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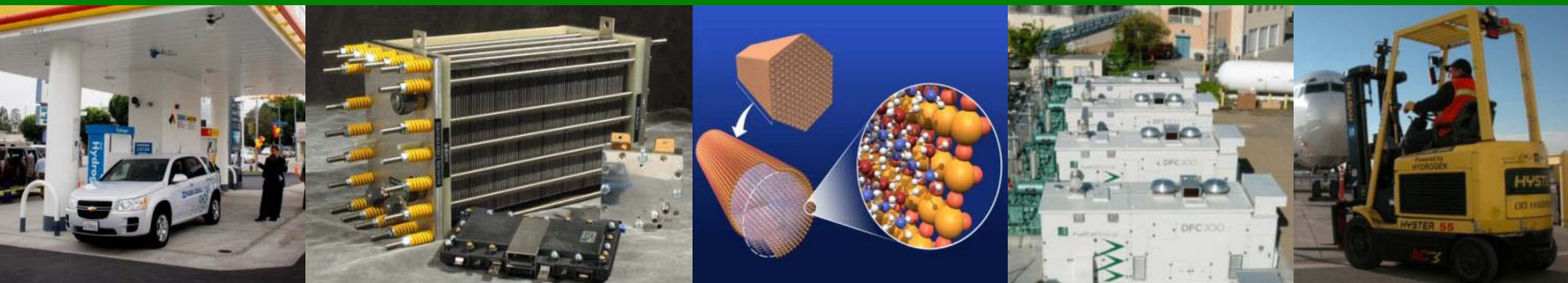

Fuel Cells

Dimitrios Papageorgopoulos

2011 Annual Merit Review and Peer Evaluation Meeting

May 9, 2011

Goal and Objectives

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

Develop fuel cell systems to meet DOE targets, including:

Transportation:
- Efficiency of 60% at 25% of rated power
- Cost of $30/kW
- Durability of 5000 hours

Stationary (CHP):
- Efficiency of 45%
- Durability of 60,000

Auxiliary Power Units:
- Efficiency of 40% at rated power
- Cost of $1000/kW
- Durability of 20,000 hours

Portable Power:
- Power density of 100 W/L
- Durability of 5000 hours

A Broad Range of Technologies and Applications

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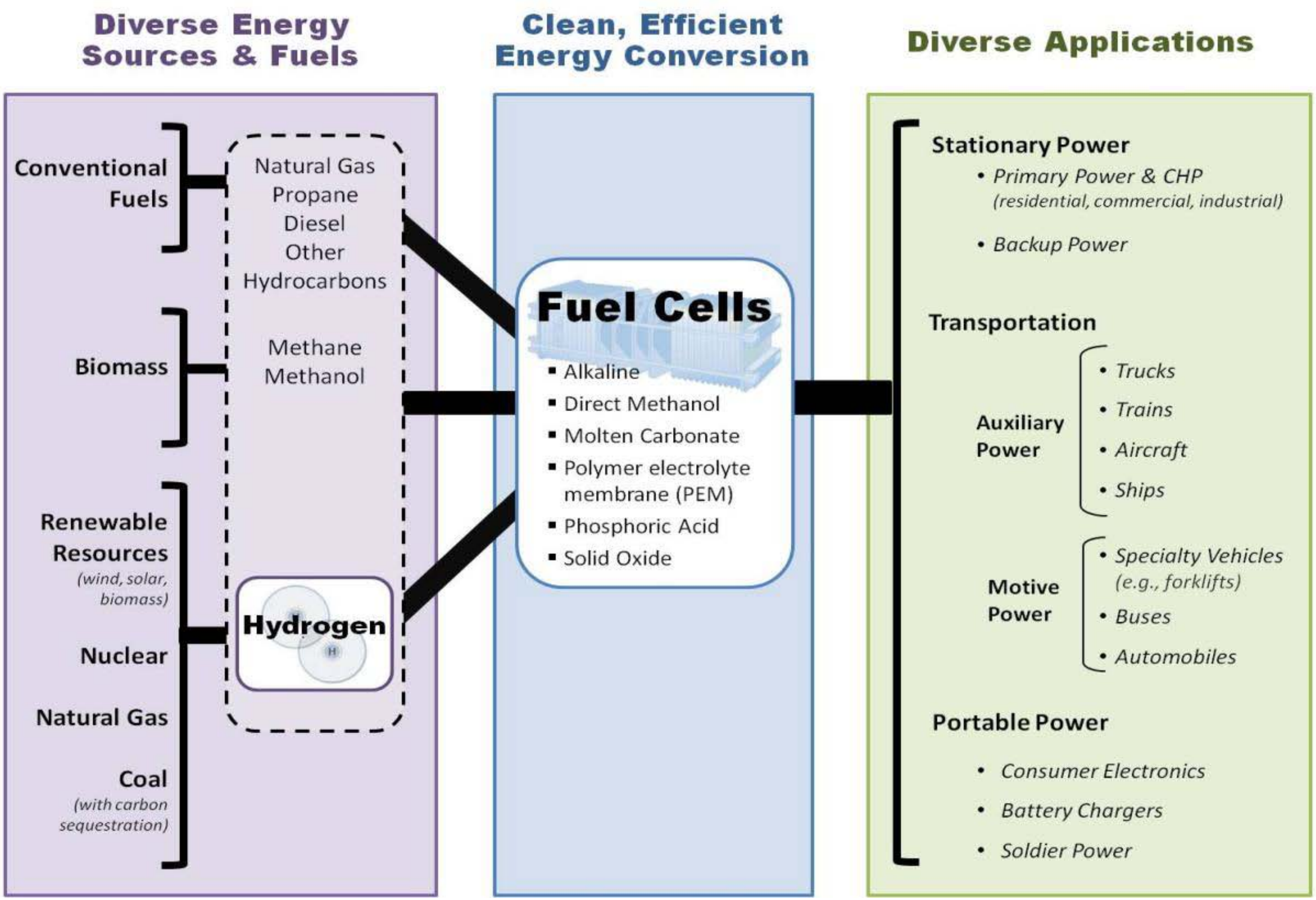
The sub-program supports a diverse portfolio of fuel cell technologies, to meet application-driven targets for commercial viability in terms of cost and performance.



Challenges & Strategy

U.S. DEPARTMENT OF ENERGY

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.

Barriers

Cost
Durability
Air/thermal/water management
Application Form Factor
Fuel flexibility for stationary applications

Strategy

Materials 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
Membranes
GDL s and Seals
Bipolar Plates
MEAs and Integration
High-Temperature Fuel Cells

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 and Strategies: Catalysts and Supports

U.S. DEPARTMENT OF ENERGY

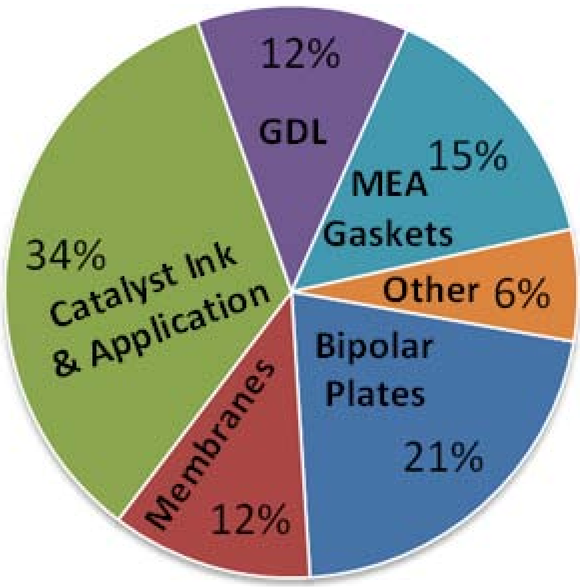
Challenges:

- ***Platinum (Pt) cost is ~34% of total stack cost***
- ***Catalyst durability needs improvement***

Four Strategies for Catalysts & Supports R&D:

- Lower PGM Content
  - Improved Pt catalyst utilization and durability
- Pt Alloys
  - Pt-based alloys with comparable performance to Pt and cost less
- Novel Support Structures
  - Non-carbon supports and alternative carbon structures
- Non-PGM catalysts
  - Non-precious metal catalysts with improved performance and durability

Stack Cost - $25/kW



DTI, 2010 analysis, scaled to high volume production of 500,000 units/yr

Used $1100/Troy Ounce for Pt Cost

Challenges and Strategies: Membranes

U.S. DEPARTMENT OF ENERGY

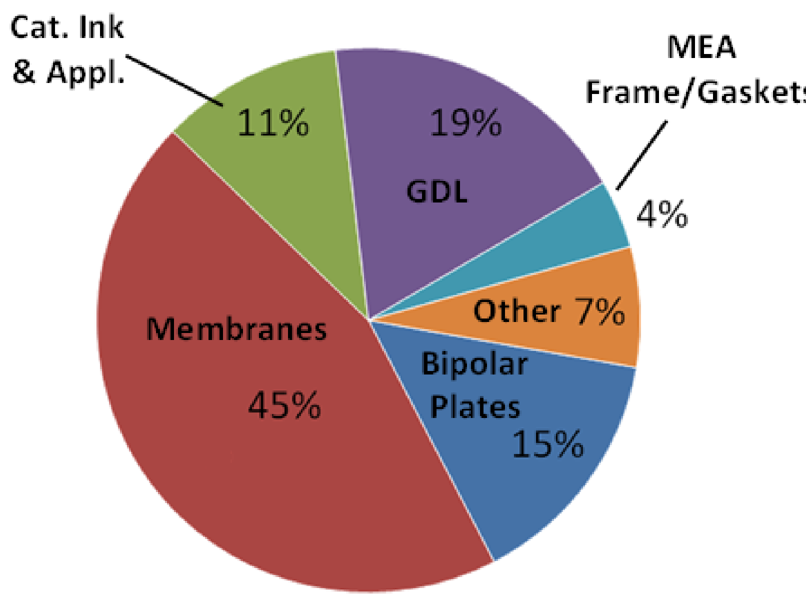
Challenges:

- ***Membranes account for 45% of stack cost at low volume***
- ***Limits on operating range***
- ***Chemical and mechanical durability***

Membrane R&D:

- High-Temperature, Low Humidity Conductivity
  - Phase segregation (polymer & membrane)
  - Non-aqueous proton conductors
  - Hydrophilic additives
- High Conductivity and Durability Across Operating Range with Cycling
  - Mechanical support or membrane reinforcement
  - Chemical stabilization (additives, end-group capping)
  - Polymer structure (side chain length, grafting, cross-linking, backbone properties, blends, EW)
  - Processing parameters (temperature, solvents)
  - New materials

Stack Cost - $144/kW



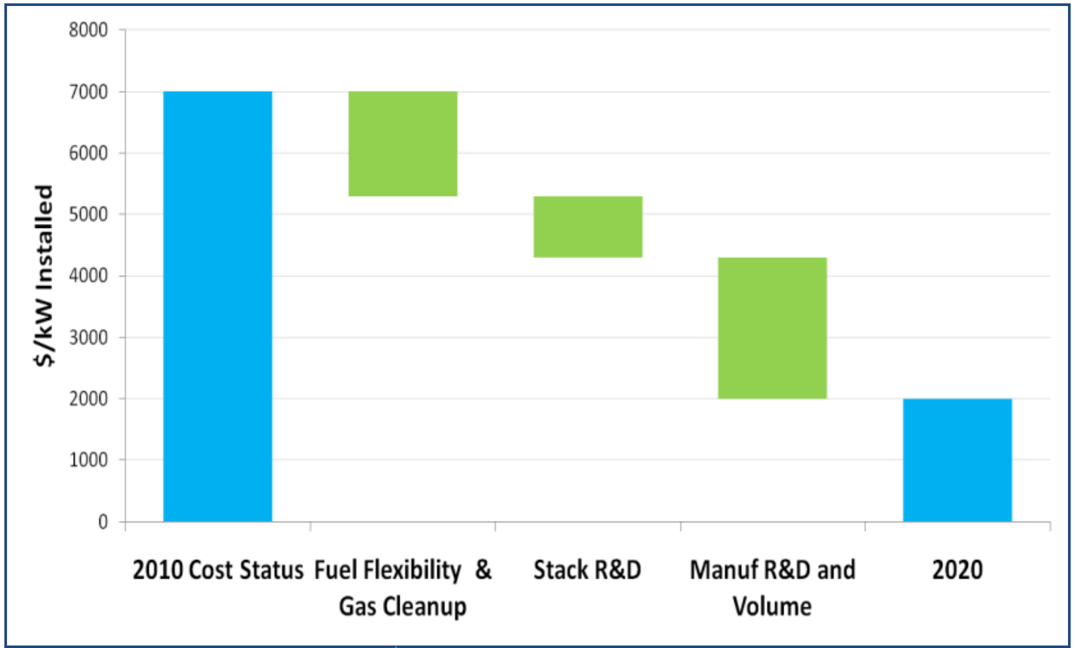
DTI, 2010 analysis, production of 1,000 units/yr

Challenges and Strategies: CHP

U.S. DEPARTMENT OF ENERGY

Technical and cost gap analyses of molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) stationary fuel cell power plants identify pathways for reducing costs.

Medium-Scale Fuel Cell CHP with Biogas



Development of a cost-effective process for removing fuel contaminants would allow for fuel flexibility.

Key areas identified:

➢For MCFC, the service life of the fuel cell stack needs to be extended by:

- reducing electrolyte losses
- reducing cathode dissolution
- increasing the stability of the electrolyte support material

➢For PAFC, cost reductions could be achieved by reducing:

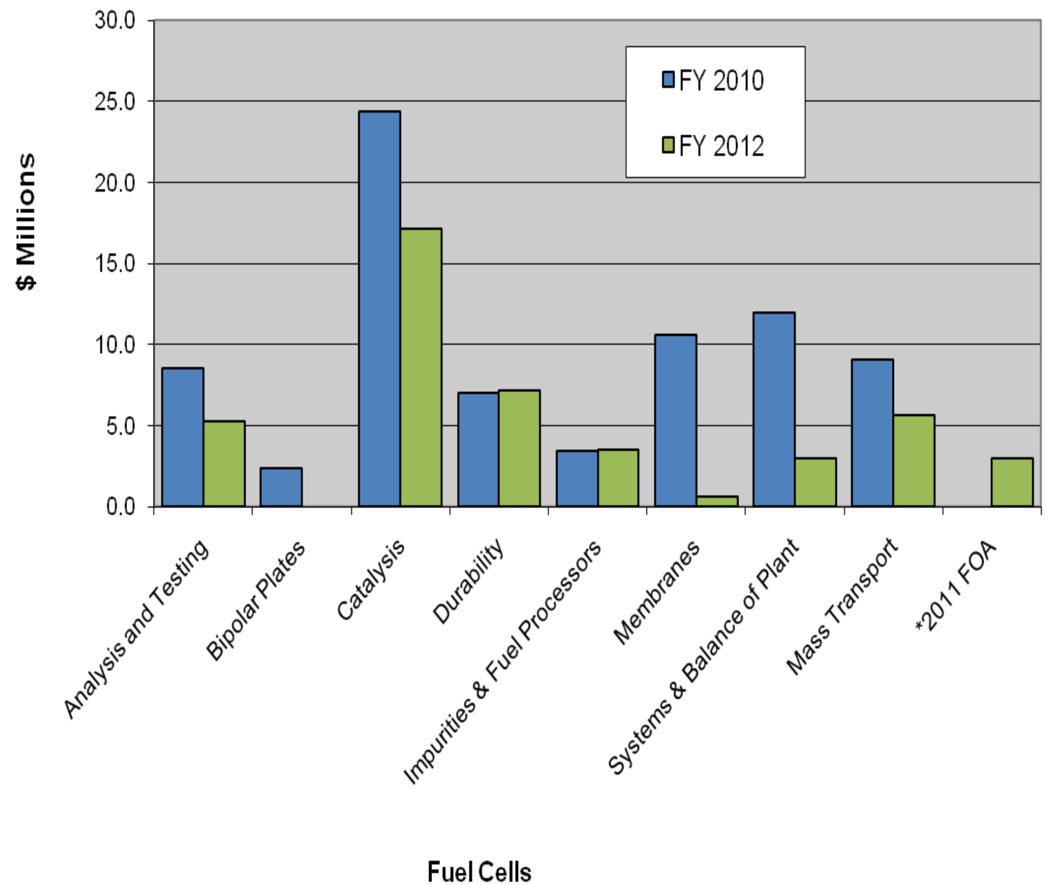
- platinum loading
- the impact of the anion adsorption on the cathode catalyst

