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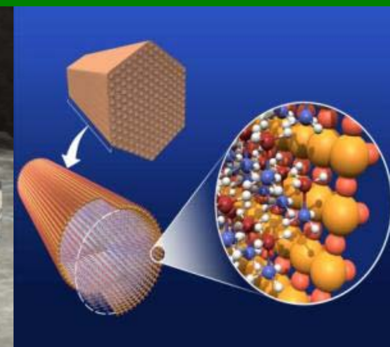

# Fuel Cells

*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**

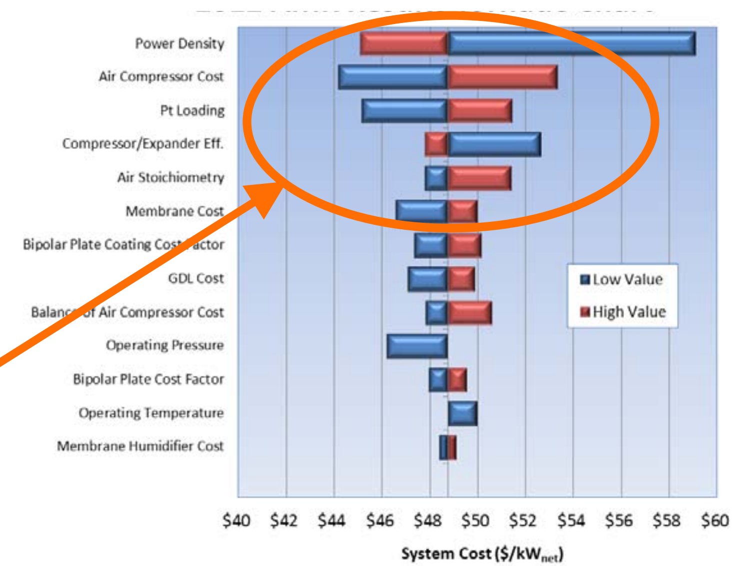
## Examples of system-level targets:

| 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% |

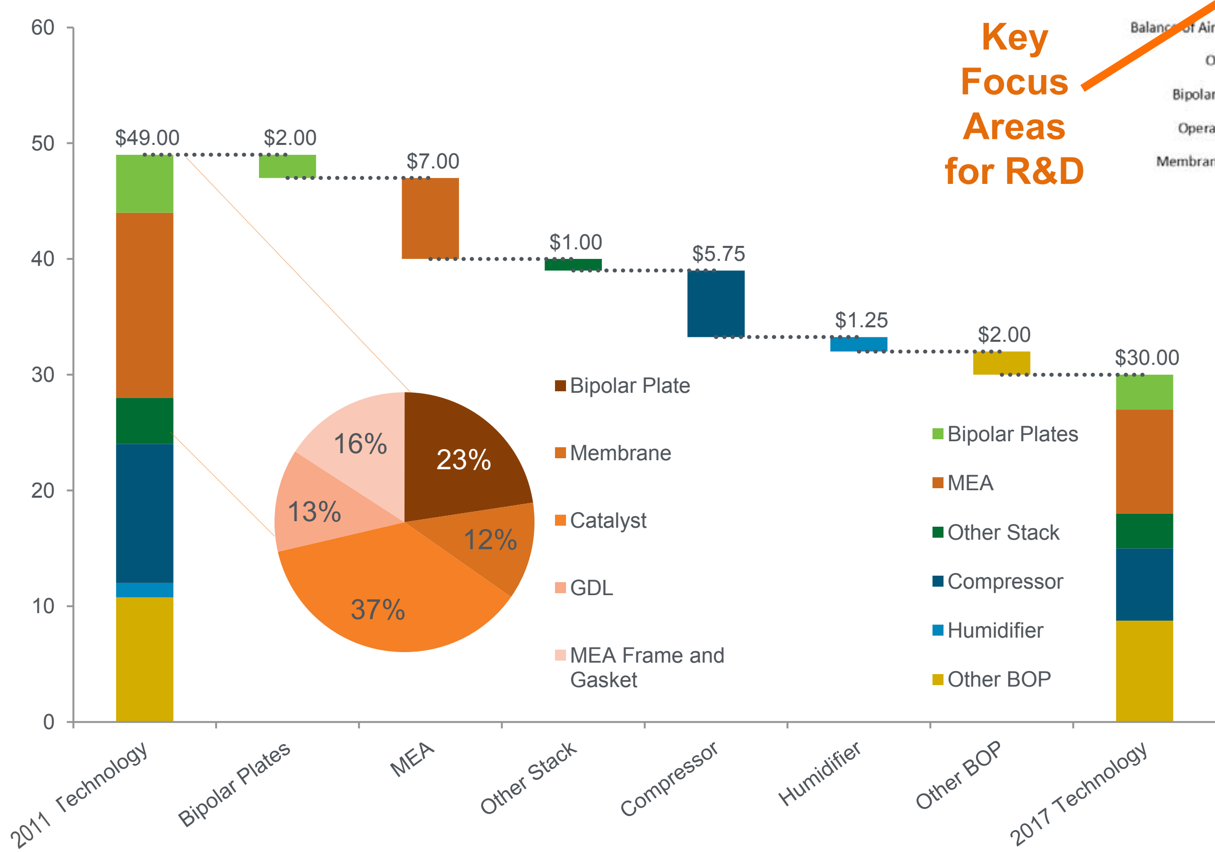
# Challenges and Strategy: Automotive Applications

