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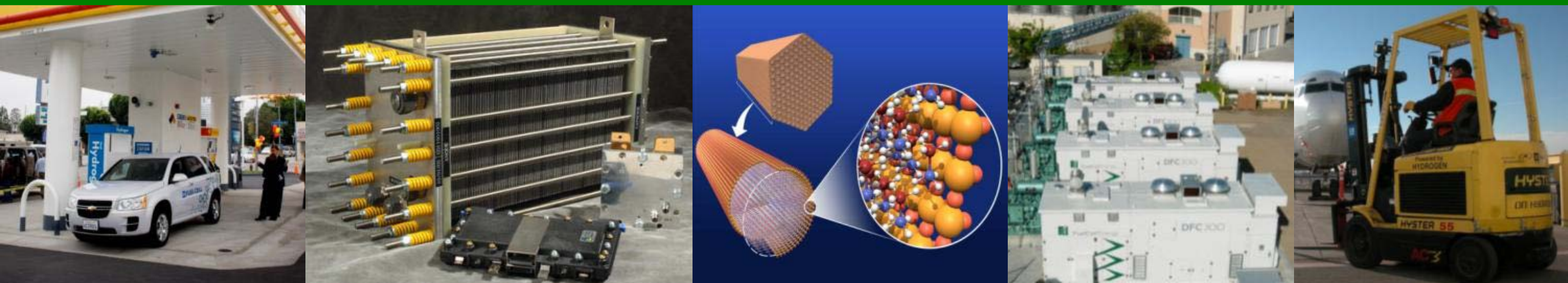

Fuel Cells

Dimitrios Papageorgopoulos

2012 Annual Merit Review and Peer Evaluation Meeting

May 14, 2012

Goal and Objectives

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

Objectives

- By 2015, a fuel cell system for portable power (<250 W) with an energy density of 900 Wh/L.
- 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 40W/L at a cost of $1000/kW.

Challenges & Strategy

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The Fuel Cells sub-program supports research and development of fuel cell 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 **recently updated:**
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
Stationary power
Fuel processor subsystems
Portable power
APUs and emerging markets

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

Challenges & Strategy

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Application-driven targets for commercial viability (in terms of cost and performance) were recently revised and updated.

- **Targets revised for the complete portfolio guiding R&D for transportation, stationary, and portable applications**
- **Revised targets in recently released *MYRD&D Plan***
  http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Examples of system-level targets:

Technical Targets: 1–10 kW_e Residential Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas			
Characteristic	**2011 Status**	**2015 Targets**	**2020 Targets**
Electrical efficiency at rated power	34-40%	42.5%	>45%
CHP energy efficiency	80-90%	87.5%	90%
Equipment cost, 2-kW_{avg} system	NA	$1,200/$kW_{avg}$	$1,000/$kW_{avg}$
Equipment cost, 5-kW $_{avg}$ system	$2,300 - $4,000/kW	$1,700/$kW_{avg}$	$1,500/$kW_{avg}$
Equipment cost, 10-kW_{avg} system	NA	$1,900/$kW_{avg}$	$1,700/$kW_{avg}$
Transient response (10 - 90% rated power)	5 min	3 min	2 min
Start-up time from 20°C ambient temperature	<30 min	30 min	20 min
Degradation with cycling	<2%/1,000 h	0.5%/1,000 h	0.3%/1,000 h
Operating lifetime	12,000 h	40,000 h	60,000 h
System availability	97%	98%	99%

Challenges and Strategy: Automotive Applications

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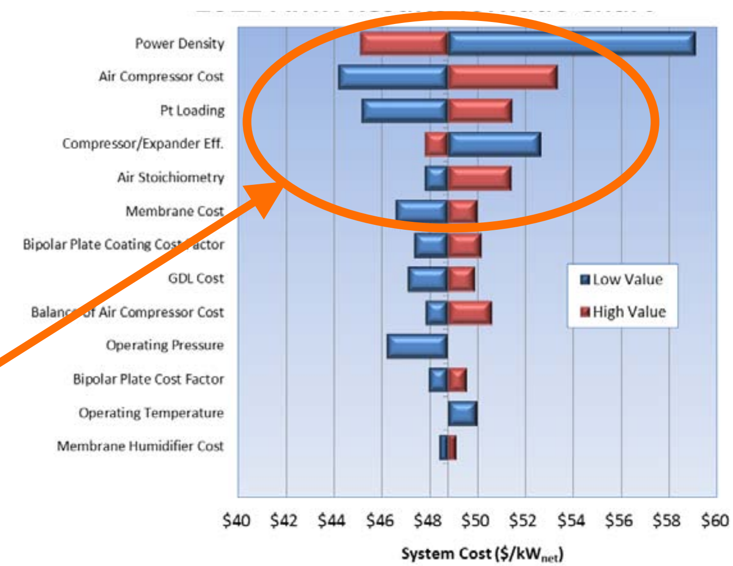
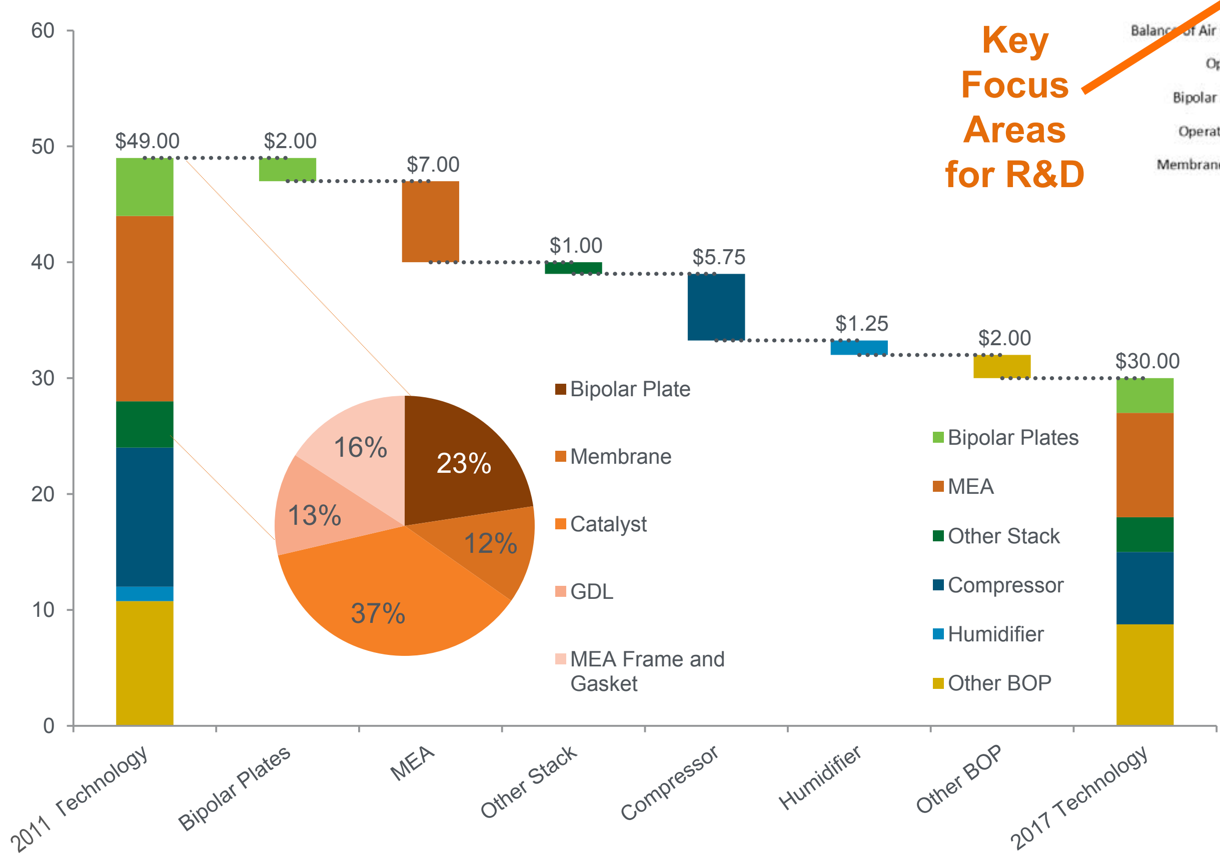
- ***Strategic technical analysis guides focus areas for R&D and priorities.***
- ***Need to reduce cost from $49/kW to $30/kW and increase durability from 2,500 to 5,000 hours***
- ***Advances in PEMFC materials and components could benefit a range of applications.***

