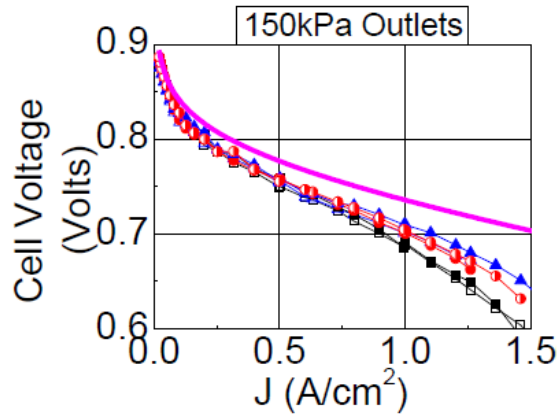
A. Kongkanand et al., GM

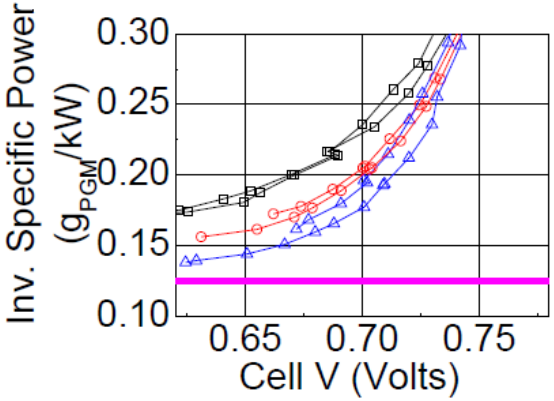
Progress: MEA Integration

U.S. DEPARTMENT OF ENERGY

Improved MEA and flowfield led to record low g_{PGM}/kW



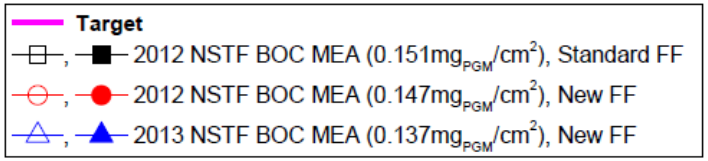




Improvements in MEA and flowfield allowed reduction from 0.20 g_{PGM}/kW in 2012 to 0.16 g_{PGM}/kW in 2013

Status vs. targets:

- PGM loading: 0.16 g_{PGM}/kW (target: 0.125 g/kW)
- Mass activity: 0.40-0.48 A/mg (target: 0.44 A/mg)
- Durability w/ cycling: 66% MA loss (target: <40%)