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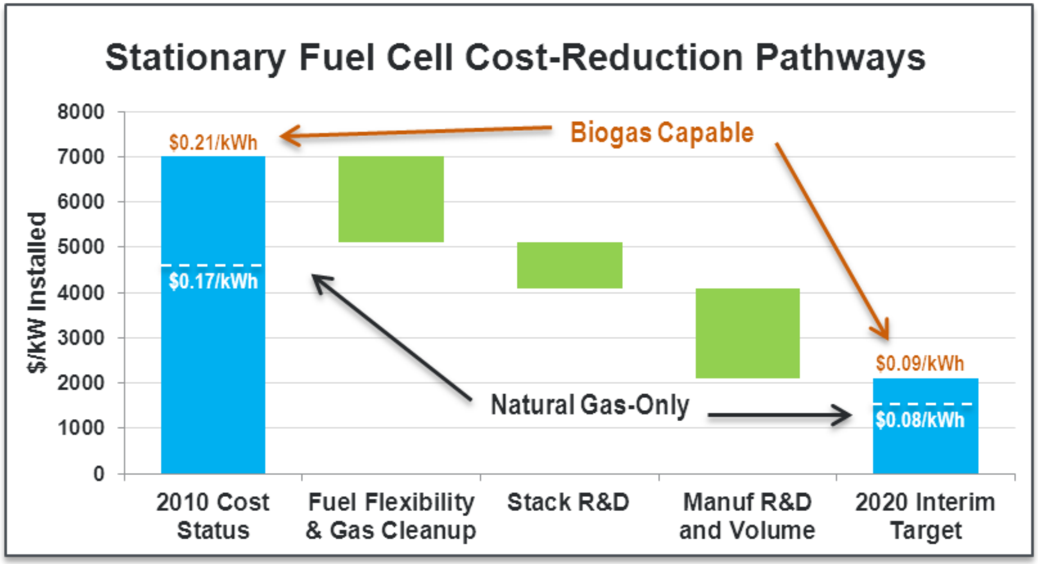
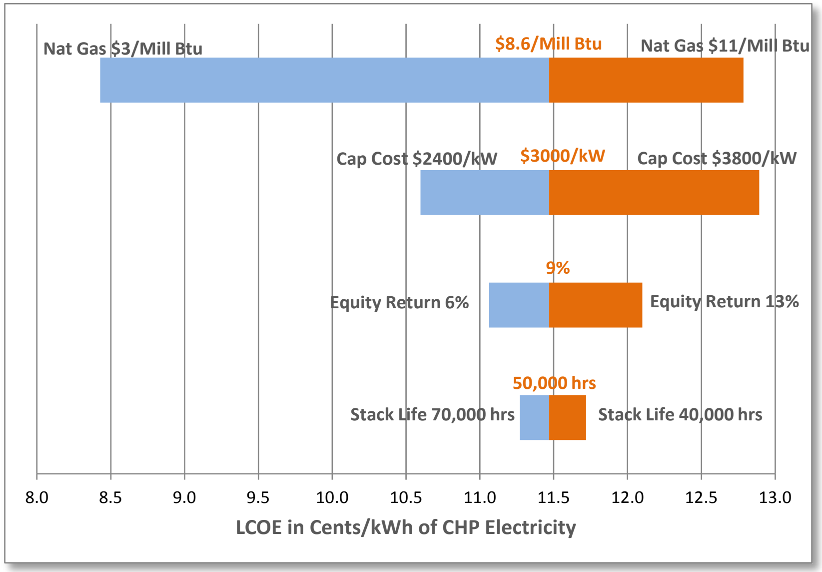
***Further reduction in capital cost of medium scale DG/CHP(100kW-3 MW) and natural gas availability will facilitate commercialization.***




- **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

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*Analysis highlights need for fuel processor cost reduction.*

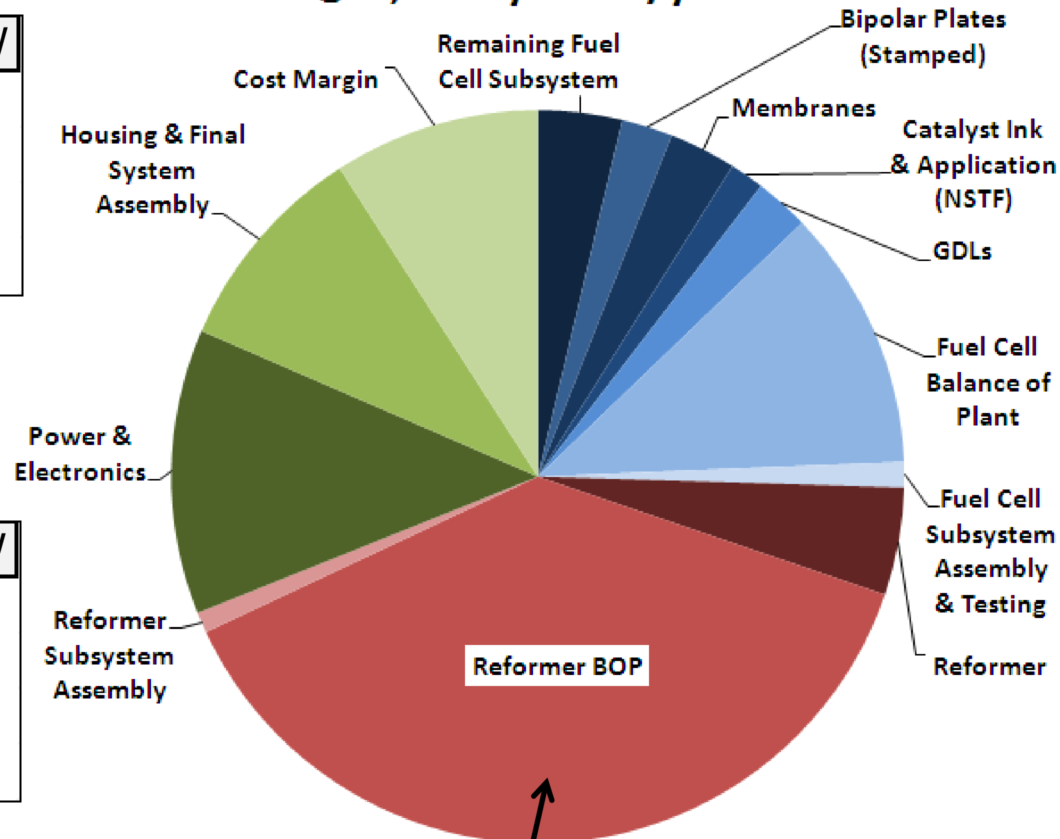
**LT-PEM (~ 80 °C)**

| 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

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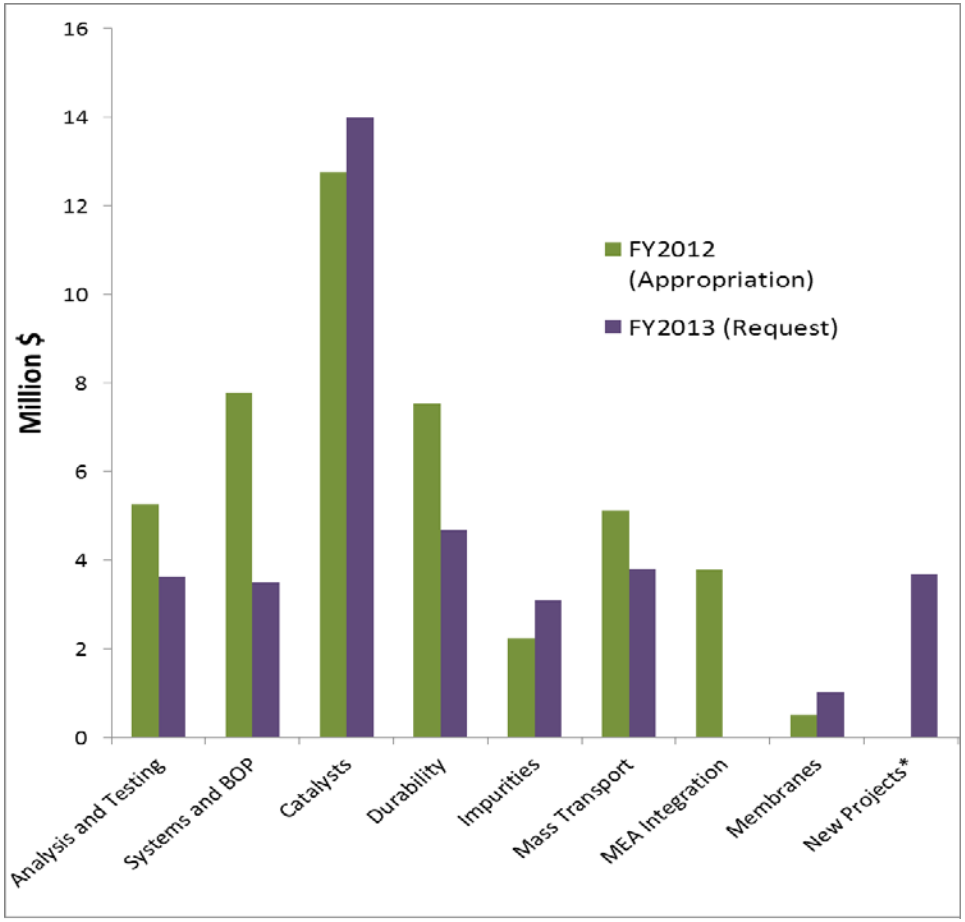
**FY 2012 Appropriation = $45.0 M**
**FY 2013 Request = $38.0 M**