Sensitivity Analysis helps guide R&D



Key Focus Areas for R&D



Targeted 80 kW PEM fuel cell system cost: $30/kW at 500,000 units/yr

Strategies to Address Challenges – Catalyst Examples

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

Challenges and Strategy: Stationary Applications

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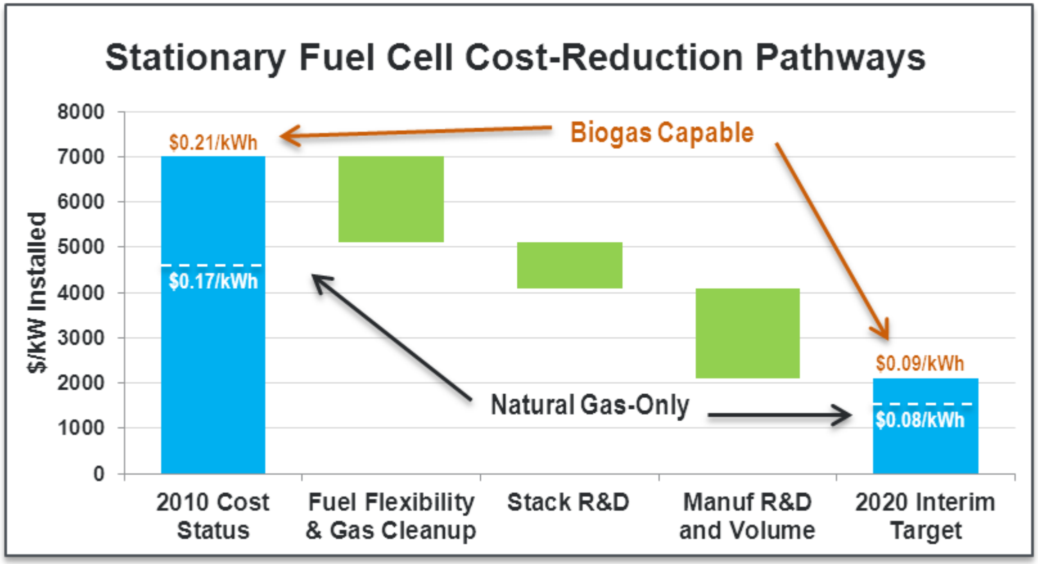
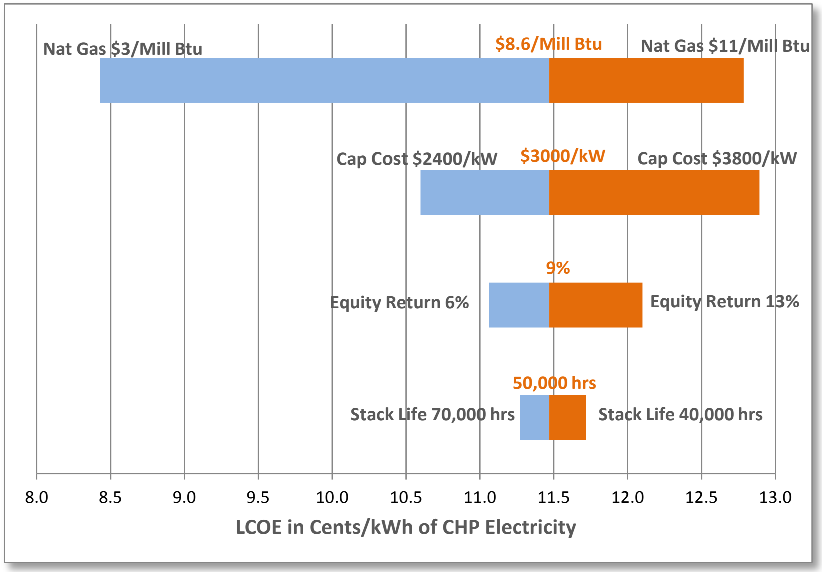
Further reduction in capital cost of medium scale DG/CHP(100kW-3 MW) and natural gas availability will facilitate commercialization.



- **Natural gas availability and fuel cell performance (efficiency) gains will enhance the technology's market attractiveness.**
- **Further reduction of fuel cell system cost required to expedite commercialization**
- **Development of a cost-effective process for removing fuel contaminants would allow for fuel flexibility.**

Sensitivity analysis around 2015 targets assesses impact of fuel cell system cost and durability on commercialization prospects

Technical Parameters (2015)	
Electric Efficiency (LHV)	45.0%
Combined Efficiency (LHV)	87.5%
Size, MWe	1
Operating Life, years	20
Equipment, $/kWe	2,300
Engineering& Installation, $/kWe	700
Fixed O&M, $/MWh	13
Variable O&M, $/MWh	8.0



Challenges and Strategy: New Stationary Cost Analysis

U.S. DEPARTMENT OF ENERGY

Analysis highlights need for fuel processor cost reduction.

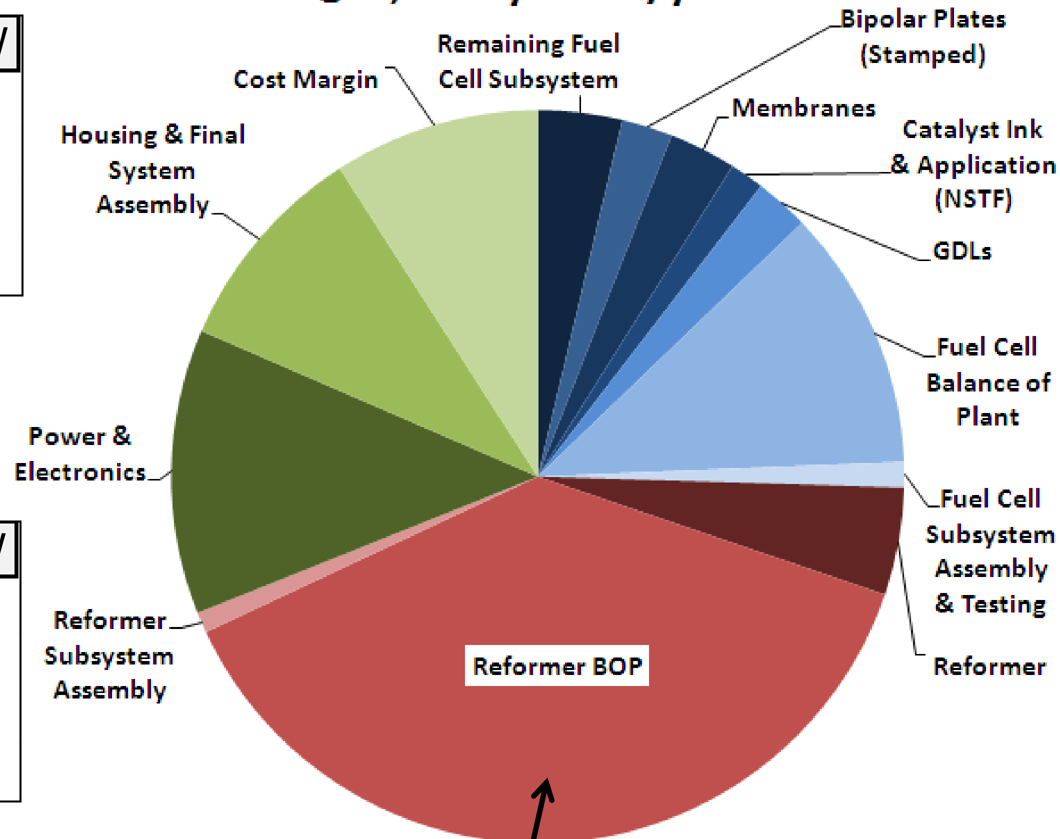
LT-PEM (~ 80 °C)

Sys/yr	1 kW	5 kW	25 kW	100 kW
100	\$12K	\$3.9K	\$1.7K	\$1.1K
1,000	\$9.3K	\$3.1K	\$1.4K	\$0.9K
10,000	\$7.9K	\$2.6K	\$1.1K	\$0.7K
50,000	\$7.2K	\$2.4K	\$1K	\$0.6K

HT-PEM (~ 160 °C)

Sys/yr	1 kW	5 kW	25 kW	100 kW
100	\$11K	\$4.2K	\$1.7K	\$1.3K
1,000	\$8.8K	\$3.3K	\$1.5K	\$1.1K
10,000	\$7.5K	\$2.8K	\$1.2K	\$0.8K
50,000	\$6.9K	\$2.5K	\$1K	\$0.7K