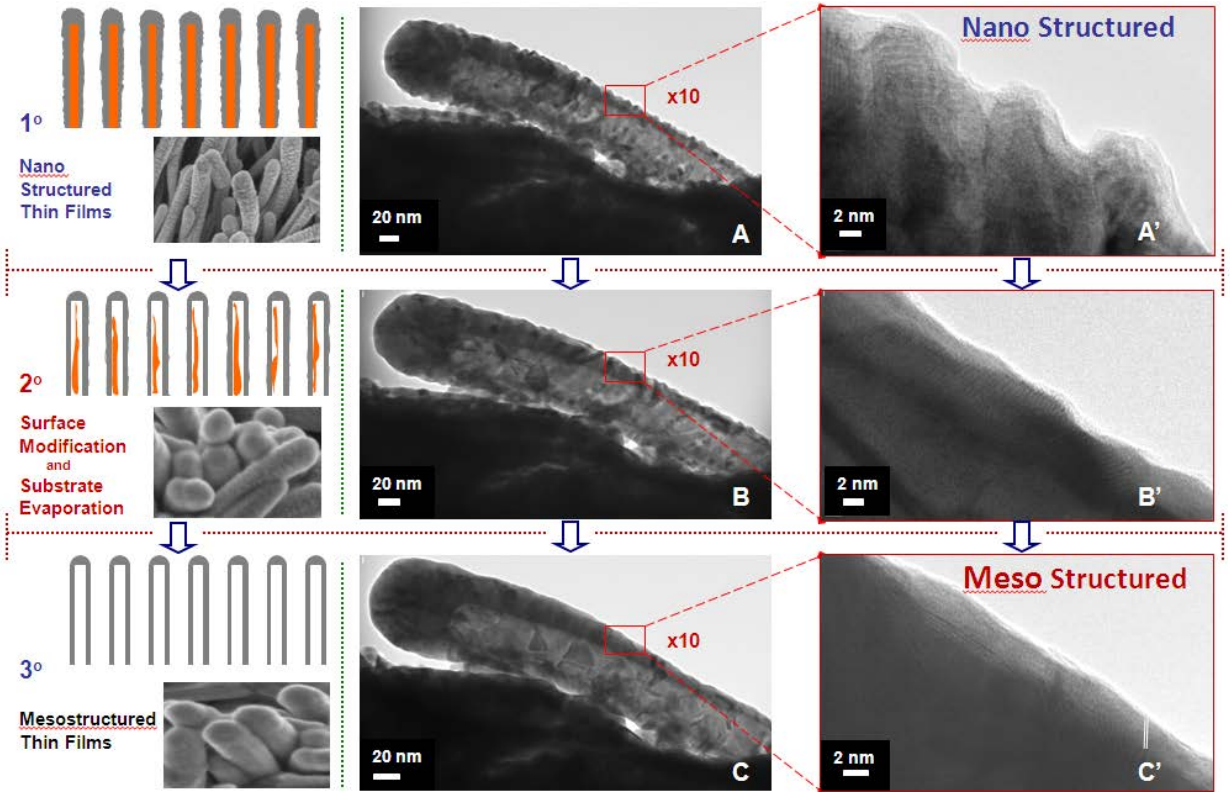


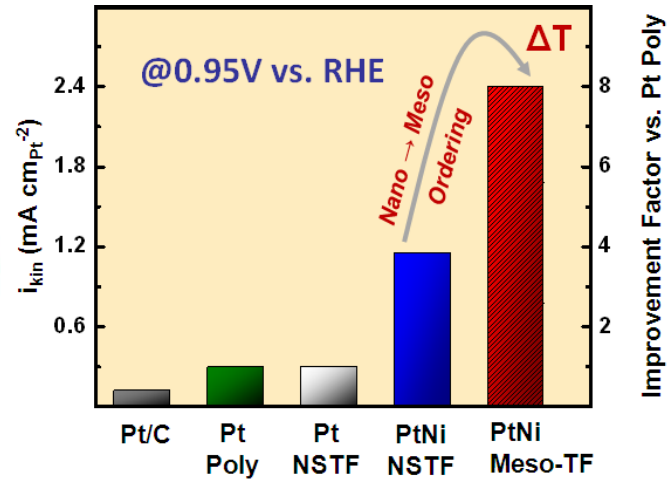
A. Steinbach et al., 3M

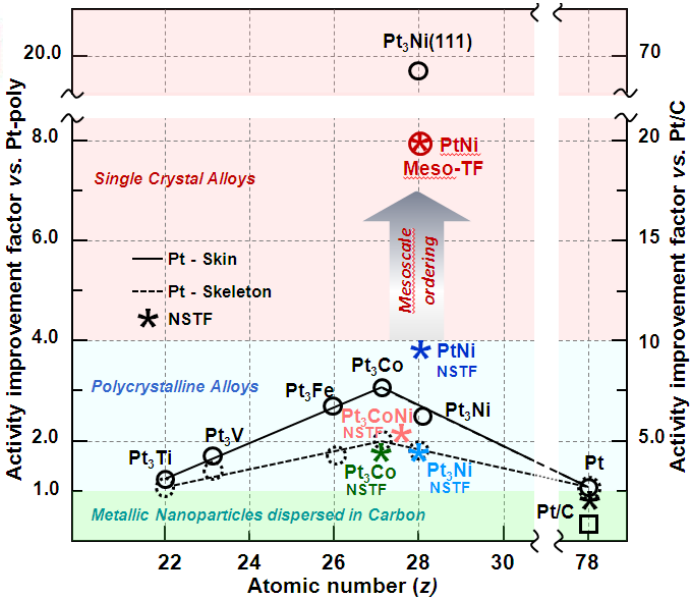
Progress: Mesostructured Thin Films

U.S. DEPARTMENT OF ENERGY

Surface modification and substrate evaporation of NSTF yields mesostructured surface with superior ORR activity







2X increase in specific activity vs. PtNi NSTF and 8x vs. Pt-poly realized through surface modification in which grains coalesce to form surfaces with single crystalline properties