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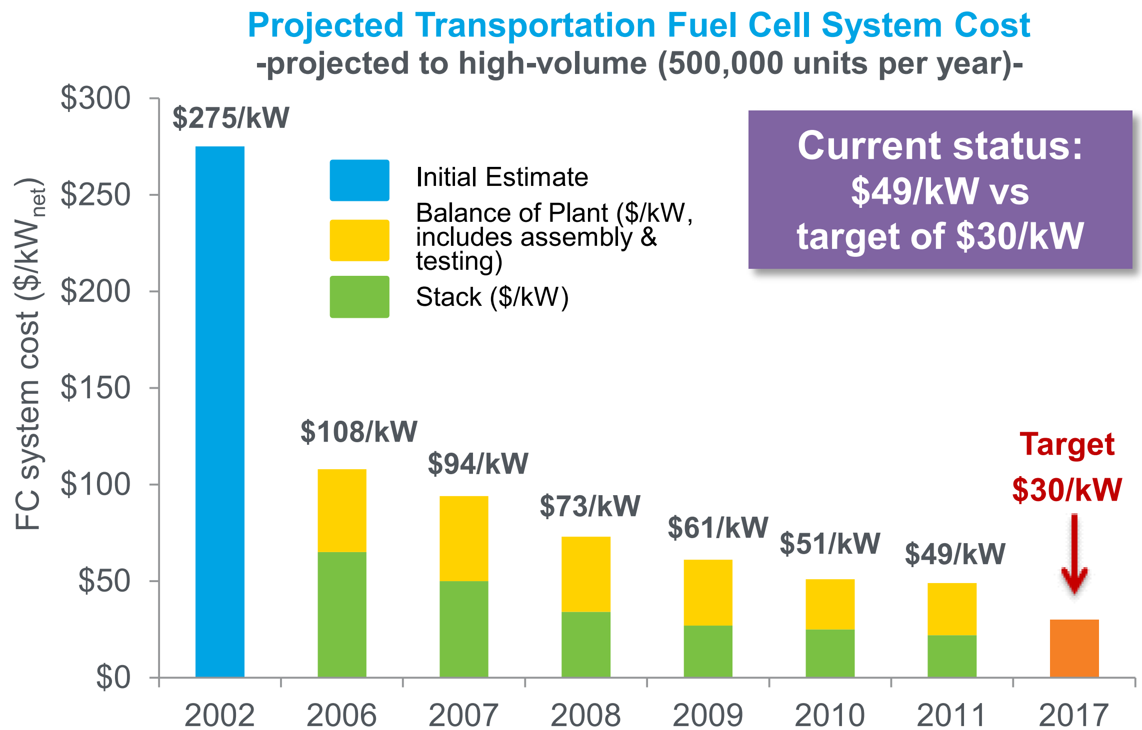
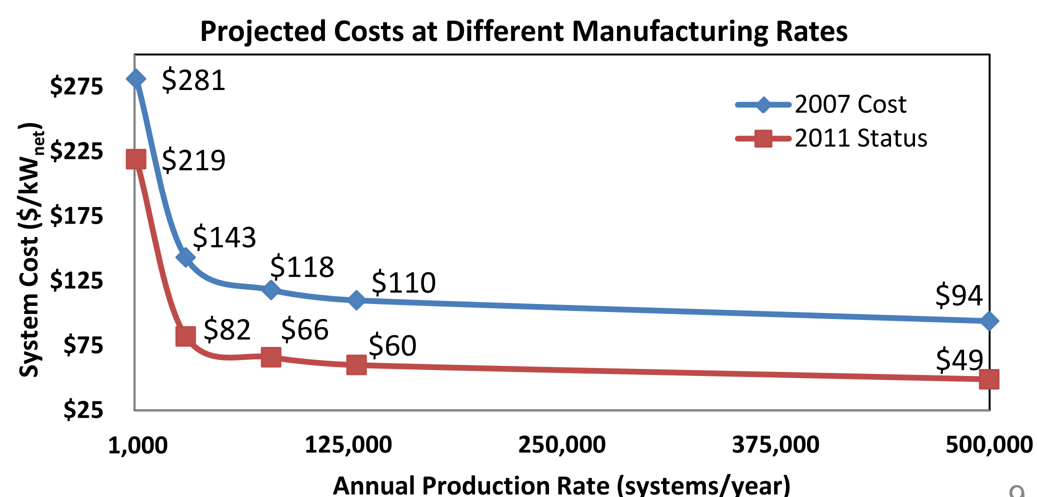
## Projected high-volume cost of fuel cells has been reduced to $49/kW (2011)*