Cost Breakdown, 5 kW LT PEM @ 1,000 systems/year



Fuel processor is largest cost component for LT PEM and HT PEM

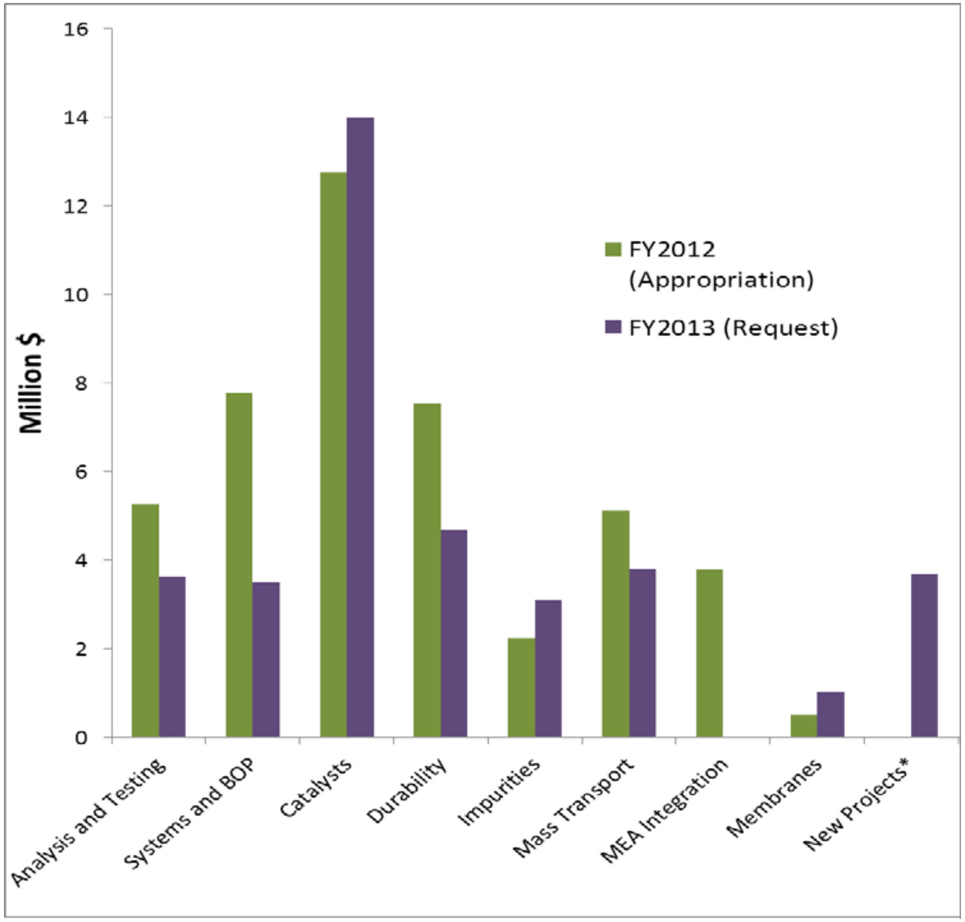
SOFC system analysis currently underway

***B. D. James et al., SA**

Fuel Cells Budget

U.S. DEPARTMENT OF ENERGY

FY 2012 Appropriation = $45.0 M
FY 2013 Request = $38.0 M



Systems and BOP includes projects related to portable and stationary power

New projects in FY2012 for BOP and MEA Integration were fully funded up front

****Subject to appropriations***

EMPHASIS:

- Develop improved ultra-low PGM and non-PGM fuel cell catalysts and membrane electrolytes
- Improve PEM-MEAs through integration of state-of-the-art MEA components
- Identify degradation mechanisms and approaches for mitigating the effects
- Characterize and optimize transport phenomena improving MEA and stack performance
- Investigate and quantify effects of impurities on fuel cell performance
- Develop low-cost, durable, system balance-of-plant components
- Maintain core activities in components, subsystems and systems specifically tailored for stationary and portable power applications

Progress – Fuel Cells R&D

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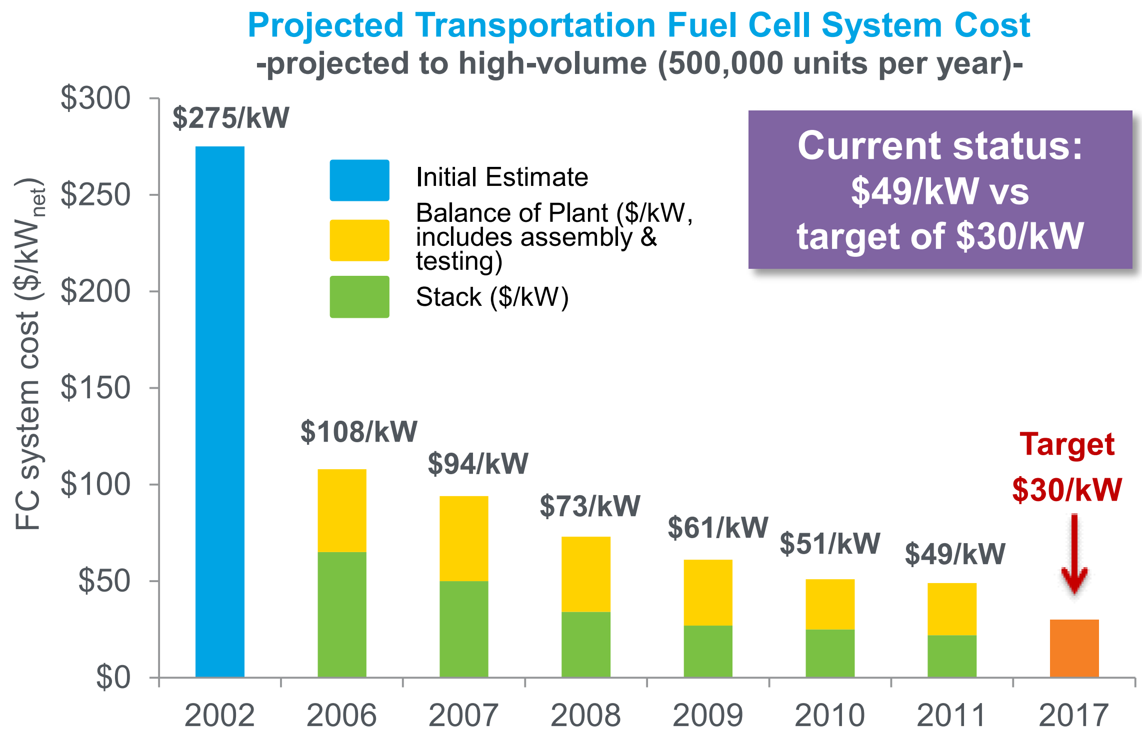
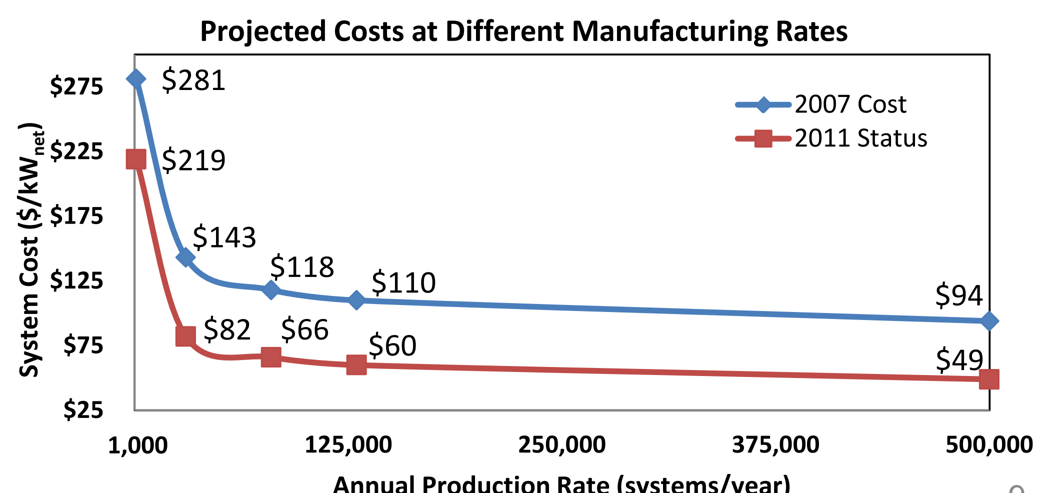
Projected high-volume cost of fuel cells has been reduced to $49/kW (2011)*