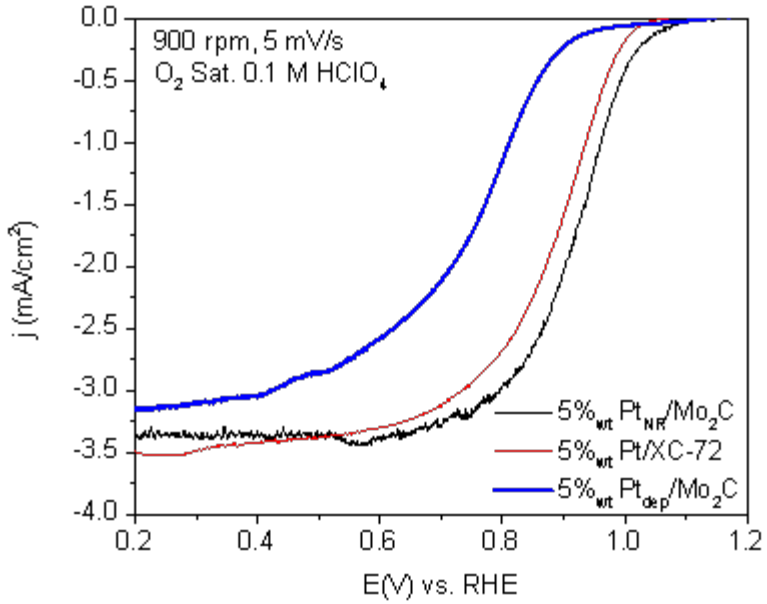
N. Markovic/V. Stamenkovic et al., ANL

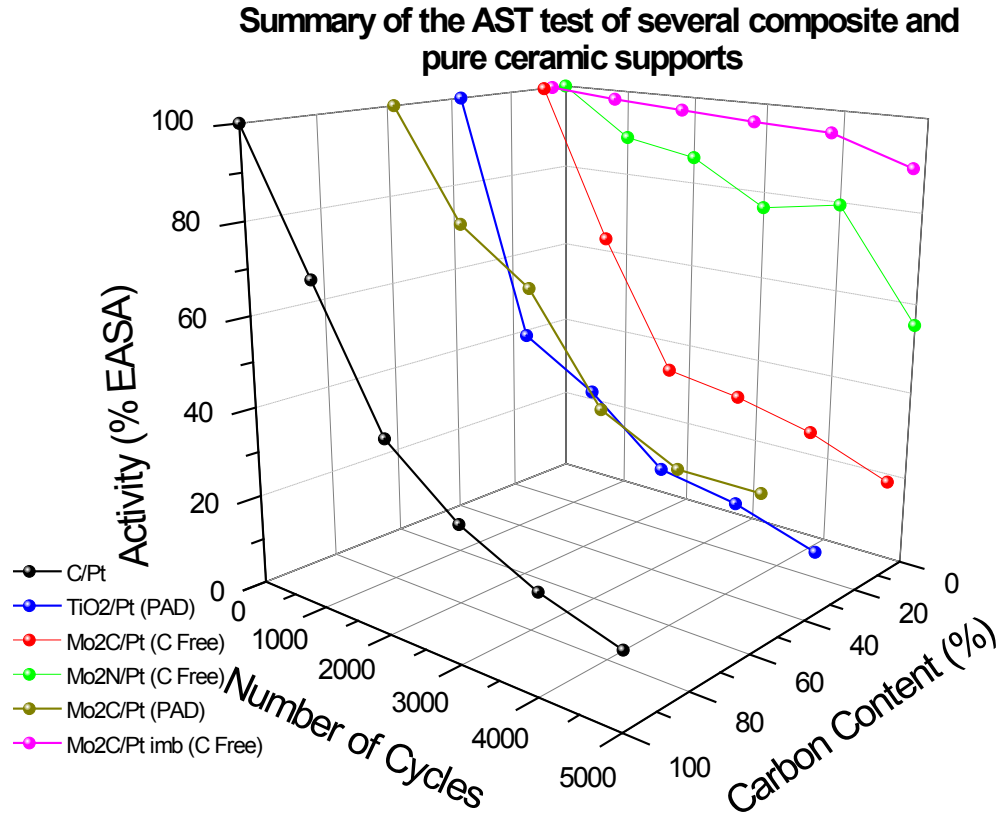
Nature Materials 11 (2012) 1051

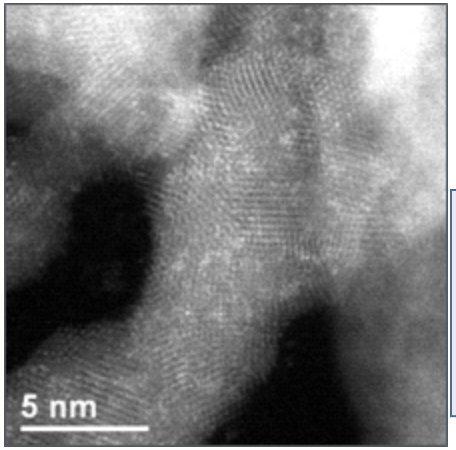
Progress: Alternative Catalyst Supports

U.S. DEPARTMENT OF ENERGY

Pt on Mo_2C shows higher performance and durability than Pt/C in ex situ testing







- Pt is homogeneously dispersed on the Mo_2C crystallite surfaces as single atoms and as 3-6 atom clusters/rafts, not as Pt nanoparticles
- RDE mass activity is 0.29 A/mg_{Pt} for Pt/Mo_2C, vs. 0.19 A/mg_{Pt} for Pt/XC-72
- Pt/Mo_2C retains > 90% of ECSA during LANL AST, vs. <10% for Pt/XC-72