- ***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.*

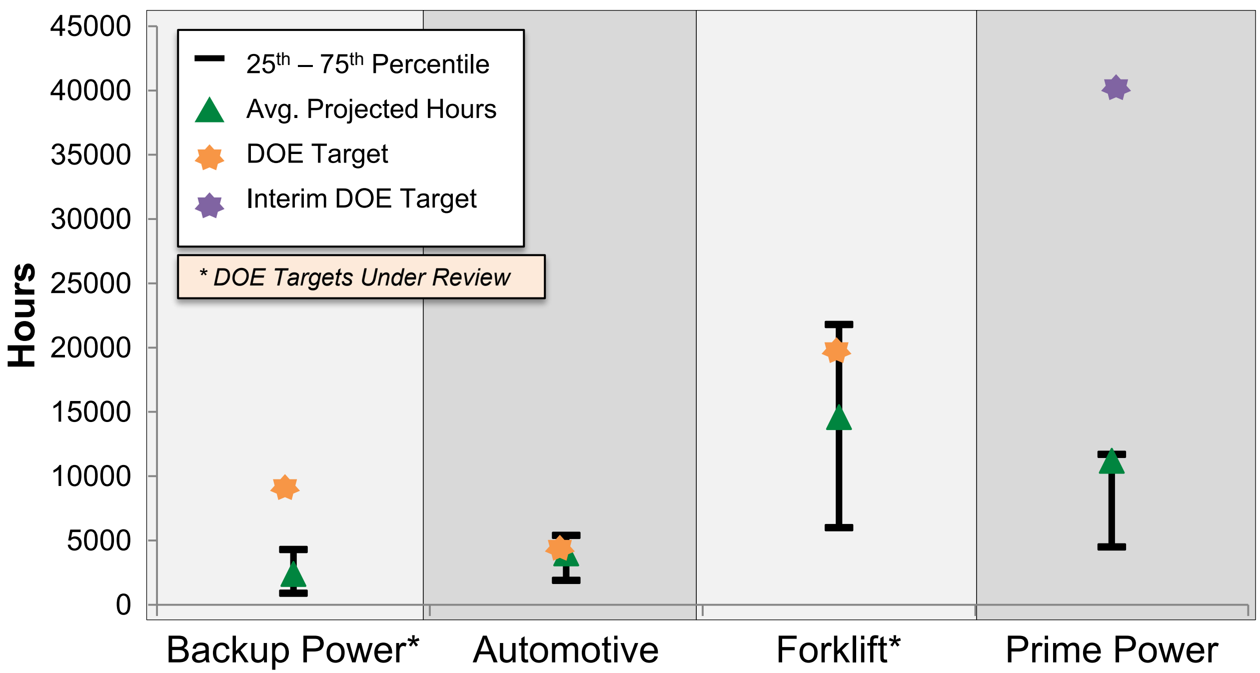
# Progress – Durability Assessment

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

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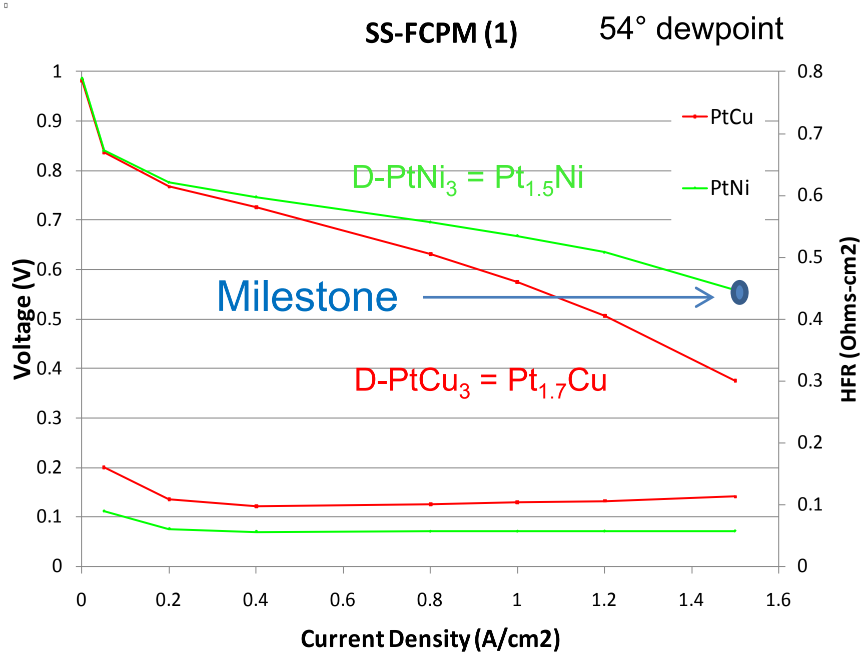
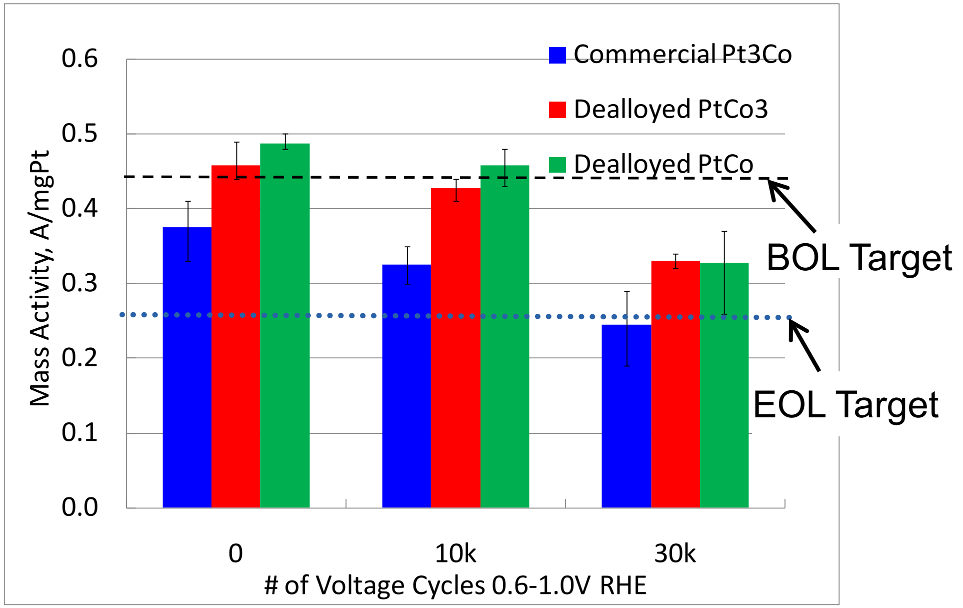
***Low-PGM de-alloyed catalysts meet mass activity and durability targets.***

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




GM 50 $cm^2$ 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 $A/cm^2$ milestone