Fuel Cells Budget

U.S. DEPARTMENT OF ENERGY

FY 2012 REQUEST = $45.4M

FY 2010 APPROPRIATION = $77.4M



[1]Systems & Balance of Plant includes Stationary and Portable Power

*subject to appropriations

EMPHASIS:
is on science and engineering at the cell level, and from a systems perspective, on integration and component interactions:

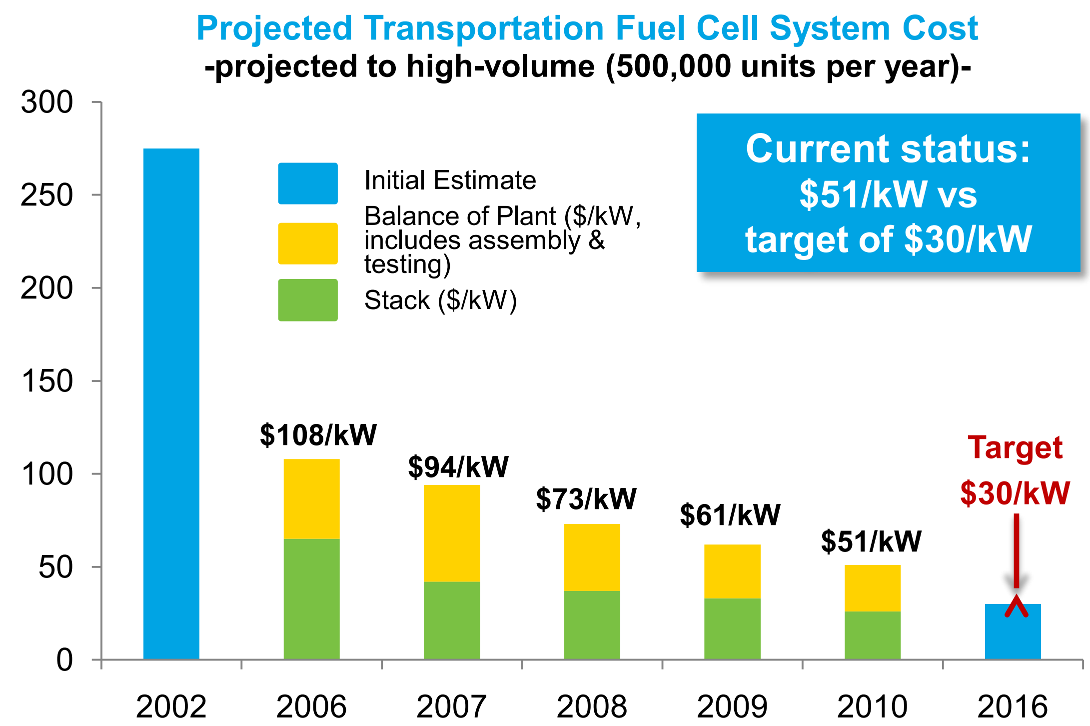
- Develop improved fuel cell catalysts and membrane electrolytes
- Identify degradation mechanisms and approaches for mitigating the effects
- Characterize and optimize transport phenomena improving MEA and stack performance
- Investigate and quantify effects of impurities on fuel cell performance
- Develop low-cost, durable, system balance-of-plant components

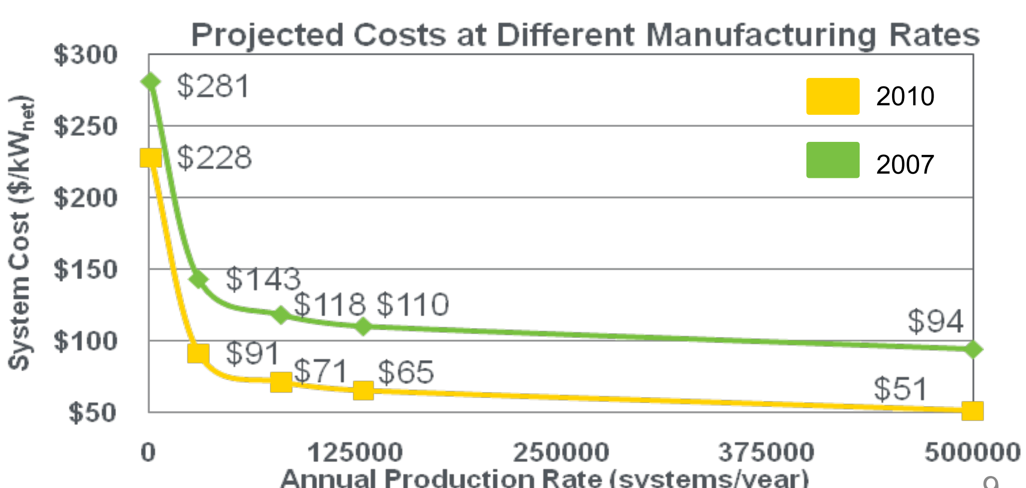
Progress: Fuel Cells

U.S. DEPARTMENT OF ENERGY

Reduced the projected high-volume cost of fuel cells to $51/kW (2010)*

- ***More than 30% reduction since 2008***
- ***More than 80% reduction since 2002***





**Based on projection to high-volume manufacturing (500,000 units/year).*

***Panel found $60 – $80/kW to be a "valid estimate": http://hydrogendoedev.nrel.gov/peer_reviews.html*

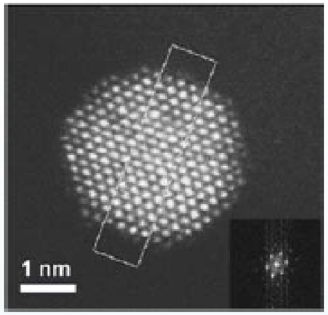
http://www.hydrogen.energy.gov/pdfs/10004_fuel_cell_cost.pdf

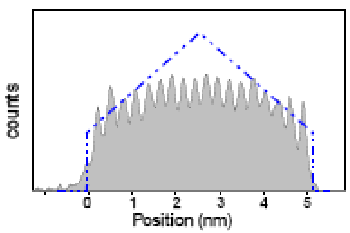
Progress: Catalysts

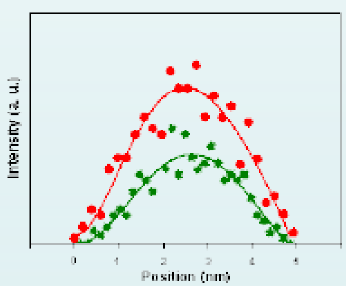
U.S. DEPARTMENT OF ENERGY

Nano-segregated binary and ternary catalysts demonstrate performance more than 6X that of platinum.