E. Brosha et al., LANL

Progress: Low-cost Membrane Supports

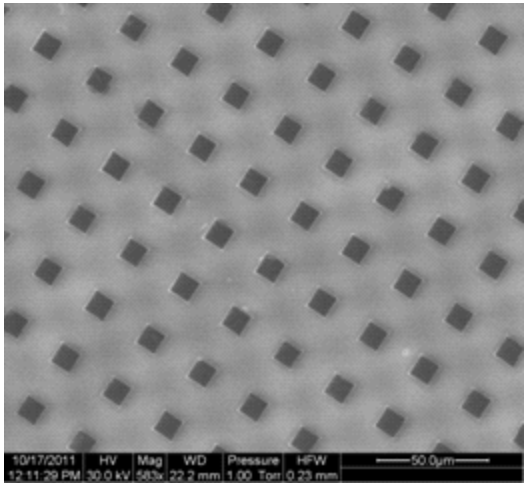
U.S. DEPARTMENT OF ENERGY

SBIR Phase III Xlerator program develops roll-to-roll compatible support manufacturing

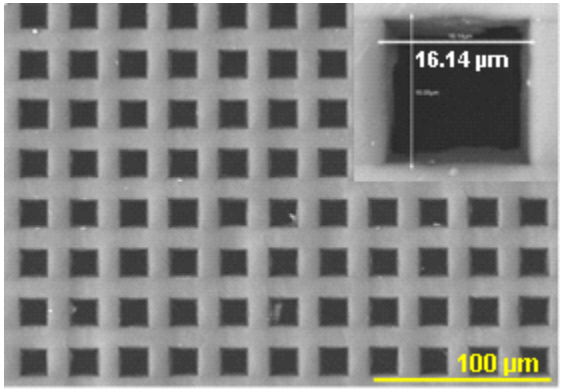
- Goal: reduce support cost while maintaining performance
- Mechanical deformation manufacturing technique is the primary focus
- Current porosity on an 8 μm thick film is 35%, up from last year's 15% (target porosity: 50%)
- Current cost is $50/m^2, but could be reduced through roll-to-roll processing (cost target $20/m^2 for complete membrane, including ionomer and support)

Mechanical Deformation

1/2012, ~15% porosity

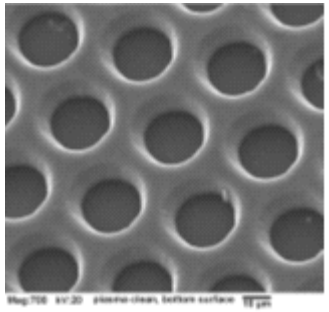


8/2012, ~35% porosity



Laser-drilled prototype

- **Developed in earlier EERE-funded project**
- **High performance, but too expensive**