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

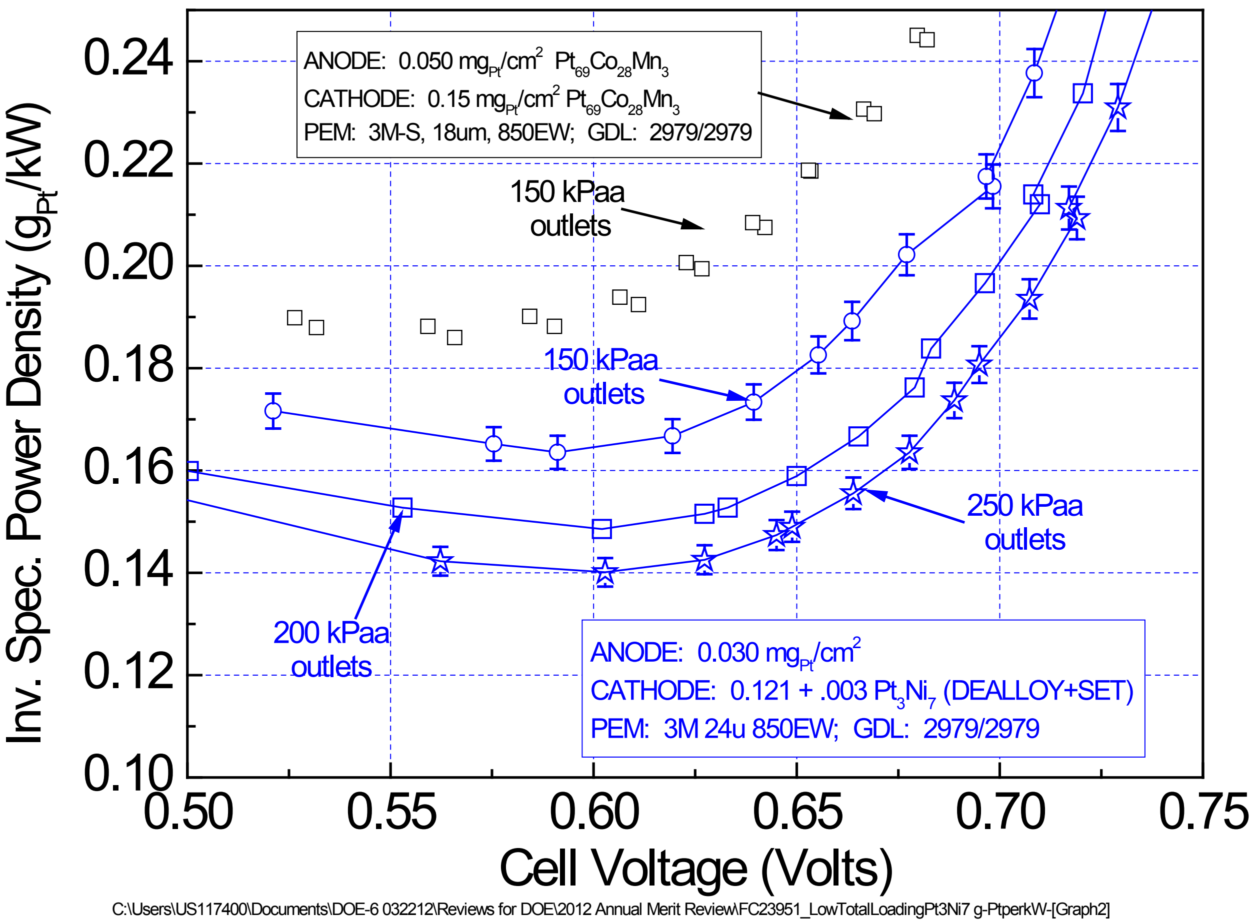
**0.52 $A/mg_{PGM}$ for $PtNi_3$ in 50 $cm^2$ MEA testing**

*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

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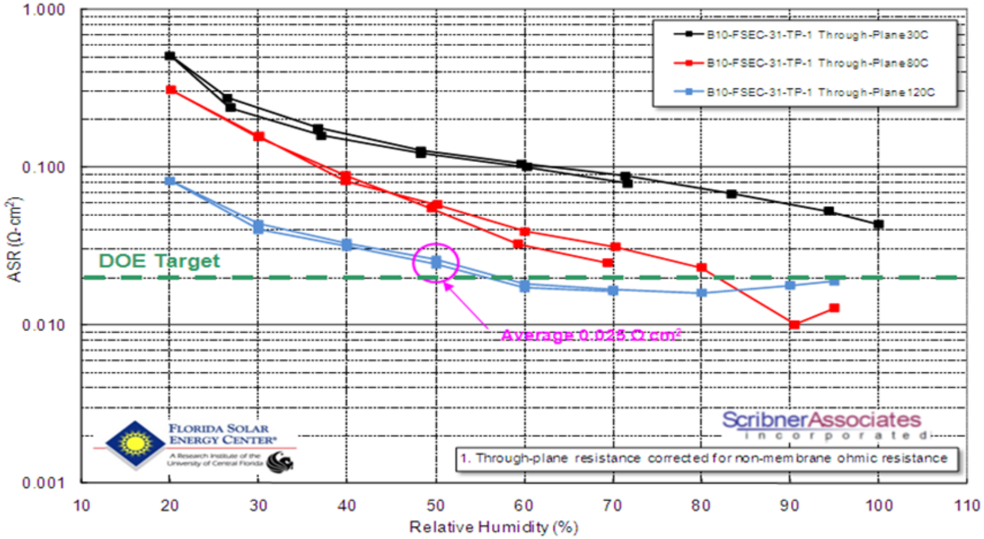
***Membranes containing multi-acid side chains or additives demonstrate conductivity higher than 0.1 S/cm under hot, dry conditions.***




**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)<br>0.012 (80 kPa) | ≤0.02 |
| ASR at 80°C ($p_{H2O}$ 25-45 kPa) | Ohm cm² | 0.013 (25 kPa)<br>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<br>Chemical Durability (OCV) | RH Cycles<br>Hours | >20,000<br>2,025 | ≥20,000<br>≥ 500 |

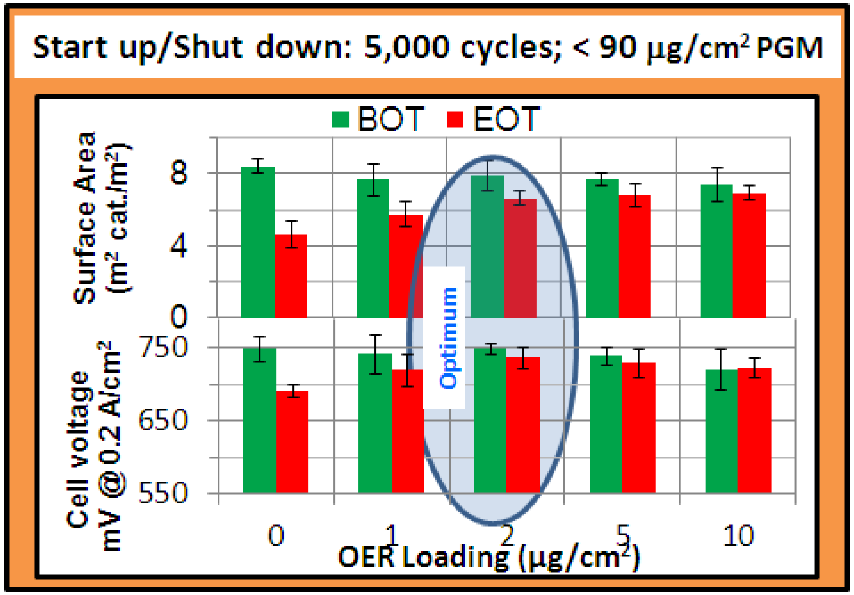
**3M: multi-acid side chain polymers have met most membrane targets**