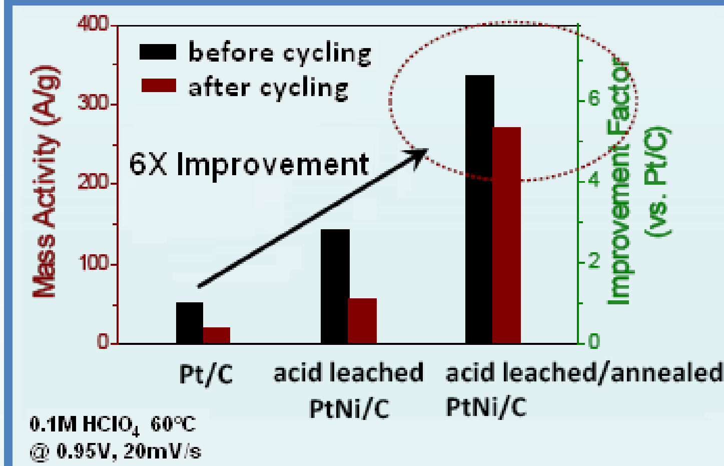
Nanosegregated Binary (PtNi)







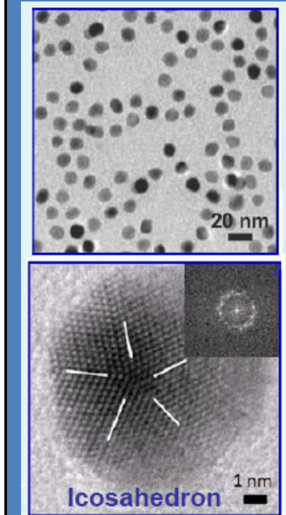
Multilayered Pt-skin surfaces confirmed for PtNi annealed NPs

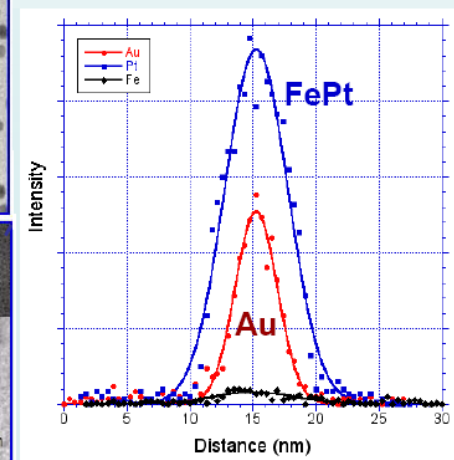


Performance: Nanosegregated PtNi/C catalysts have ORR mass activity **~0.35 A/mg** in MEA testing – *approaching 0.44 A/mg target*

Durability: 3X improved retention of mass activity after 20,000 potential cycles compared to Pt/C

NanosegregatedTernary (PtFeAu)





Performance:
FePt(shell)/Au(core) demonstrates ORR mass activity more than 3X that of Pt/C

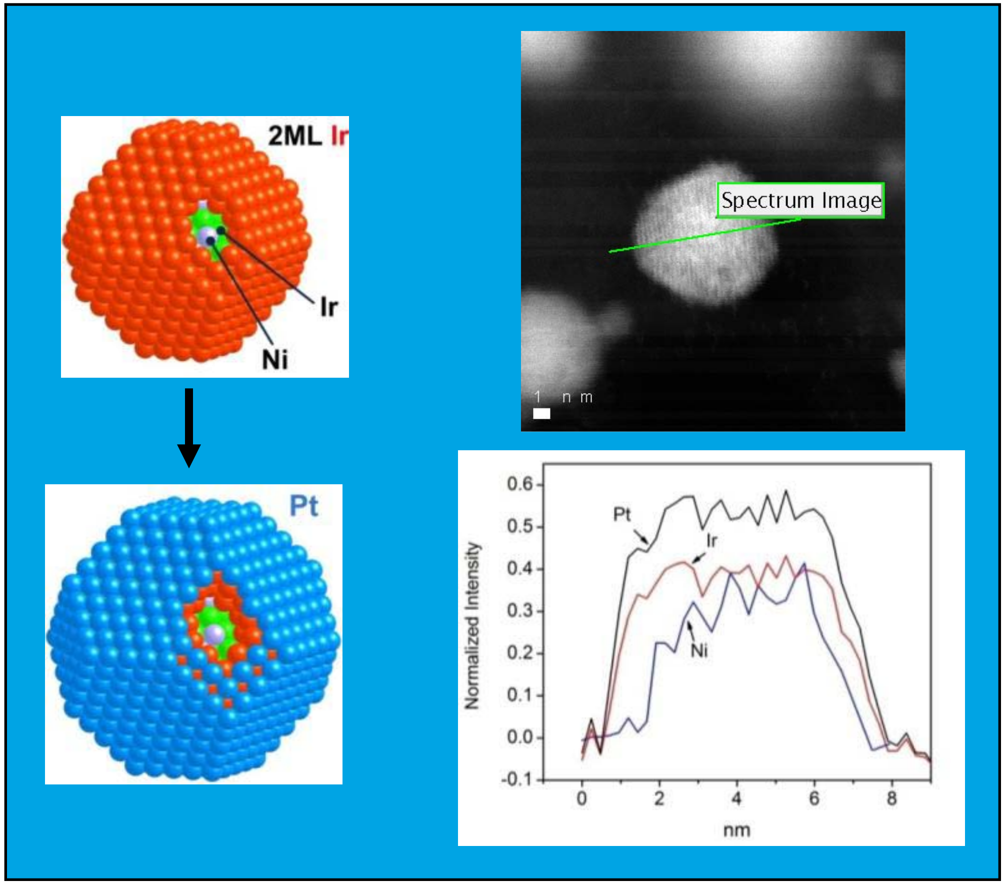
Durability:
Maintains 80% of initial activity after 80,000 potential cycles (cf. less than 20% for Pt/C)

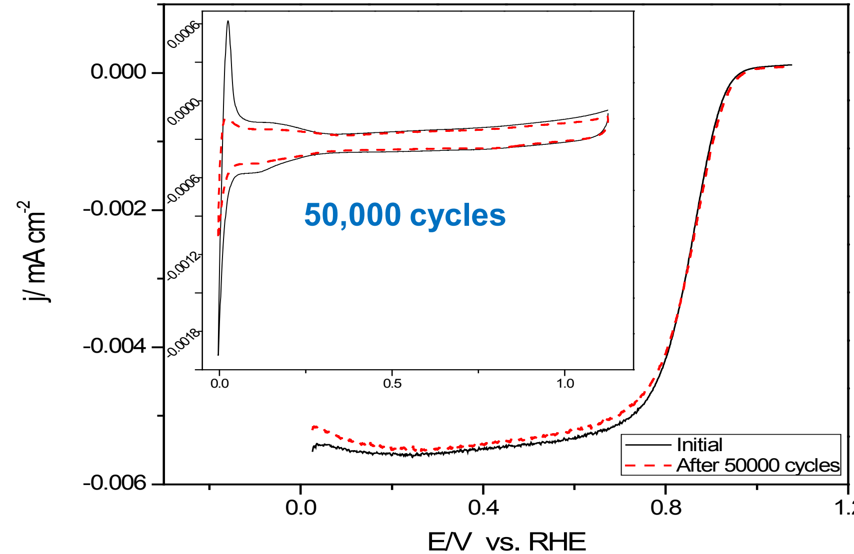
N. Markovic et al., ANL

Progress: Catalysts

U.S. DEPARTMENT OF ENERGY

New core-shell catalysts achieve high performance and high durability.