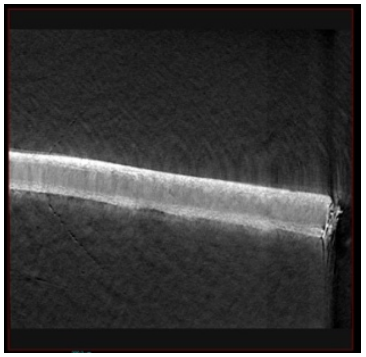


C. Mittelsteadt et al., Giner

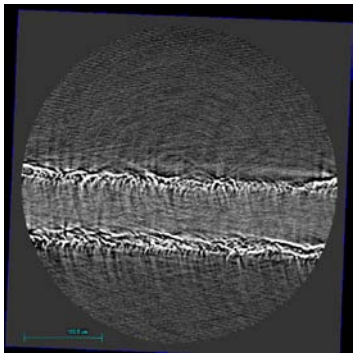
Progress: Degradation Studies

U.S. DEPARTMENT OF ENERGY

Degradation mechanisms revealed using advanced characterization techniques



Fresh

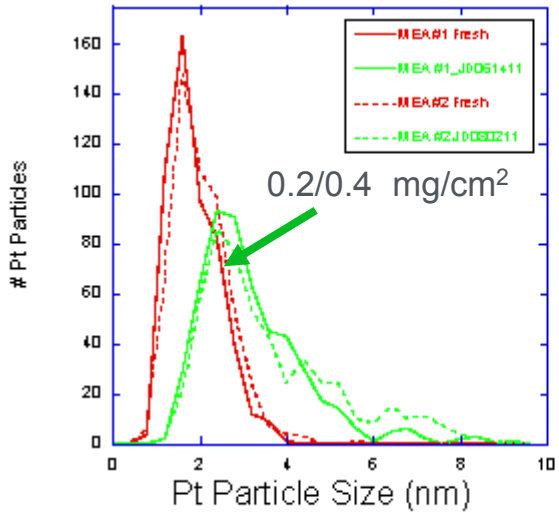


Aged ~ 2000 hours

3-D tomography shows MEA electrodes and interfaces are roughened from operation

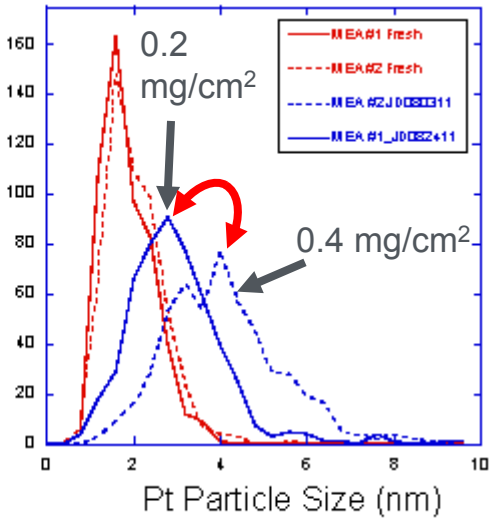
Catalyst Cycling AST

Before/after 30,000 cycles 0.6-1.0V

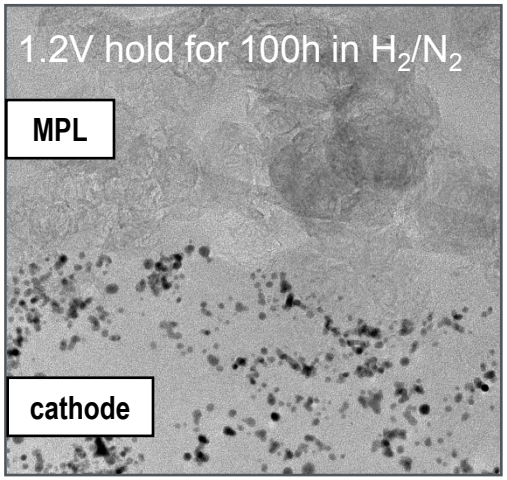


Catalyst Support AST

Before/After 1.2V Hold



High catalyst loading accelerates agglomeration during carbon corrosion, but does not affect Pt dissolution/re-precipitation



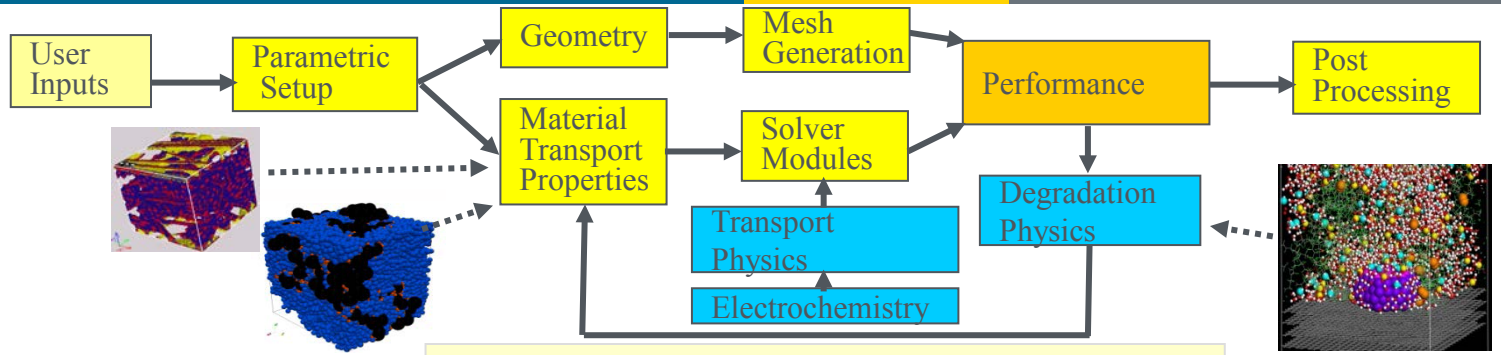
Interface between Pt/High Surface Area Carbon (HSAC) cathode and MPL is distinct – MPL carbon retains its meso-graphitic structure and porous network (even adjacent to the cathode surface) whereas the HSAC directly at the interface is fully oxidized