- ***More than 30% 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.*

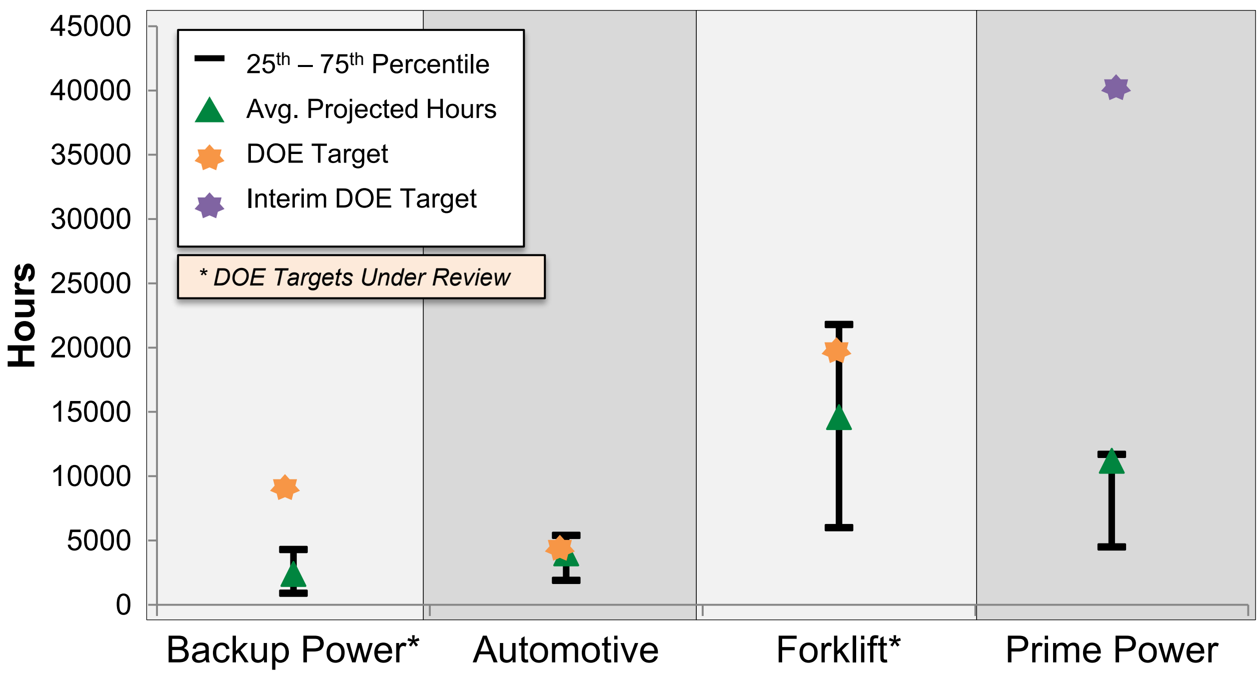
Progress – Durability Assessment

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 82 data sets from 10 fuel cell developers.

Application	Avg Projected Time to 10% Voltage Drop	Avg Operation Hours
Backup power	2,400	1,100
Automotive	4,000	2,700
Forklift	14,600	4,400
Prime	11,200	7,000



PEM & 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

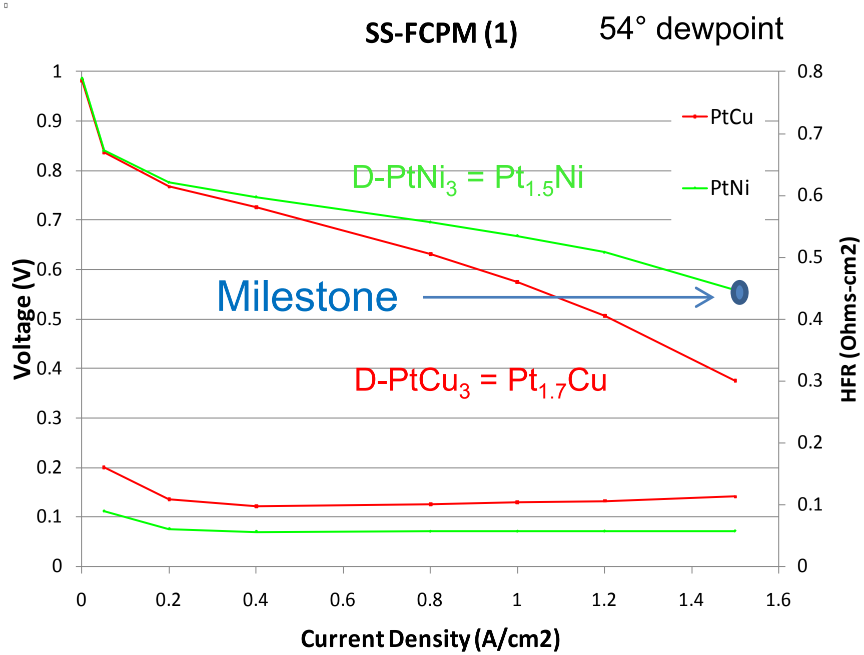
J. Kurtz, et al., NREL

Progress: De-alloyed Catalysts

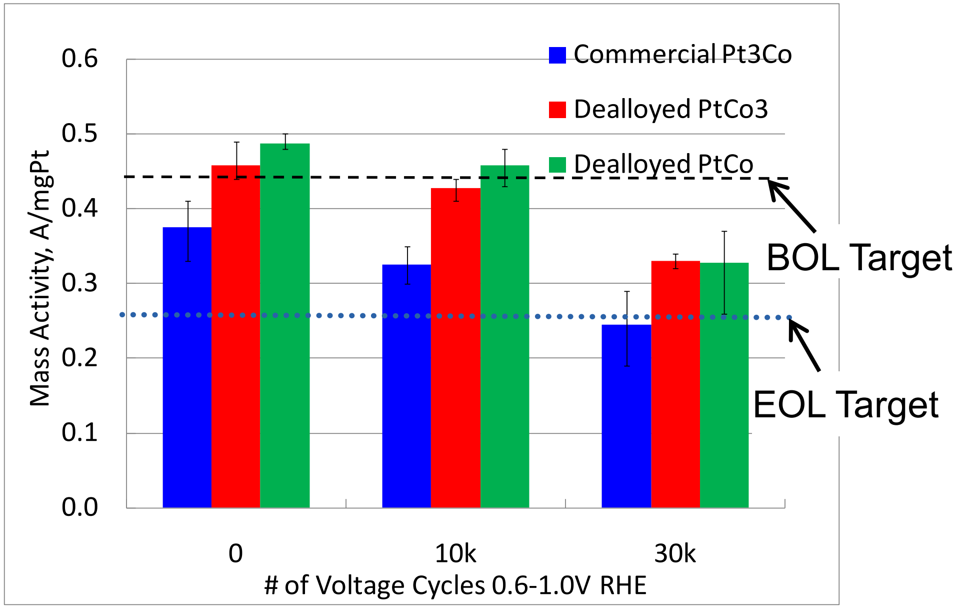
U.S. DEPARTMENT OF ENERGY

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

GM 50 cm² MEAs, at 0.1 mg_{Pt}/cm^2
H_2/air, 80° C, 170 kPa_{abs}, stoichs 2/2



GM 50 cm² MEAs, 0.2 mg_{Pt}/cm^2



- $PtCo_3$ and $PtNi_3$ meet 0.44 A/mg_{PGM} mass activity target
- $PtCo_3$ meets 30,000 cycle durability target
- $PtNi_3$ meets 0.56 V @ 1.5 A/cm² milestone