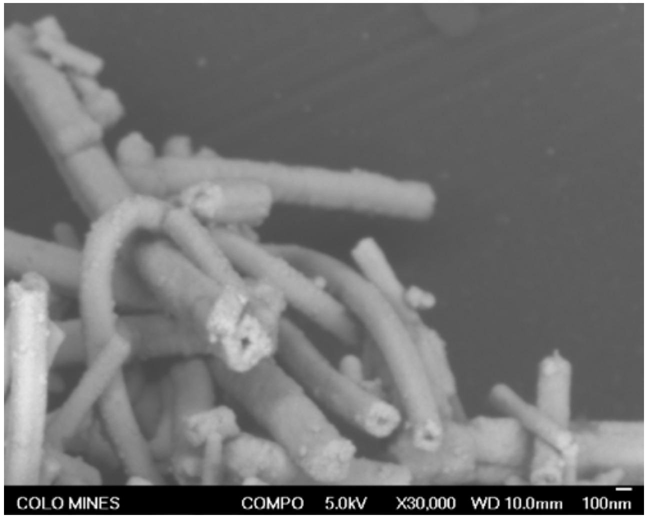
- **Performance: 0.78 A/mg$_{PGM}$ for Pt/IrNi/C in RDE testing – high chance of achieving 0.44 A/mg$_{PGM}$ target in MEA**
- **Durability: Demonstrated 50,000 potential cycles with no loss in performance (cf. 39 mV loss for Pt/C after 30,000 cycles)**

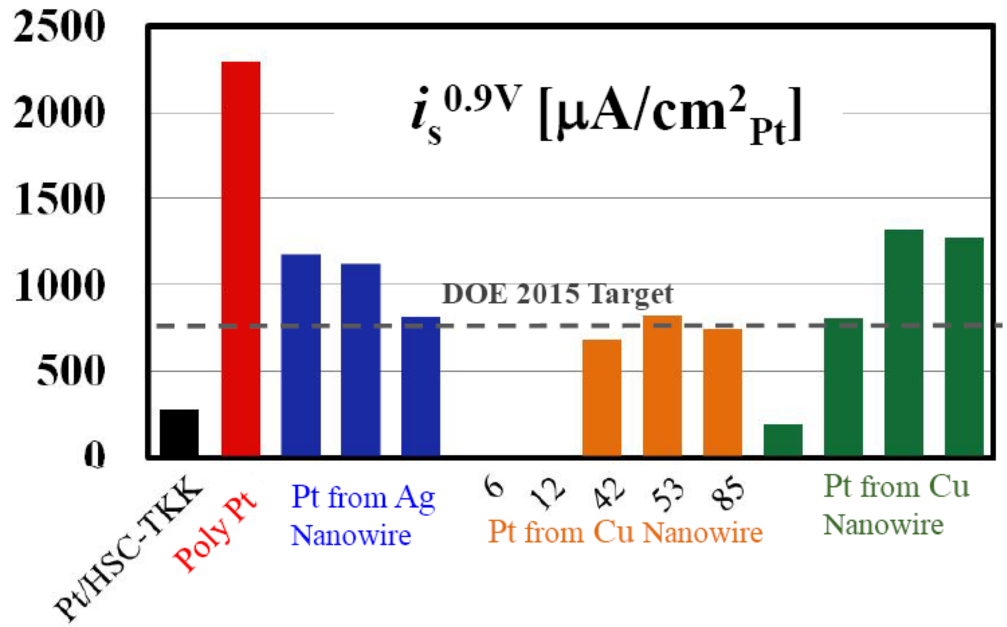
Radoslav Adzic honored as BNL Inventor of the Year for his work on fuel cell catalysis!

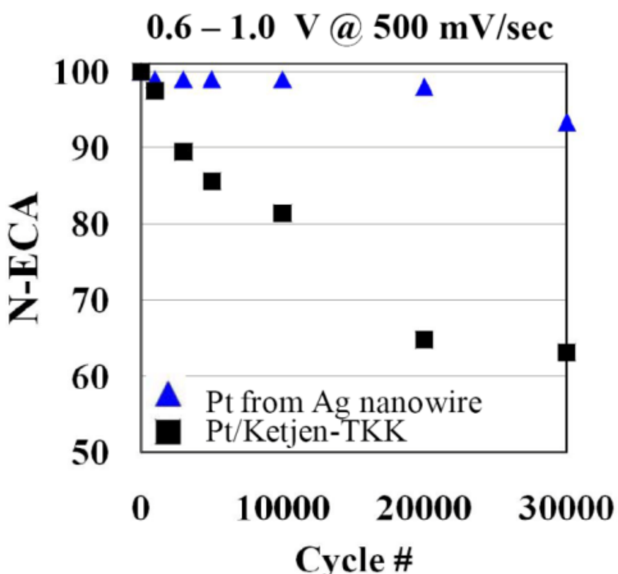
Progress: Catalysts

U.S. DEPARTMENT OF ENERGY

Demonstrated Pt nanotube catalysts with high activity and durability







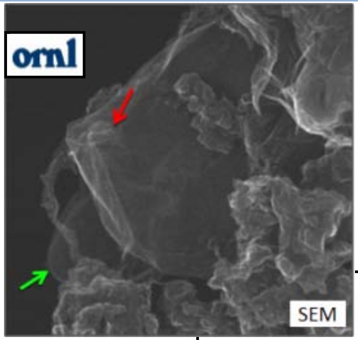
- **Pt nanotube catalysts achieve specific activity higher than 1200 µA/cm², exceeding 720 µA/cm² target**
- **Loss in catalyst surface area during 30,000 potential cycles is more than 75% lower for Pt nanotubes than for conventional Pt/C**

B. Pivovar et al., NREL

Progress: Catalysts

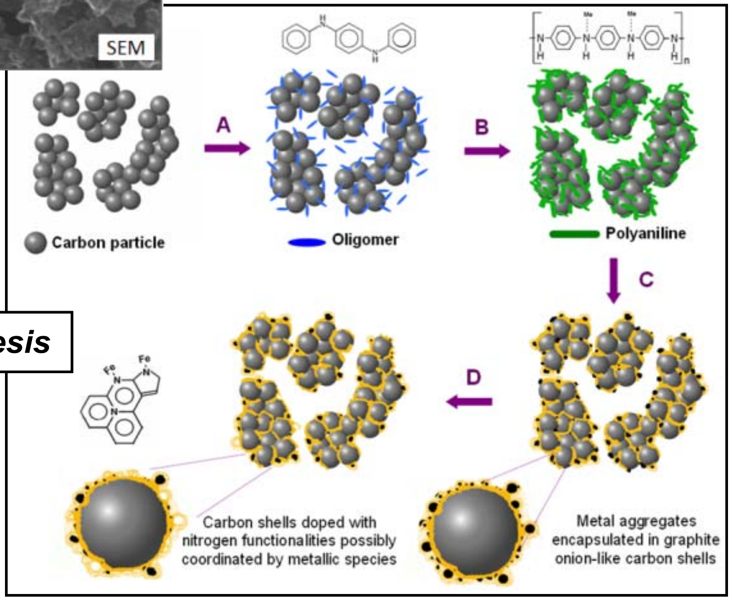
U.S. DEPARTMENT OF ENERGY

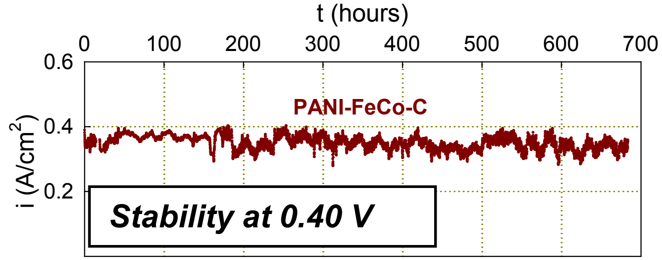
Non-PGM catalysts demonstrate activity approaching that of platinum.