R. Borup et al., LANL

Progress: Performance/Durability Modeling

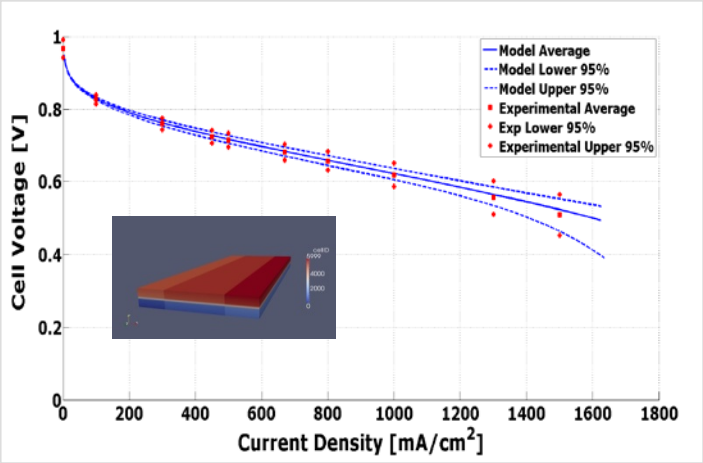
U.S. DEPARTMENT OF ENERGY

Open-source FC-PEM performance and durability model developed to address micro-structural mitigation strategies for PEMFCs



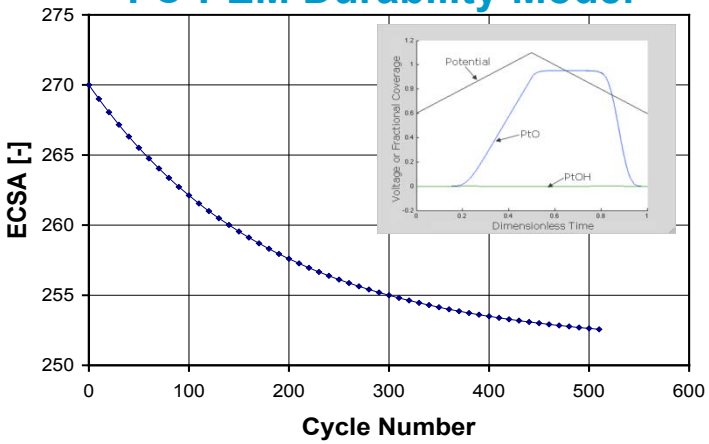
Open-source FC-PEM Package

FC-PEM Performance Model



- Modifiable material properties, geometries, and operational conditions (i.e. loading, ionomer content, thickness, T, RH, etc.)

FC-PEM Durability Model



- Platinum dissolution process coupled to improved Pt oxide model (Air/Nitrogen)
- Carbon oxidation and corrosion using surface oxidation and corrosion steps

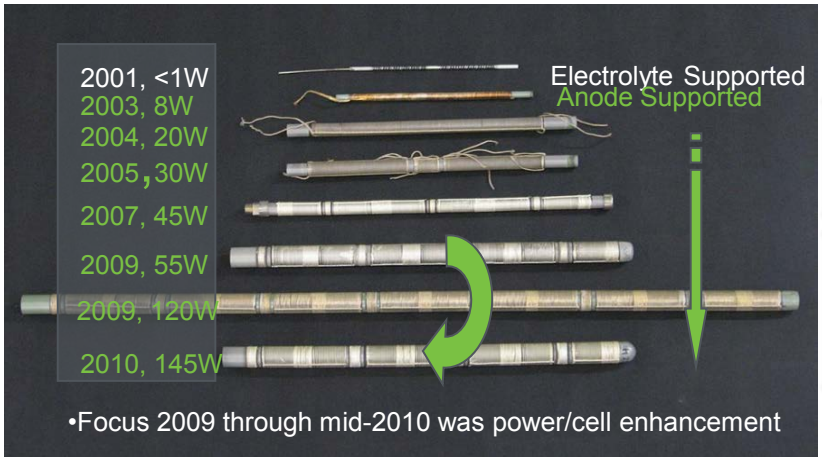
S. Wessel et al., Ballard

Progress: Stationary SOFCs

U.S. DEPARTMENT OF ENERGY

Enhanced performance and reduced cost via advances in cell technology, manufacturing operations, and in system design and product development