0.46 A/mg_{PGM} for $PtCo_3$,

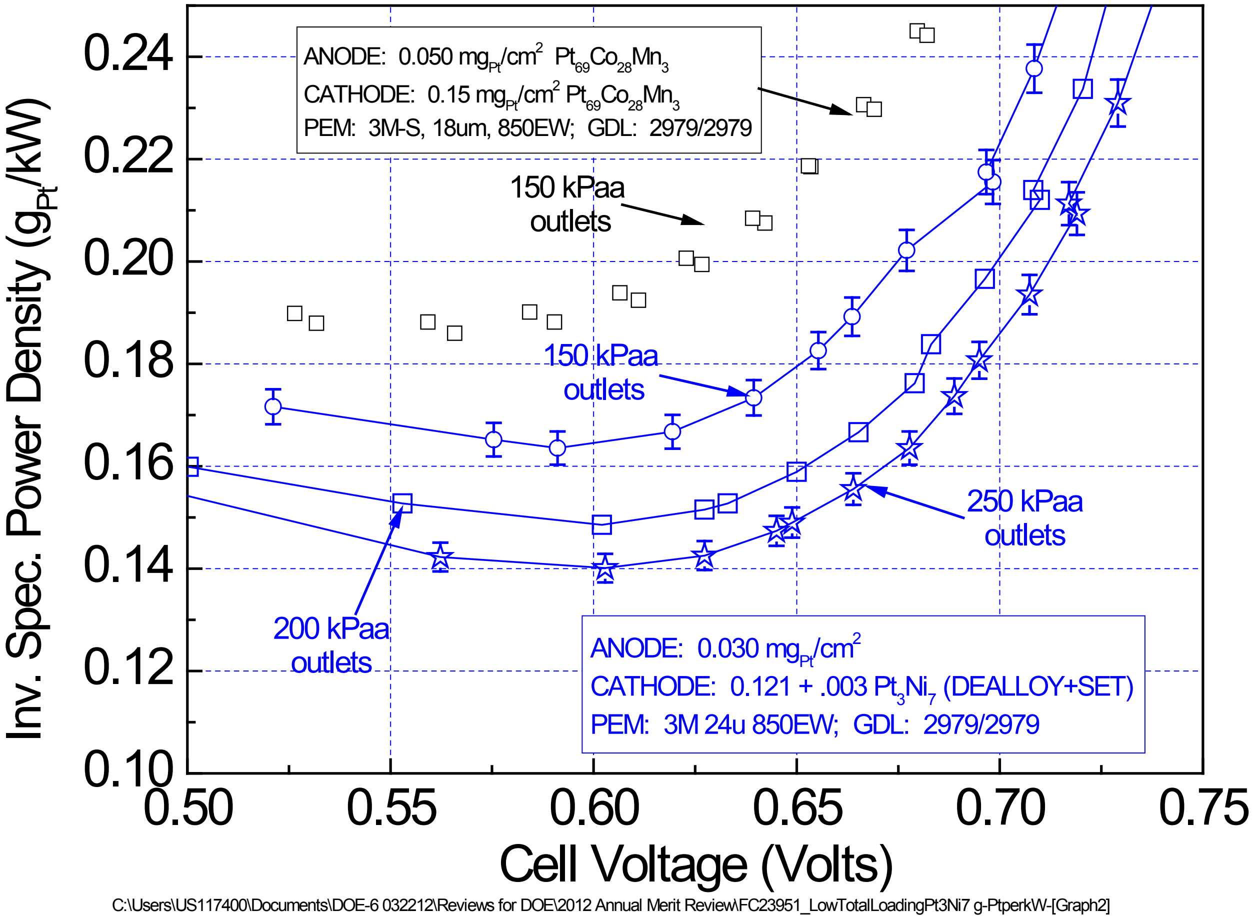
0.52 A/mg_{PGM} for $PtNi_3$ in 50 cm² MEA testing

F. Wagner et al., GM

Progress: NSTF Catalysts

U.S. DEPARTMENT OF ENERGY

Roll-to-roll PtNi NSTF catalyst meets 0.44 A/mg$_{PGM}$ mass activity target.



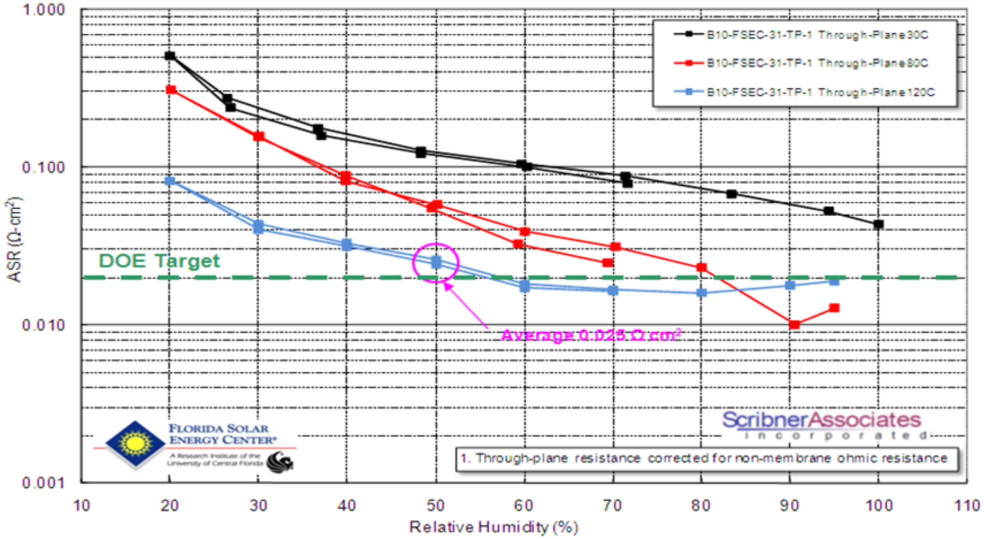
- **Achieved 0.44 A/mg$_{PGM}$ target** on roll-to-roll produced MEAs through improvements in Pt_3Ni_7 catalyst processing techniques
- **Reduced PGM total content to 0.14 – 0.18 g/kW**, with 0.15 mg/cm^2 (2017 targets: 0.125 g/kW, 0.125 mg/cm^2)
- Progress in improving high-current performance of Pt_3Ni_7; still opportunity for further improvement

M. Debe et al., 3M

Progress: Membranes

U.S. DEPARTMENT OF ENERGY

Membranes containing multi-acid side chains or additives demonstrate conductivity higher than 0.1 S/cm under hot, dry conditions.



FuelCell Energy: mC² membranes use short side chains and additives to reach high conductivity

L. Lipp et al., FuelCell Energy

		3M PFIA Status	DOE 2017 Target
ASR at 120°C (p_{H2O} 40-80 kPa)	Ohm cm²	0.023 (40 kPa) 0.012 (80 kPa)	≤0.02
ASR at 80°C (p_{H2O} 25-45 kPa)	Ohm cm²	0.013 (25 kPa) 0.006 (44 kPa)	≤ 0.02
ASR at 30°C (p_{H2O} 4 kPa)	Ohm cm²	0.02 (3.8 kPa)	≤ 0.03
ASR at -20°C	Ohm cm²	0.1	≤ 0.2
O_2 Crossover	mA/cm²	<1.0	≤ 2
H_2 crossover	mA/cm²	<1.8	≤ 2
Mechanical Durability Chemical Durability (OCV)	RH Cycles Hours	>20,000 2,025	≥20,000 ≥ 500

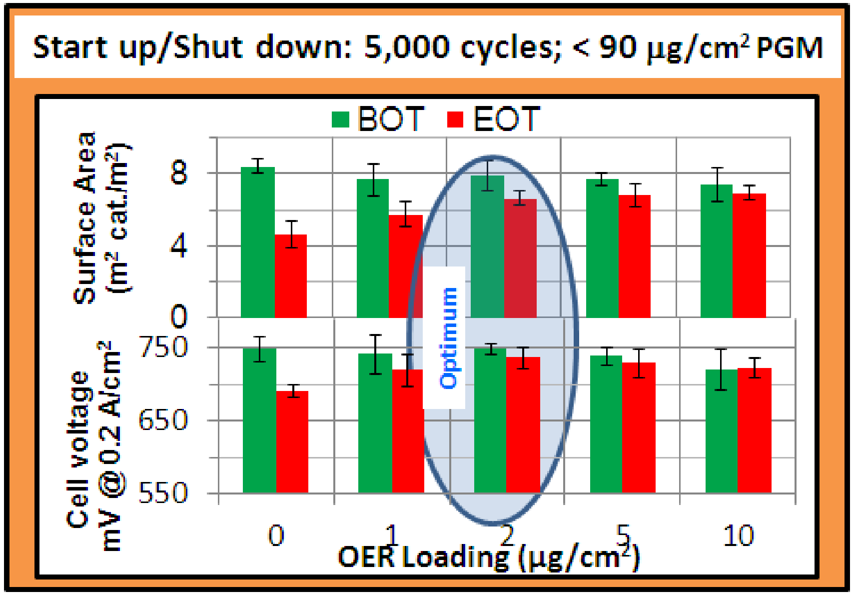
3M: multi-acid side chain polymers have met most membrane targets