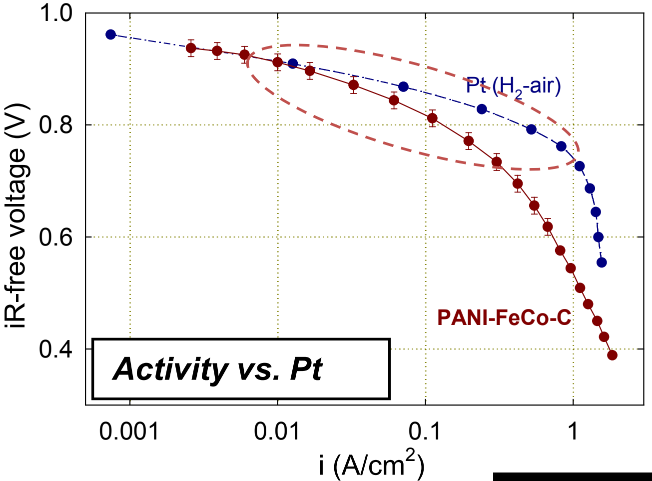


Catalyst SEM: *Layered-graphene sheet marked with green arrow; FeCo-containing nanoparticle shown with red arrow.*

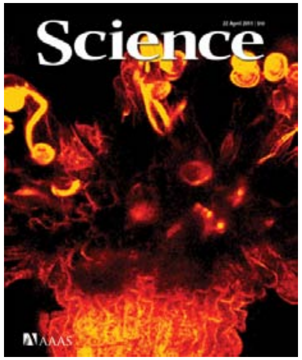
The Synthesis







G. Wu, K. L. More, C. M. Johnston, P. Zelenay, *Science*, **332**, 443-7 (2011)



P. Zelenay et al., LANL

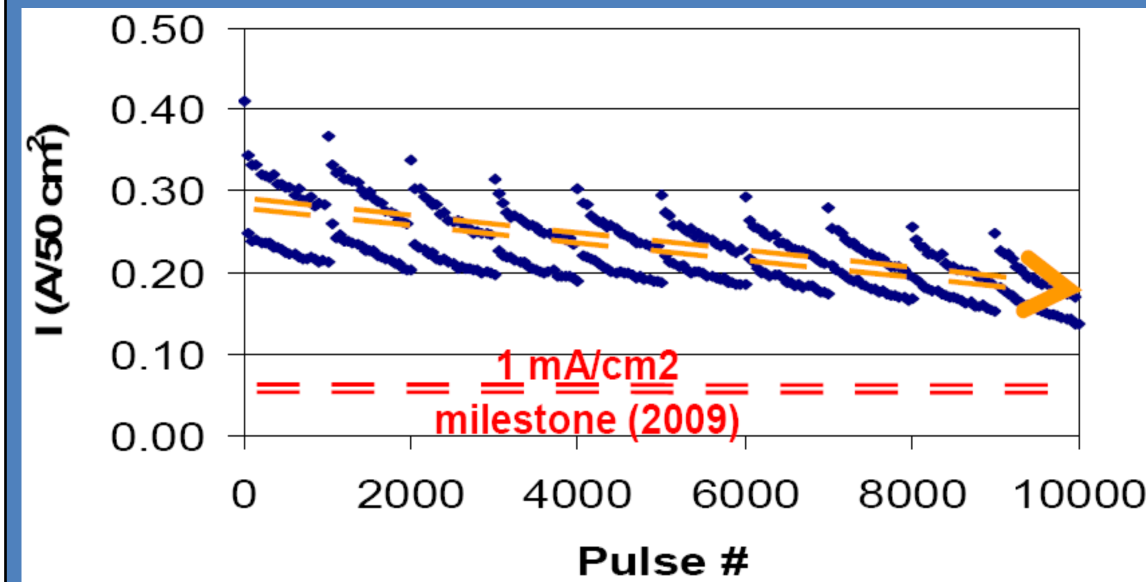
- **High ORR activity reached with polyaniline-based and cyanamide-based catalysts**
- **Intrinsic catalyst activity is projected to exceed target of 130 A/cm^3 at 0.80 V**

Progress: Catalysts

U.S. DEPARTMENT OF ENERGY

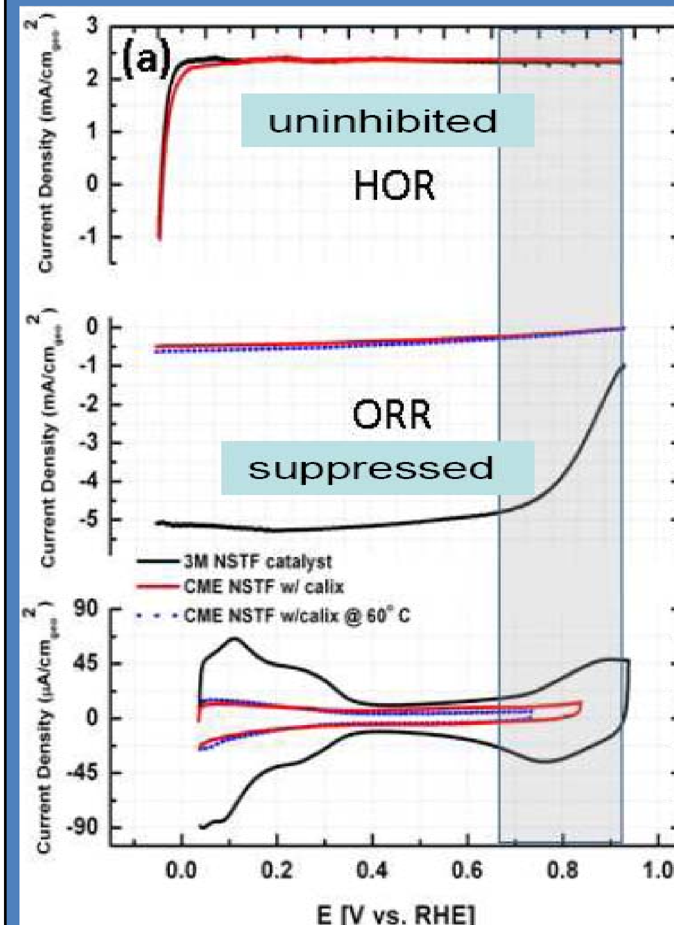
New cathode and anode catalysts demonstrate durability under startup/shutdown.

Cathode side: enhance OER to prevent catalyst/support oxidation, while maintaining ORR performance



OER performance greatly exceeds milestone, and is durable for more than 10,000 cycles

Anode side: suppress ORR to prevent cell reversal, while maintaining HOR performance



New catalyst modifiers allow achievement of 10,000 simulated startup/shutdown cycles with only 2 µg/cm² additional PGM

R. Atanasoski et al., 3M

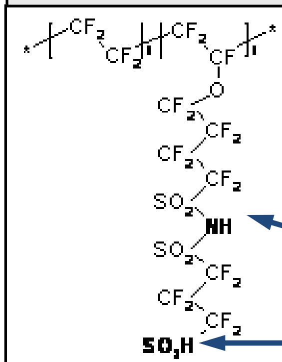
Progress: Membranes

Innovative membranes demonstrate high conductivity at low RH.