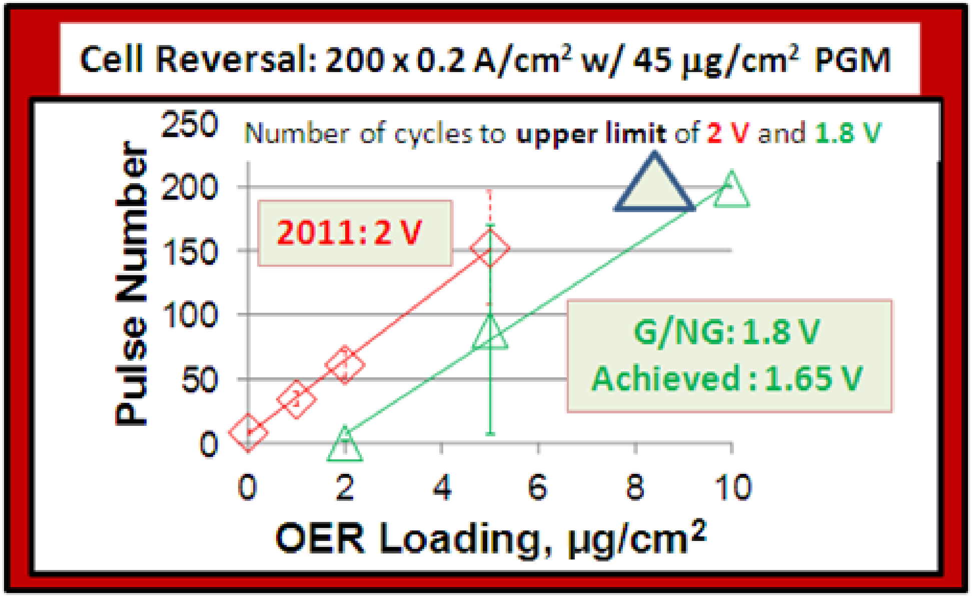
***S. Hamrock et al., 3M***

# 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

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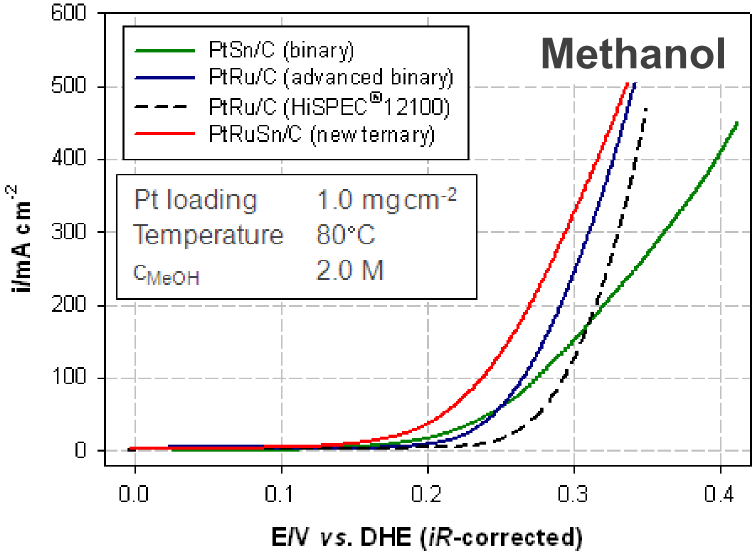
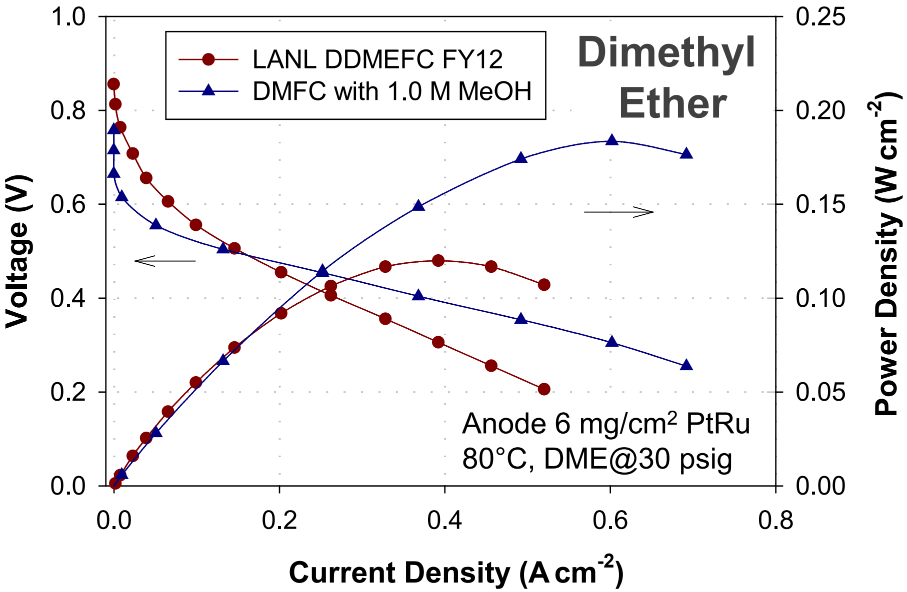
## *High-activity catalysts developed for liquid fuels*




- 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/cm$^2$** at 0.5 V – **60% higher than FY11**, **130% higher than best published data**

*P. Zelenay et. al., LANL*

# Progress: Portable Power

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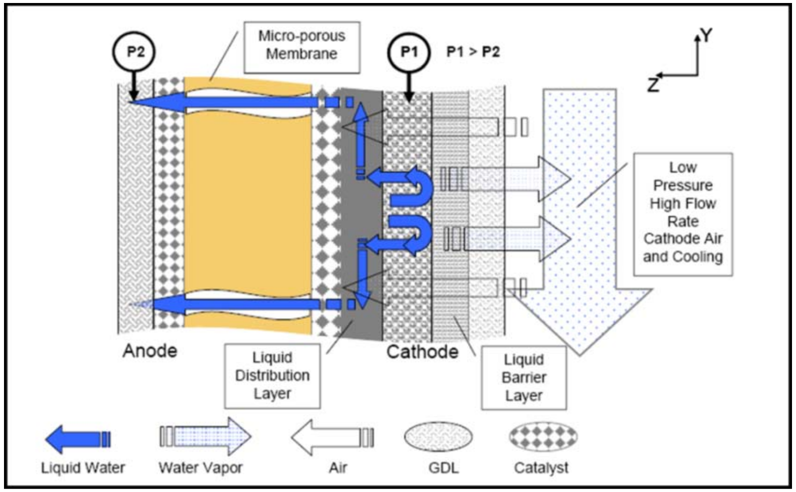
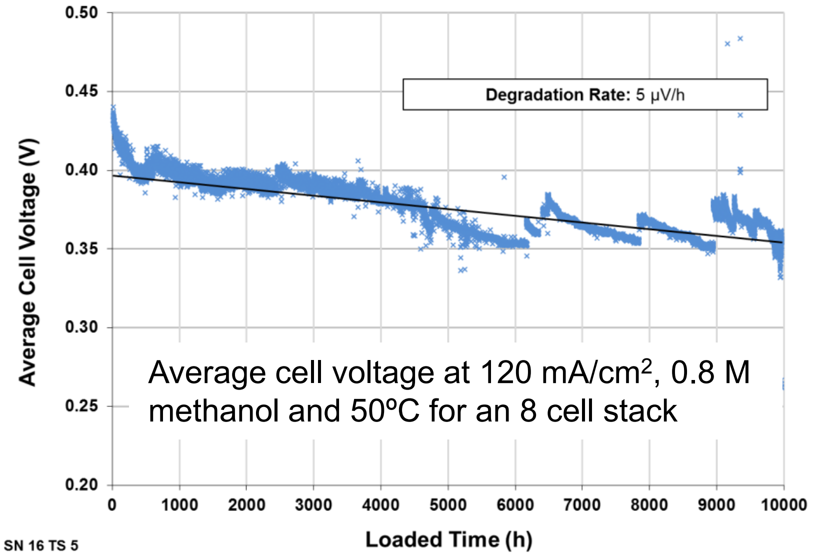
## *Passive water recovery DMFC enables BOP reduction.*




**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**




Average cell voltage at 120 mA/cm$^2$, 0.8 M methanol and 50°C for an 8 cell stack

| 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.