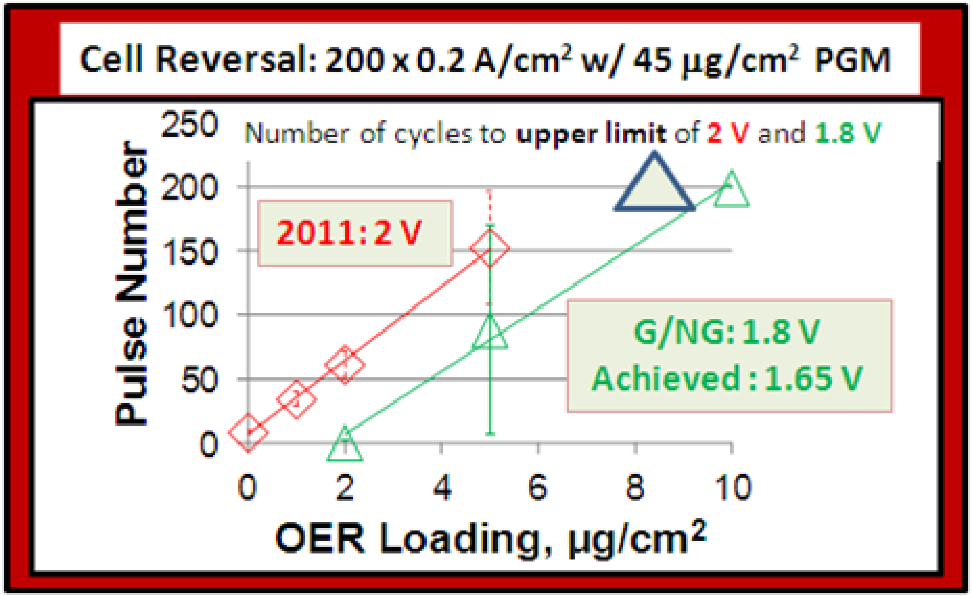
S. Hamrock et al., 3M

Progress: Durable Catalysts

U.S. DEPARTMENT OF ENERGY

3M catalysts demonstrate durability under startup, shutdown, and cell reversal.





IrRu-modified cathodes have achieved the SU/SD Go/No Go requirement: 5,000 cycles with end voltage < 1.60 V, ECSA loss <10% with < 0.09 mg/cm² PGM

IrRu-modified anodes have achieved the cell reversal Go/No Go requirement: 200 cycles with end voltage < 1.80 V, with < 0.045 mg/cm² PGM

All Go/No-go milestones surpassed at:

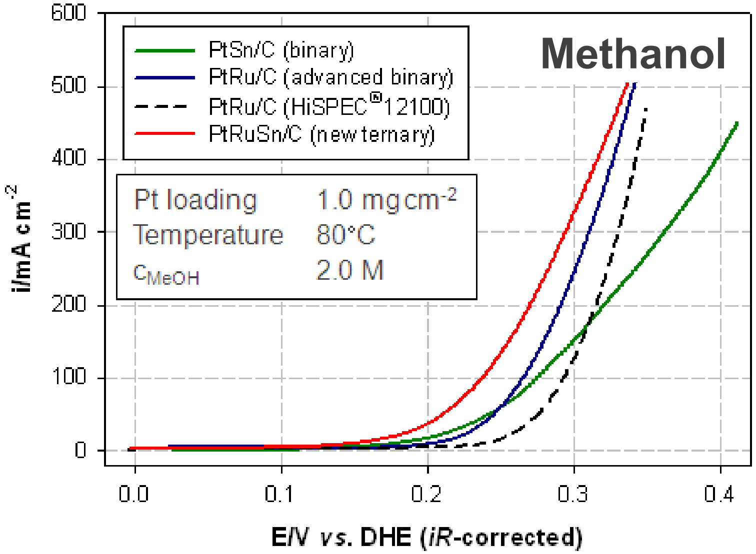
- **PGM loading < 0.135 mg/cm² total**
- **Voltages meet the set goals**

R. Atanasoski et al., 3M

Progress: Portable Power

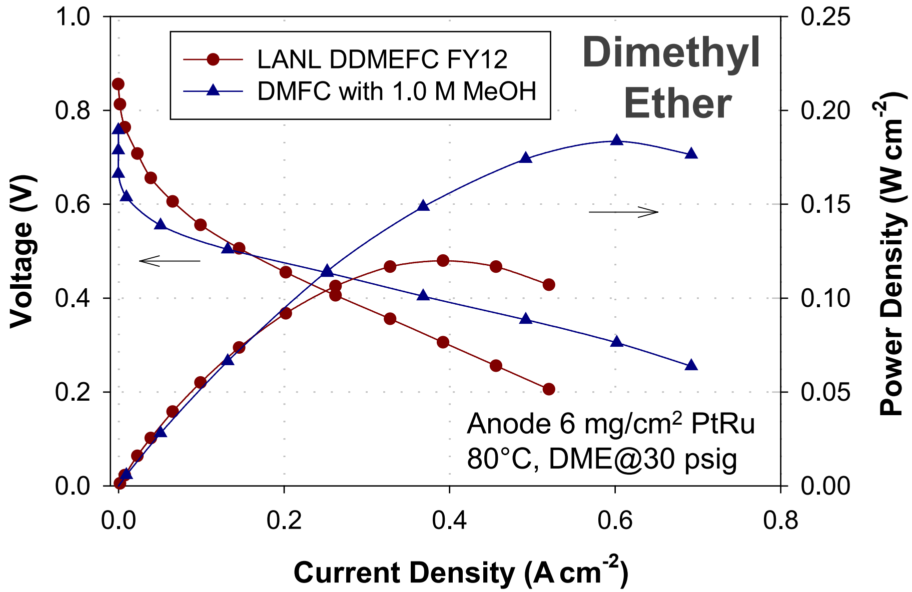
U.S. DEPARTMENT OF ENERGY

High-activity catalysts developed for liquid fuels



- JMFC's ternary PtRuSn/C DMFC catalyst combines advantages of PtSn at low overpotentials and PtRu at high overpotentials
- PtRuSn/C outperforms the best thrifted PtRu/C catalyst

PtRuSn/C methanol mass activity exceeds **500 mA/mg$_{Pt}$** at 0.35 V, **150% higher than FY12 milestone**



- DME fuel cell outperforms DMFC at low current due to **low DME crossover**

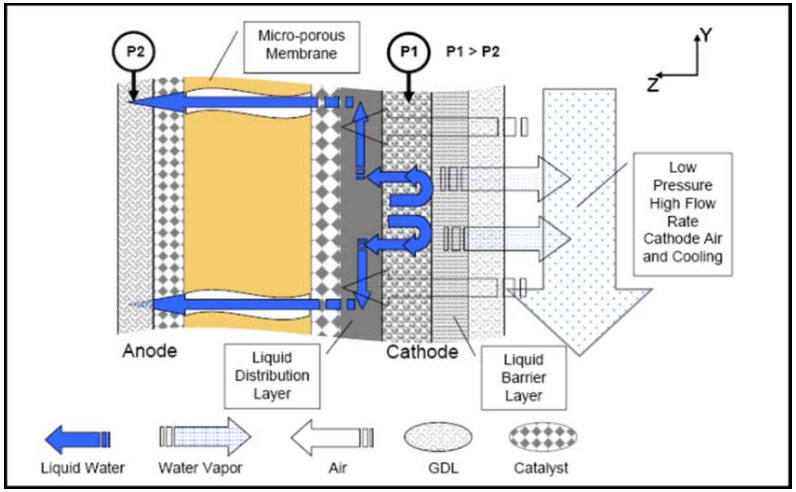
DME fuel cell achieves **150 mA/cm²** at 0.5 V – **60% higher than FY11**, **130% higher than best published data**

P. Zelenay et. al., LANL

Progress: Portable Power

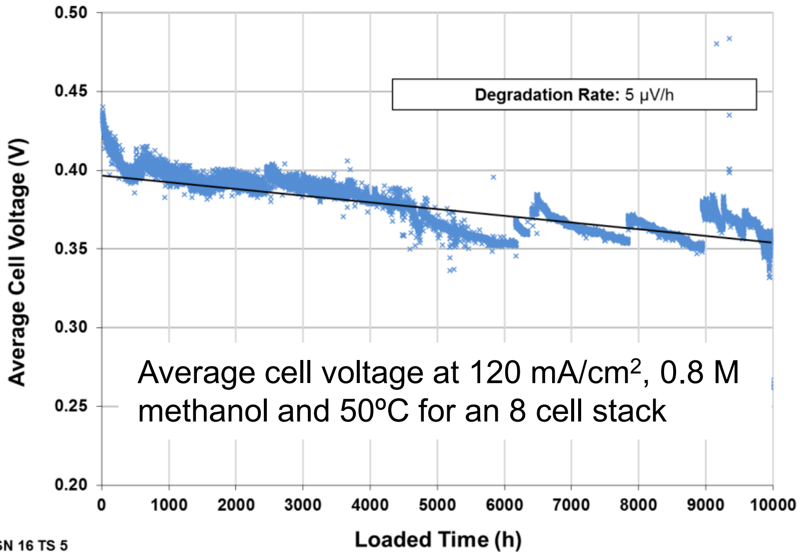
U.S. DEPARTMENT OF ENERGY

Passive water recovery DMFC enables BOP reduction.