- PFIA membranes **meet most DOE targets** for performance and durability
- PFIA maintains high crystallinity at lower equivalent weight than PFSAs → **better mechanical properties**
- High conductivity with PFIA under dry conditions: 0.087 S/cm @ 120 C, 25% RH

Remaining gap

		3M 2011 Status	2015 target
ASR at 120° C (H_2O pp 40-80 kPa)	Ohm cm²	.023 (40 kPa) 0.012 (80kPa)	<0.02
ASR at 80° C (H_2O pp 25-45 kPa)	Ohm cm²	0.013 (25 kPa) 0.006 (44 kPa)	<0.02
ASR at 30° C (H_2O pp 4 kPa)	Ohm cm²	0.02 (3.8 kPa)	<0.03
ASR at -20° C	Ohm cm²	0.10	<0.2
O_2 cross-over	mA/cm²	≤1.0	<2
H_2 cross-over	mA/cm²	≤1.8	<2
Durability Mechanical (%RH Cycle) Chemical (OCV)	Cycles Hours	>20,000 >1100+	>20,000 >500



PFIA

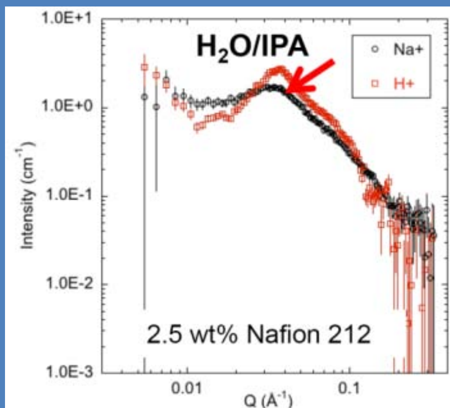
Two superacid sites per side chain

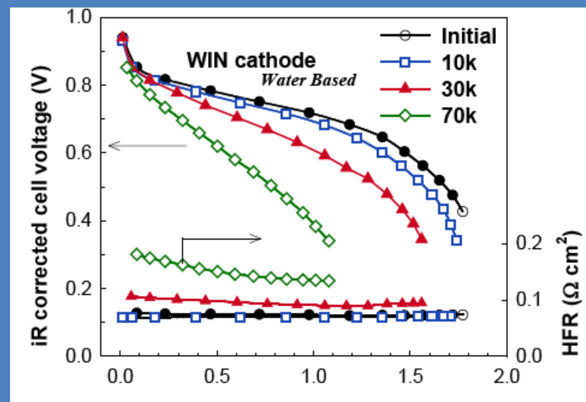
S. Hamrock et al., 3M

Progress: Degradation Studies

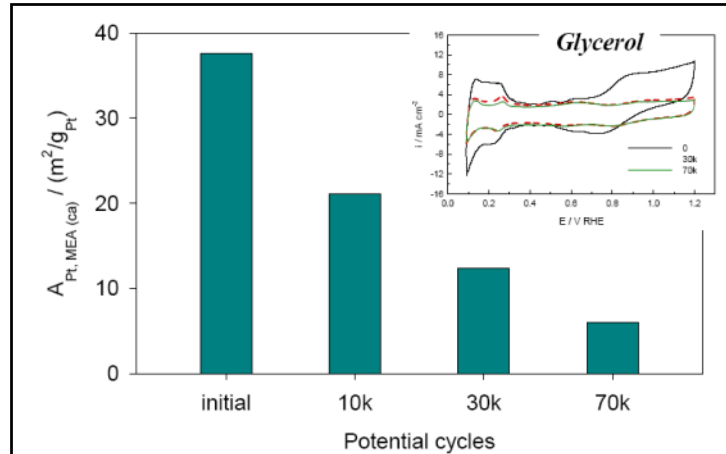
U.S. DEPARTMENT OF ENERGY

Degradation studies enable design of more durable electrodes.

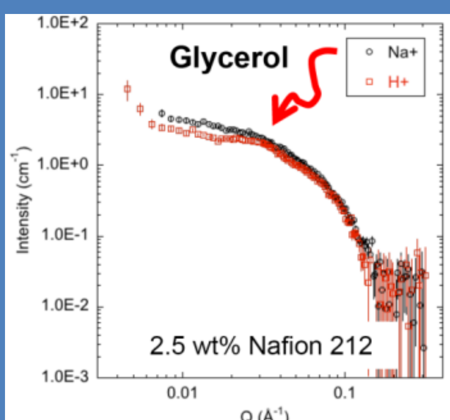


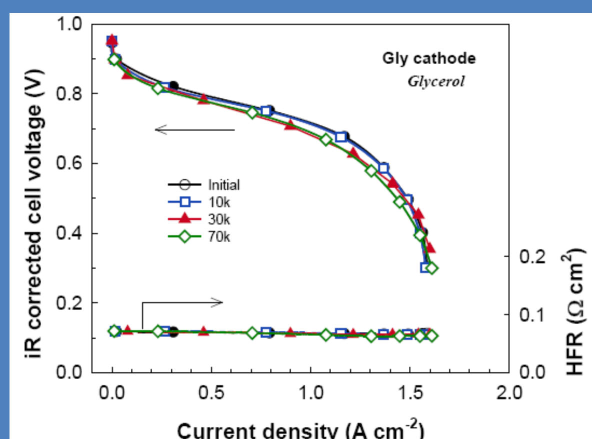


Ionomer ordering in water/alcohol → **Poor durability**

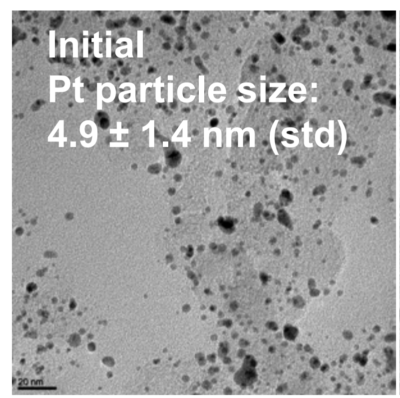


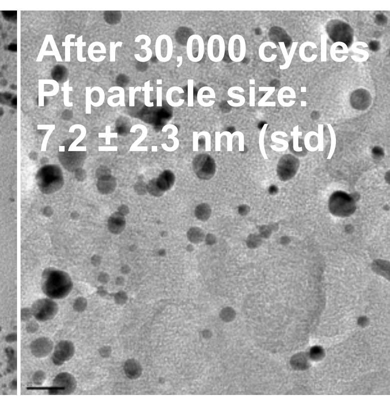
Catalyst degradation is complex – major loss in ECSA with negligible loss in performance





Lack of ordering in glycerol → **High durability – exceeds 30,000 cycle target**





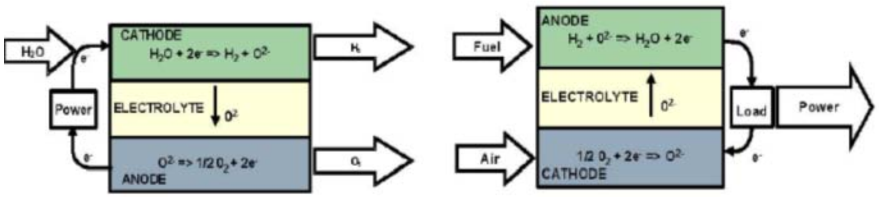
Y. Kim, C. Johnston et al., LANL

Progress: Stationary SOFCs

U.S. DEPARTMENT OF ENERGY

Improved performance and durability of SOFC systems

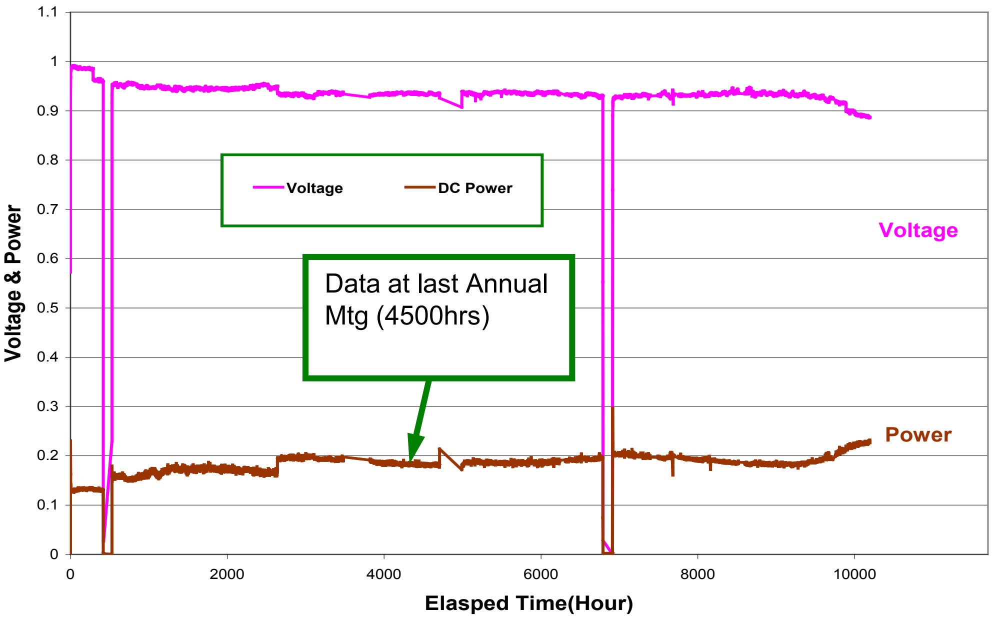
Reversible SOFCs under development at Versa Power Systems provide hydrogen generation and energy storage capability