- Tubular cell technology advances under DOE-funded project at Acumentrics led to progress in stack size and weight reduction.
- Since 2004:
  - Number of tubes reduced by 64%
  - Weight reduced 75%
  - Volume reduced 82%
  - System cost reduced by 5X

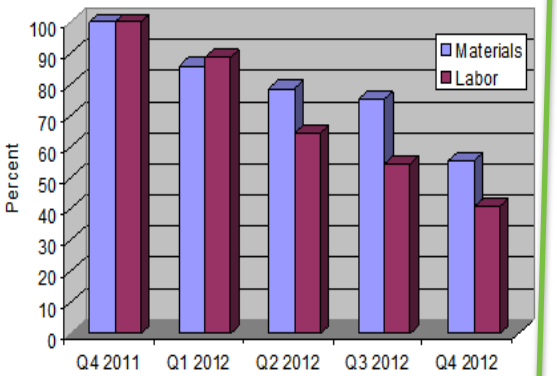


FE/SECA funded project

EERE funded project

Manufacturing cost reduction strategy

- Reduced part count
- Combined steps
- Deployed automation
- Moved to more cost effective materials
- Simplified fabrication



N. Bessette et al., Acumentrics

Systems have accumulated:

- >300,000 hours of operation
- System Availabilities of > 97%

Much of the 'down-time' is actually other system BOP components, with interruption of the fuel supply being the single biggest contributor.

New Fuel Cell Projects

U.S. DEPARTMENT OF ENERGY

5 new fuel cell R&D projects initiated in FY 2012 and FY 2013

High Performance, Durable, Low Cost MEAs for Transportation Applications

3M Company, with General Motors Company, Michigan Technological University, LBNL

Roots Air Management System with Integrated Expander

Eaton Corporation, with Ballard Power Systems, Kettering University, Electricore Inc.

Rationally Designed Catalyst Layers for PEMFC Performance

ANL, with United Technologies Research Center, Johnson Matthey Fuel Cells, Purdue University, University of Texas at Austin

Non-Precious Metal Fuel Cell Cathodes: Catalyst Development and Electrode Structure Design

LANL, with General Motors Company, IRD Fuel Cells, Carnegie Mellon University, University of Waterloo, University of Rochester, ORNL

Advanced Ionomers and MEAs for Alkaline Membrane Fuel Cells

NREL, with 3M Company, Colorado School of Mines, CellEra

2013 Requests For Information

U.S. DEPARTMENT OF ENERGY

Released 2/1/2013

Cost and durability targets for fuel cells designed for automotive applications; comments from stakeholders requested.

The proposed targets included in this RFI were developed with input from the U.S. DRIVE Partnership, specifically the Fuel Cell Technical Team

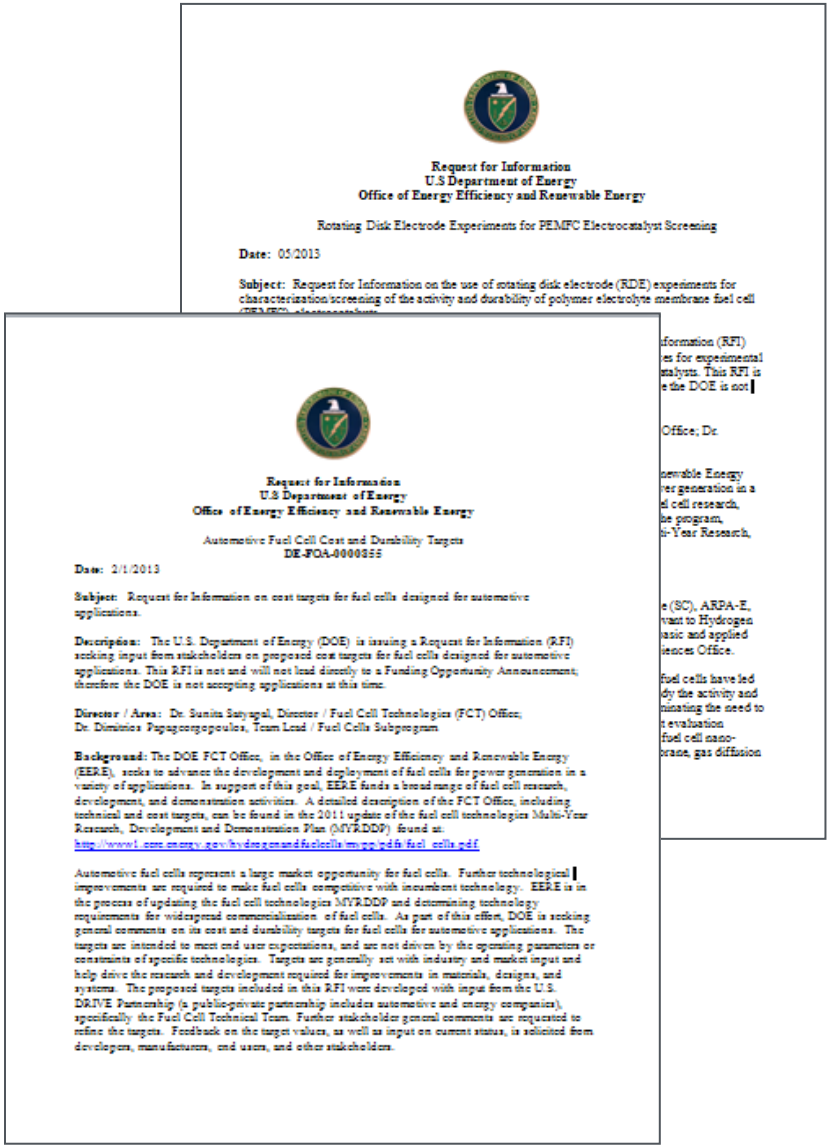
Questions and RFI responses may be addressed to FCcosttargets@go.doe.gov