Cathode liquid barrier layer retains water; passive recirculation returns water to anode

- **>10,000 hour stack durability demonstrated in steady-state testing**
- **Startup/shutdown durability improvements still needed**



DOE Technical Targets: Portable Power Fuel Cell Systems (10-50 Watts)					
Characteristic	Units	DOE 2011 Status	UNF Status (25 W Net)[1]	2013 Targets	2015 Targets
Specific Power	W/kg	15	26.3	30	45
Power Density	W/l	20	28.0	35	55
Specific Energy	(W-hr)/kg	150	263	430	650
Energy Density	(W-hr)/l	200	280	500	800

1. Values based on 10 hour operation duration.

SN 16 TS 5

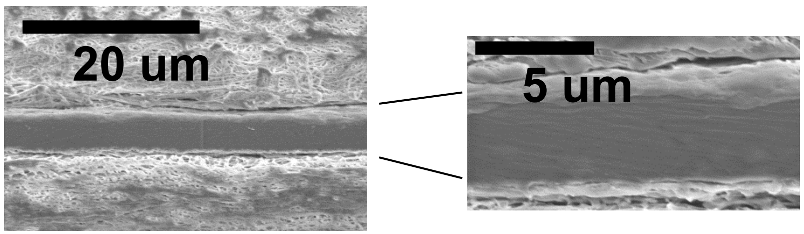
J. Fletcher et. al., UNF

Progress: Balance of Plant

U.S. DEPARTMENT OF ENERGY

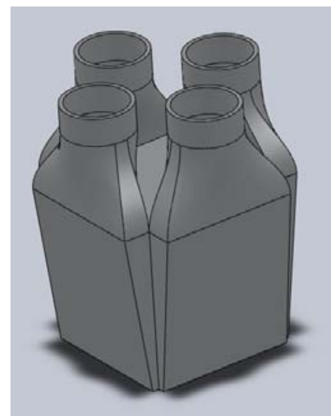
Compact, low-cost humidifier module projected to meet $100/unit 2017 cost target

High performance, cost-effective humidification membranes developed



Scale-up of these materials is underway.

Flow field, pleat geometry and module design optimization to take advantage of very high transport rate materials, while maintaining low-cost assembly process.



Membrane pocket over plate assembly concept selected

- **Module performance consistent with single cell and *ex situ* testing shows loss of performance of 20-30% over 5500 hours.**
- **Developed understanding of source of durability loss – chemical changes in PFSA**
- **Sub-scale module design complete; sub-scale prototypes built and under test**
- **Final full scale module to be built**

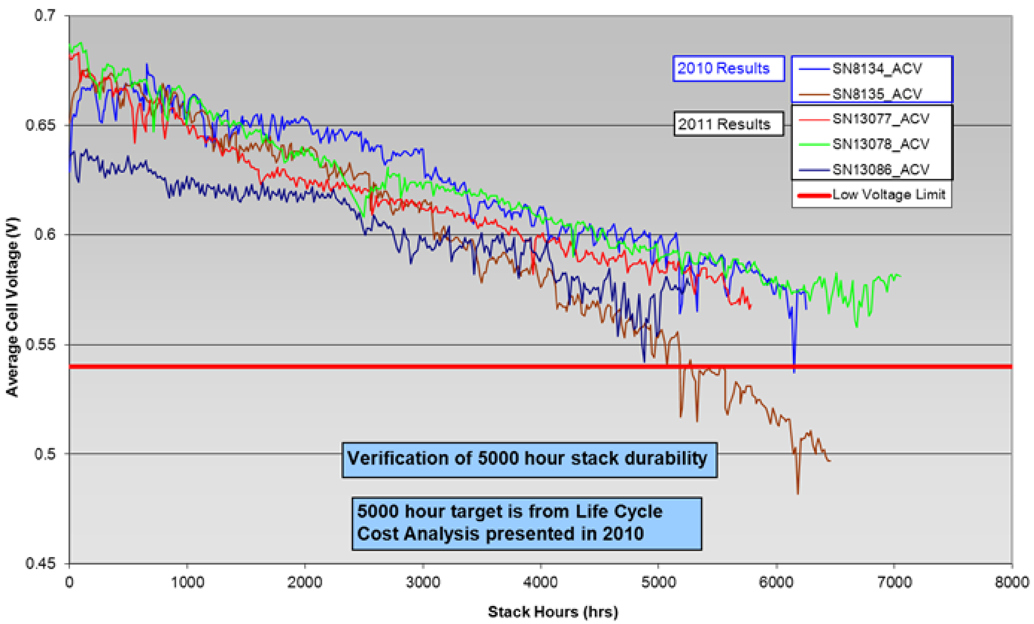
Module cost estimated to be ~$100 at high volumes.

W. B. Johnson et al., Gore

Progress: Stack technology for material handling

U.S. DEPARTMENT OF ENERGY

Increased freeze-tolerance and durability for material handling applications



- **Air cooled stack technology enabled reduction in projected order picker cost by 57%, life cycle cost by 32%.**
- **Minimal degradation seen from freeze start-ups from -10 °C**
- **Substantial operation at -30 °C possible with system mitigation strategies**

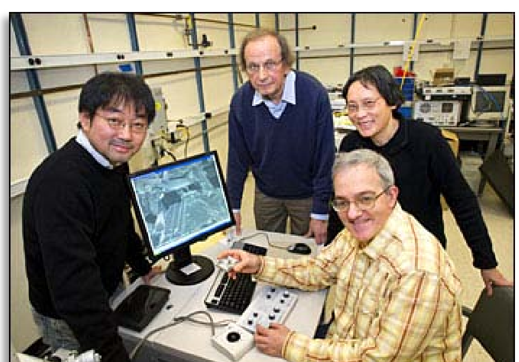
- **Next Generation Order Picker based on technology developed in this project, with over 100 units shipped to at least 4 customers in Q4 2011**
- **Units can operate in a freezer environment; operating range -30°C to +40°C**

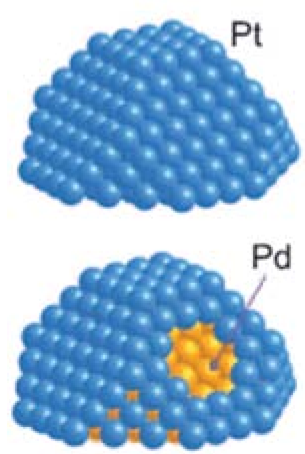
D. Hancock et al., Plug Power

Catalyst Scale-up

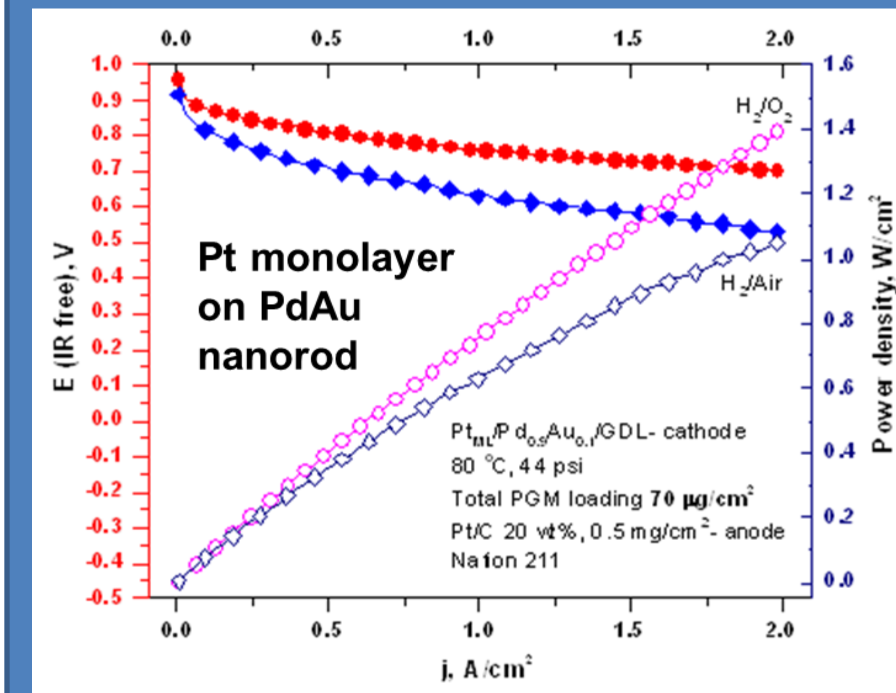
Brookhaven core-shell catalyst technology licensed by leading catalyst manufacturer

- **Jan. 3, 2012 – N.E. Chemcat Corporation, a leading catalyst and precious metal compound manufacturer, licensed core-shell electrocatalysts developed by BNL under previous EERE project.**
- **Includes catalysts with Pd or Pd-alloy cores, Pt shells**
- **N.E. Chemcat also licensed innovative methods for making the catalysts and an apparatus design used in manufacturing them.**





Current BNL project is developing new core-shell structures and improving performance and durability.