*J. Fletcher et. al., UNF*

SN 16 TS 5

# Progress: Balance of Plant

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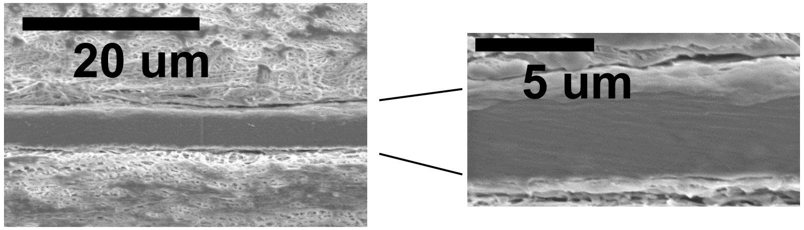
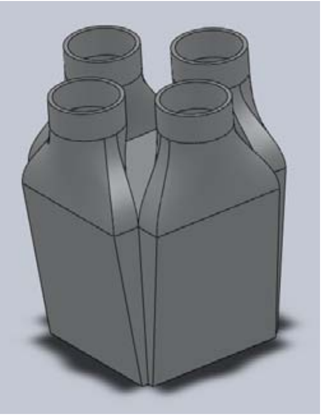
***Compact, low-cost humidifier module projected to meet $100/unit 2017 cost target***

**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

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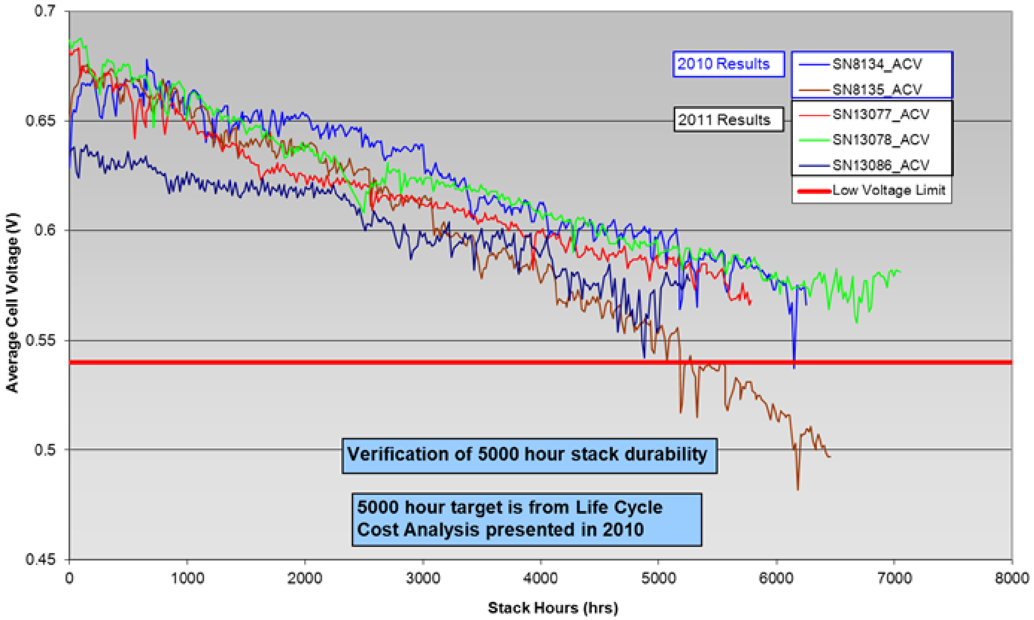
## *Increased freeze-tolerance and durability for material handling applications*




- **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

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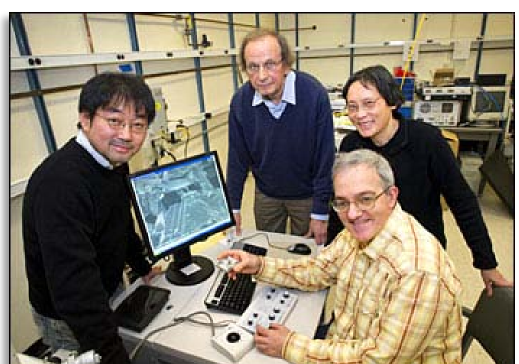
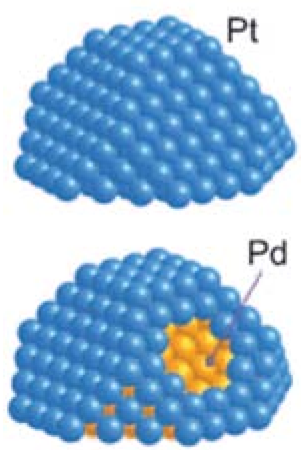
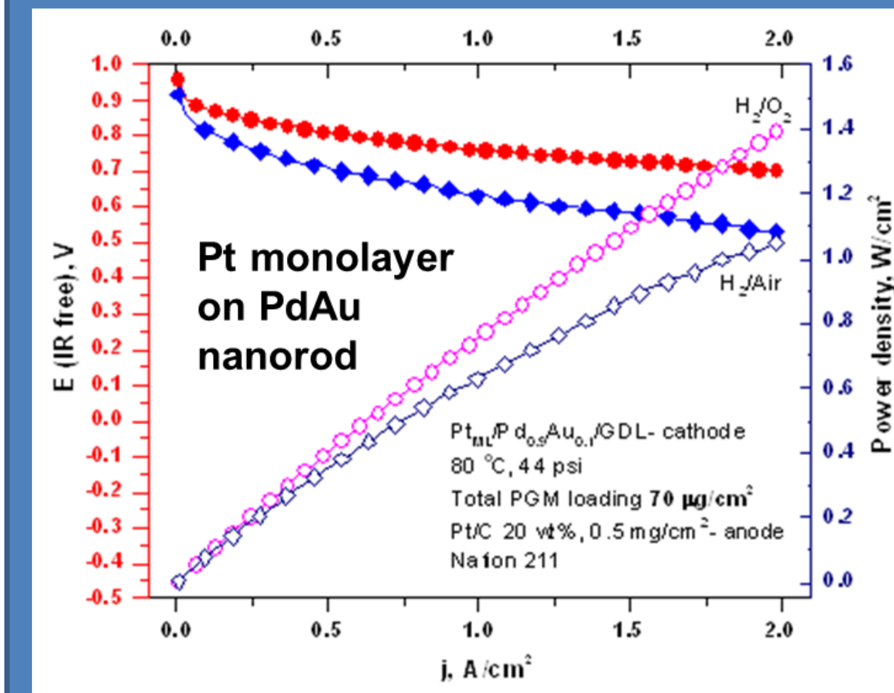
## *Brookhaven core-shell catalyst technology licensed by leading catalyst manufacturer*