Comments must be provided by 6/1/2013

Released 5/2013

RDE experiments for characterization and screening of activity and durability of PEMFC electrocatalysts.

Comments must be provided by 7/12/2013



Request for Information
U.S Department of Energy
Office of Energy Efficiency and Renewable Energy

Rotating Disk Electrode Experiments for PEMFC Electrocatalyst Screening

Date: 05/2013

Subject: Request for Information on the use of rotating disk electrode (RDE) experiments for characterization/screening of the activity and durability of polymer electrolyte membrane fuel cell

Request for Information
U.S Department of Energy
Office of Energy Efficiency and Renewable Energy

Automotive Fuel Cell Cost and Durability Targets
DE-FOA-0000855

Date: 2/1/2013

Subject: Request for Information on cost targets for fuel cells designed for automotive applications.

Description: The U.S. Department of Energy (DOE) is issuing a Request for Information (RFI) seeking input from stakeholders on proposed cost targets for fuel cells designed for automotive applications. This RFI is not and will not lead directly to a Funding Opportunity Announcement; therefore the DOE is not accepting applications at this time.

Director / Area: Dr. Sunita Satyapal, Director / Fuel Cell Technologies (FCT) Office; Dr. Dimitrios Papagiorgopoulos, Team Lead / Fuel Cells Subprogram

Background: The DOE FCT Office, 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. A detailed description of the FCT Office, including technical and cost targets, can be found in the 2011 update of the fuel cell technologies Multi-Year Research, Development and Demonstration Plan (MYRDDP) found at: http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf

Automotive fuel cells represent a large market opportunity for fuel cells. Further technological improvements are required to make fuel cells competitive with incumbent technology. EERE is in the process of updating the fuel cell technologies MYRDDP and determining technology requirements for widespread commercialization of fuel cells. As part of this effort, DOE is seeking general comments on its cost and durability targets for fuel cells for automotive applications. The targets are intended to meet end user expectations, and are not driven by the operating parameters or constraints of specific technologies. Targets are generally set with industry and market input and help drive the research and development required for improvements in materials, designs, and systems. The proposed targets included in this RFI were developed with input from the U.S. DRIVE Partnership (a public-private partnership includes automotive and energy companies), specifically the Fuel Cell Technical Team. Further stakeholder general comments are requested to refine the targets. Feedback on the target values, as well as input on current status, is solicited from developers, manufacturers, end users, and other stakeholders.

Fuel Cell Collaborations

U.S. DEPARTMENT OF ENERGY

INTERNATIONAL ACTIVITIES

FCT Program

IEA Hydrogen Implementing / Advanced Fuel Cells Agreements

- 22 countries
- European Union

IPHE

- 17 counties
- European Commission

DOE

(Energy Efficiency & Renewable Energy-EERE)

Fuel Cells program

Fuel Cell R&D

- ARRA Projects
- SBIR Projects
- 38 Projects

INDUSTRY

- Fuel Cells Tech Team

TECHNOLOGY VALIDATION (DOE EERE)

National Collaboration *(inter- and intra-agency efforts)*

DOE – Basic Energy Sciences	NSF	NIST	DOT	ARPA-E	Fossil Energy
~30 Projects	New projects in basic science	Neutron imaging facility	Bus Applications	High-potential fuel cell technology projects	Solid Oxide Fuel Cells

For More Information

U.S. DEPARTMENT OF ENERGY

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