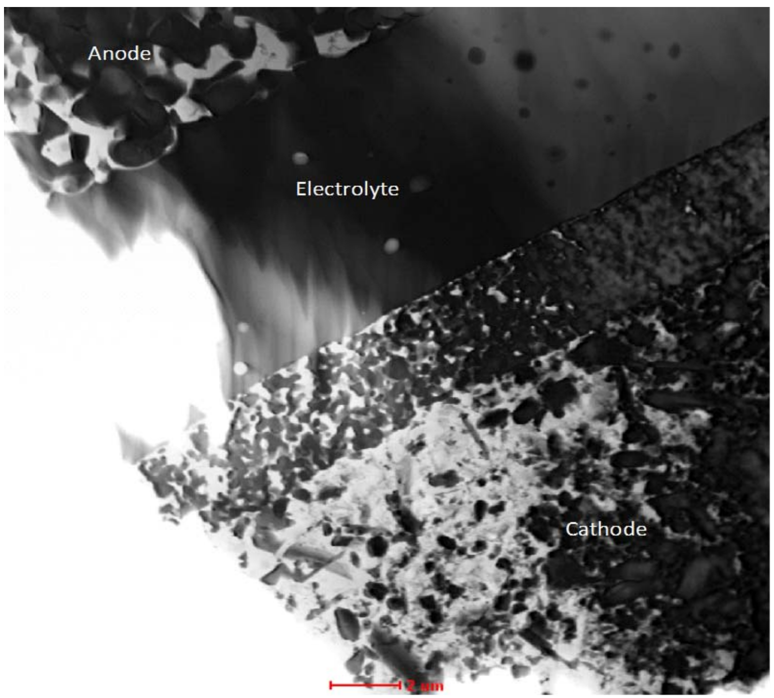


R. Adzic, et al., BNL

Solid Oxide Fuel Cells

SOFCs developed for distributed generation and energy storage

Demonstrated a kW-scale reversible SOFC stack with daily cycling between fuel cell and electrolysis mode, with SOFC degradation rate of ~1.6% per 1,000 hours



R. Petri et al., Versa Power Systems

Successfully completed 8,000 hrs desulfurizer testing and 1,000 hrs catalytic partial oxidation (CPOX) reformer testing as part of 1 MW SOFC powerplant concept running on pipeline natural gas

M. Perna et al., Rolls Royce Fuel Cell Systems

Key Milestones and Future Plans

U.S. DEPARTMENT OF ENERGY

FY 2012

- Updated Multi Year RD&D Plan & Targets Released
- Flow Cells Workshop
- Cost analysis projects kicked off
- FOA Awards Announced
- RFI for MHE released

FY 2013

- New FOA* Awards
- Develop an experimentally validated model describing mass transport in PEMFCs.
- Cost analyses updates
- Develop truck APU with projected durability of 10,000 hours, at a cost of $1400/kW, operating on standard ultra-low sulfur diesel.

FY 2014

- Develop PEM bipolar plates with a cost less than or equal to $5/kW
- Develop a 10-fold accelerated test for high-temperature fuel cell durability testing

** Subject to Appropriations*

New Fuel Cell Projects

U.S. DEPARTMENT OF ENERGY

5 new projects announced in FY 2011 (cost analysis) and FY 2012 (R&D) — total award of ~$10M

Cost Analysis

Transportation (Strategic Analysis)

- **Analyze and estimate the cost of transportation fuel cell systems for use in vehicles including light-duty vehicles and buses**

Stationary and Emerging Markets (Battelle, LBNL)

- **Develop total cost models and provide cost assessments for stationary and emerging market fuel cell system technologies**

Research & Development

MEA Integration (3M)

- **Approach is based upon integration of 3M's state-of-the-art nanostructured thin film catalyst technology platform with other components of the MEA**

System BOP (Eaton)

- **Develop and demonstrate an efficient and low-cost fuel cell air management system**

New Targets for Fuel Cell Buses

U.S. DEPARTMENT OF ENERGY

Commercialization targets have been established for fuel cell buses.

Technical Targets: Fuel Cell Transit Buses Operating on Direct Hydrogen			
Characteristic	**Units**	**2012 Status**	**Targets**
Bus Lifetime	years/miles	5/100,000	12/500,000
Power Plant Lifetime	hours	12,000	25,000
Bus Availability	%	70	90
Fuel Fills	per day	1	1 (< 5 min)
Bus Cost	$	2,000,000	600,000
Power Plant Cost	$	700,000	200,000
Hydrogen Storage Cost	$	100,000	50,000
Road Call Frequency (All/Fuel Cell System)	miles between road calls	2,500/10,000	4,000/20,000
Operation Time	hours per day/ days per week	19/7	20/7
Scheduled and Unscheduled Maintenance Cost	$/mile	1.24	0.38
Range	miles	300	300
Fuel Economy	miles per gallon diesel equivalent	6.5	8

- Targets were developed through a joint workshop and a joint RFI with the Department of Transportation.
- Status information was supplemented with data from the NREL Hydrogen Fuel Cell Bus Evaluations.

DOE Hydrogen and Fuel Cells Program Record #12012

2012 RFI on Fuel Cells for Backup, Material Handling

Preliminary cost, performance, and durability targets for backup power and for class I, II, and III lift trucks proposed; feedback from stakeholders requested.

Preliminary targets based on input from ARRA projects and NREL analysis

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

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

Material Handling and Backup Power Targets for Early Market Fuel Cell Applications
DE-FOA-0000738

Date: 05/10/2012

Subject: Request for Information on performance, durability, and cost targets for fuel cells designed for backup power and material handling applications.

Description: The U.S. Department of Energy (DOE) is issuing a Request for Information (RFI) seeking input from stakeholders on proposed technical and cost targets for fuel cells designed for backup power and material handling 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.

Program Manager / Area: Dr. Sunita Satyapal, Program Manager / Fuel Cell Technologies (FCT) Program; Dr. Dimitrios Papageorgopoulos, Team Lead / Fuel Cells Subprogram

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

Material handling equipment, including lift trucks and other industrial trucks, represents a major early market opportunity for fuel cells. Fuel cell lift trucks offer better performance, more streamlined operation, lower infrastructure requirements, higher productivity, and lower lifecycle cost than the incumbent lead acid battery lift truck technology. Driven by these advantages, significant progress in fuel cell lift truck commercialization has already been achieved, especially in the most demanding applications with the highest productivity requirements. More than 690 fuel cell lift trucks have been deployed through the American Recovery and Reinvestment Act (ARRA) and Market Transformation (MT) activities, which has led to substantial private investment in the technology, with more than 3,400 lift trucks now ordered or deployed without DOE support. According to National Renewable Energy Laboratory (NREL) analysis, fuel cell material handling equipment has logged more than one million operating hours to date.

Fuel Cell Collaborations

U.S. DEPARTMENT OF ENERGY

INTERNATIONAL ACTIVITIES

FCT Program

IEA Hydrogen Implementing Agreements

- 22 countries
- European Union

IPHE

- 17 counties
- European Commission

DOE

(Energy Efficiency & Renewable Energy-EERE)

Fuel Cells sub-program

Fuel Cell System R&D

- ARRA Projects
- SBIR Projects
- 33 R&D projects

INDUSTRY

- Fuel Cells Tech Team

TECHNOLOGY VALIDATION (DOE EERE)

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

DOE – Basic Energy Sciences
~30 Projects

NSF
New projects in basic science

NIST
- Neutron imaging facility

DOT
Bus Applications

Fossil Energy
- Solid Oxide Fuel Cells

For More Information

U.S. DEPARTMENT OF ENERGY

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