- **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

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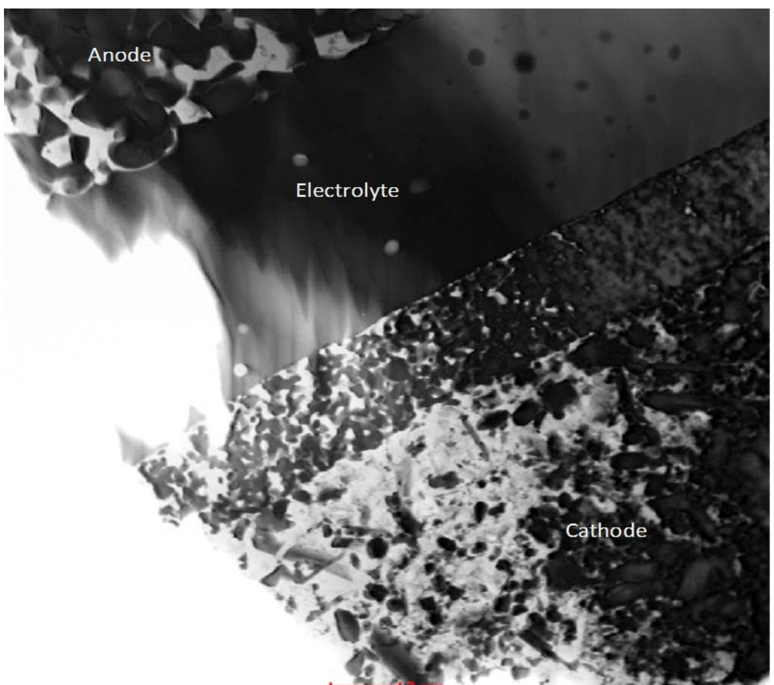
## *SOFCs developed for distributed generation and energy storage*

**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

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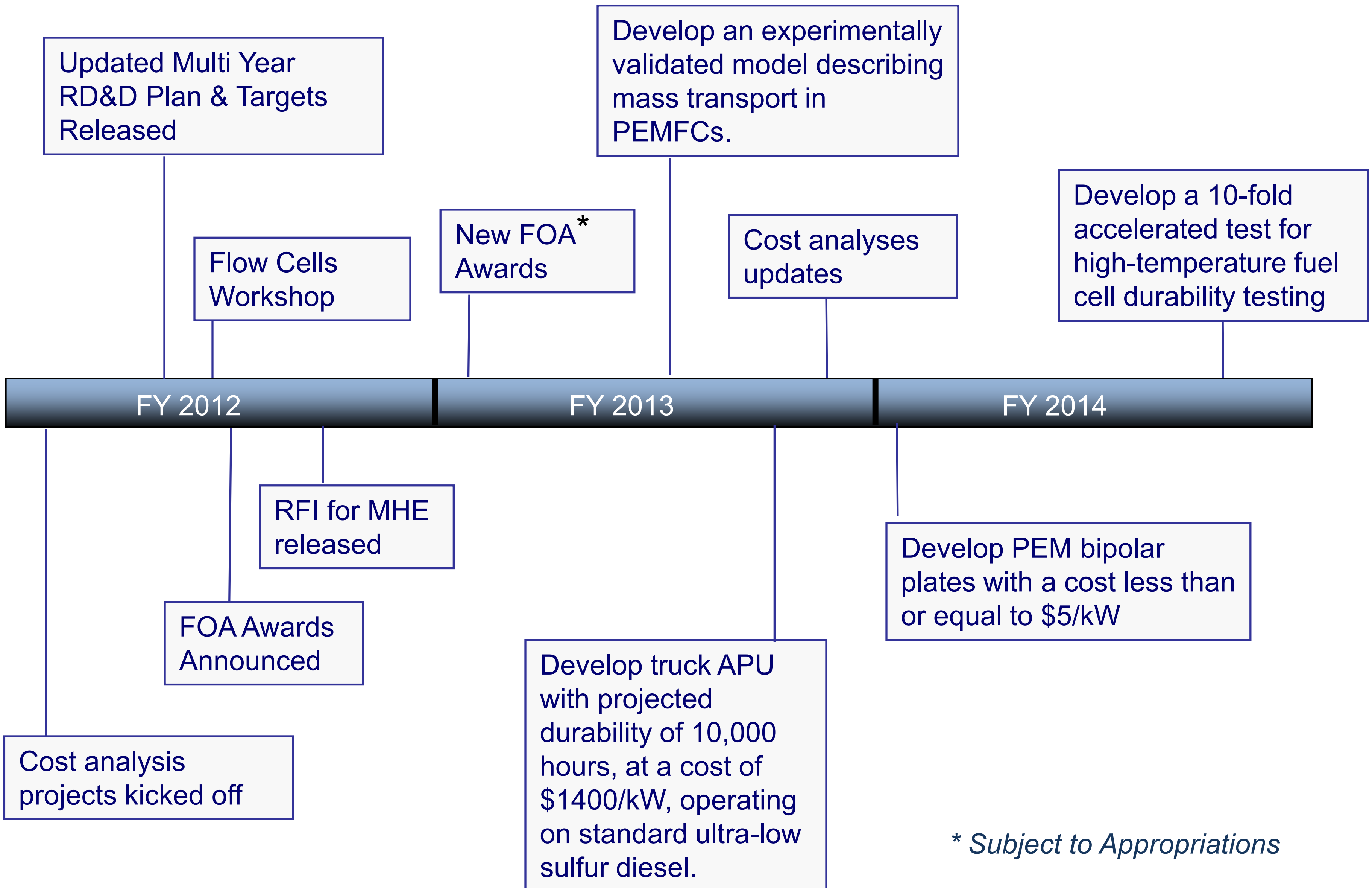


** Subject to Appropriations*

# 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

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***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



## 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

## *Fuel Cells Team*

**Dimitrios Papageorgopoulos**
Fuel Cells Team Leader
202-586-3388
dimitrios.papageorgopoulos@ee.doe.gov

**Nancy Garland**
Catalysts, Durability, Impurities, International
202-586-5673
nancy.garland@ee.doe.gov

**Donna Lee Ho**
Durability, Membranes, APUs, Portable Power, Mass Transport
202-586-8000
donna.ho@ee.doe.gov

**Greg Kleen**
Membranes, Mass Transport, MEAs, High-T Fuel Cells
720.356-1672
greg.kleen@go.doe.gov

**Jason Marcinkoski**
Cost Analysis, Bipolar Plates, BOP, Automotive, Stationary Power
202-586-7466
jason.marcinkoski@ee.doe.gov

**Kathi Epping Martin**
USDRIVE Fuel Cell Tech Team, Membranes, MEAs, Durability, Fuel Processors, Stationary Power
202-586-7425
kathi.epping@ee.doe.gov

**David Peterson**
Stationary Power, High-T Fuel Cells, Catalysts, Durability, Fuel Processors, APUs
720-356-1747
david.peterson@go.doe.gov

**Reginald Tyler**
Cost Analysis, BOP, Durability, Impurities, Portable Power, Stationary Power
720-356-1805
reginald.tyler@go.doe.gov

**Jacob Spendelow**
Technical Advisor on Detail from LANL
202-586-4796
jacob.spendelow@ee.doe.gov

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