Project Targets Met in 2011:

Metric	Target	Status
☑ **Performance** (Area specific resistance in both SOFC and SOEC operating modes)	**< 0.3 Ω-cm²**	**0.223 Ω-cm² in SOEC** **0.224 Ω-cm² in SOFC**
☑ **Degradation** (Overall decay rate)	**< 4% per 1000 hours**	**~1.5% per 1000 hours**
☑ **Operating Duration**	**> 1000 hours**	**1005 hours** (as of Go/No-Go Decision)
☑ **Operating Current Density**	**> 300 mA/cm²**	**500 mA/cm²**

R. Petri et al., Versa Power Systems



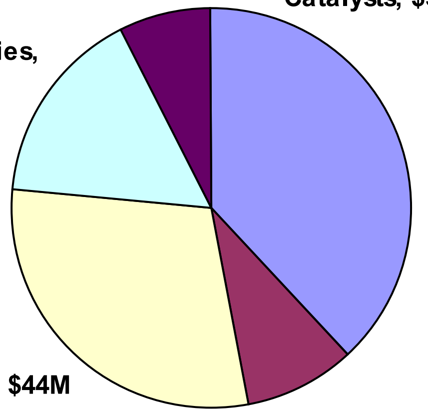
Acumentrics has achieved more than 10,000 hours operation of an SOFC in 2011 – more than double the 2010 durability

N. Bessette et al., Acumentrics

New Fuel Cell Projects

U.S. DEPARTMENT OF ENERGY

9 new R&D projects kicked off in 2010, in addition to 28 from 2009 —total award of $150M



New projects will:

- **Develop improved fuel cell catalysts**
- **Enhance fuel cell durability**
- **Characterize transport phenomena**
- **Optimize fuel cells for early market applications**
- **Develop innovative concepts leading to a new generation of fuel cell technology**

Projects led by stakeholders in industry, universities, and national labs

Industry

3M
Arkema
Ballard Power Systems
DuPont
Giner Electrochemical Systems
General Motors
Ion Power
Nuvera Fuel Cells
Plug Power
TreadStone
UTC Power
Versa Power Systems
W.L. Gore & Associates

Universities

Illinois Institute of Technology
Northeastern University
Univ. of North Florida
Univ. of Hawaii
Univ. of South Carolina

National Labs

Argonne
Brookhaven
Los Alamos
Lawrence Berkeley
National Renewable Energy Lab
Sandia

Key Milestones and Future Plans

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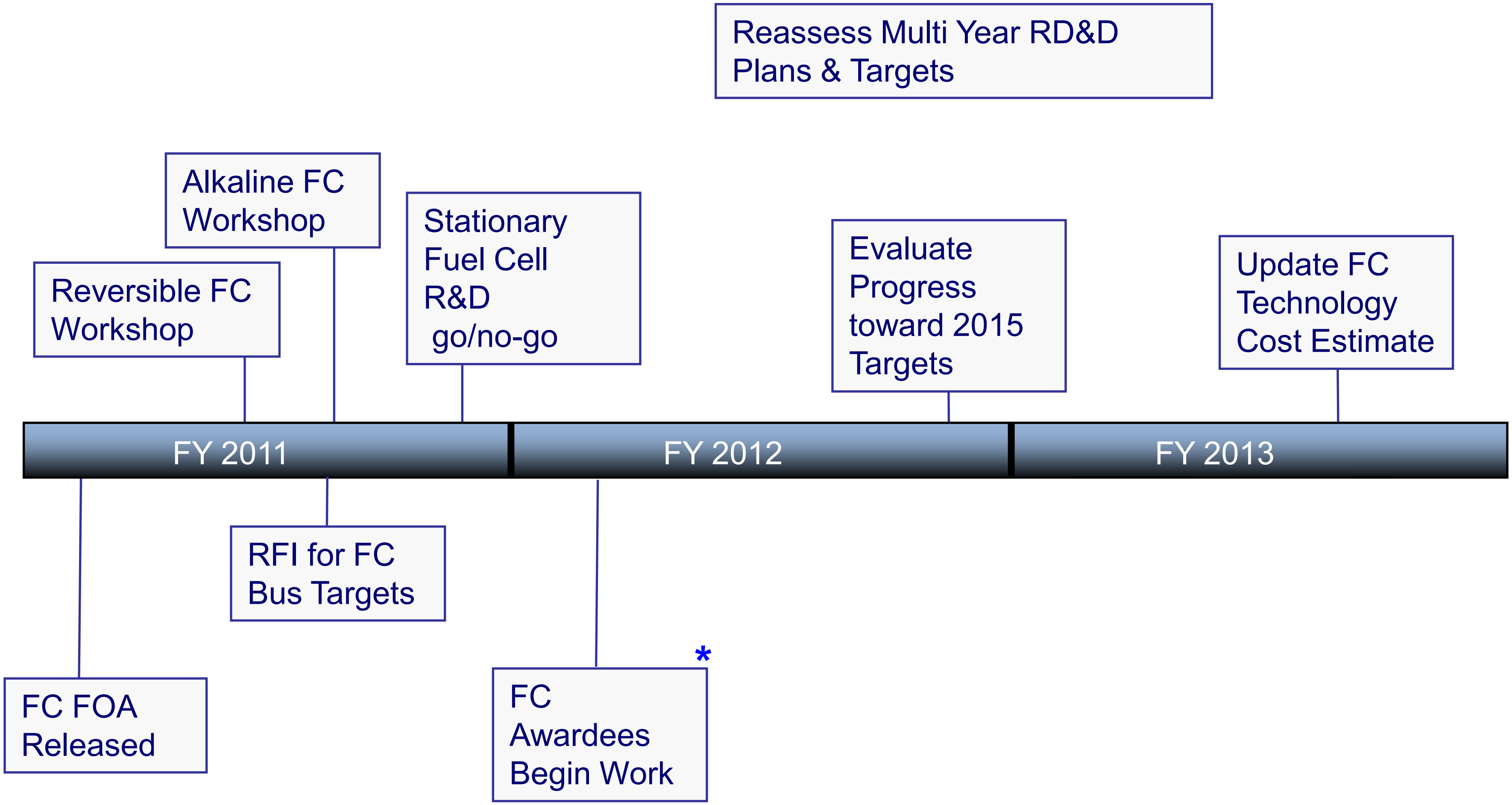


** Subject to appropriations*

2011 RFI for Buses- *Released*

U.S. DEPARTMENT OF ENERGY

Solicit feedback from stakeholders and the research community on proposed performance, durability, and cost targets for fuel cell transit bus applications

RFI is Sponsored by:

U.S. DEPARTMENT OF ENERGY

FTA United States Department of Transportation Federal Transit Administration

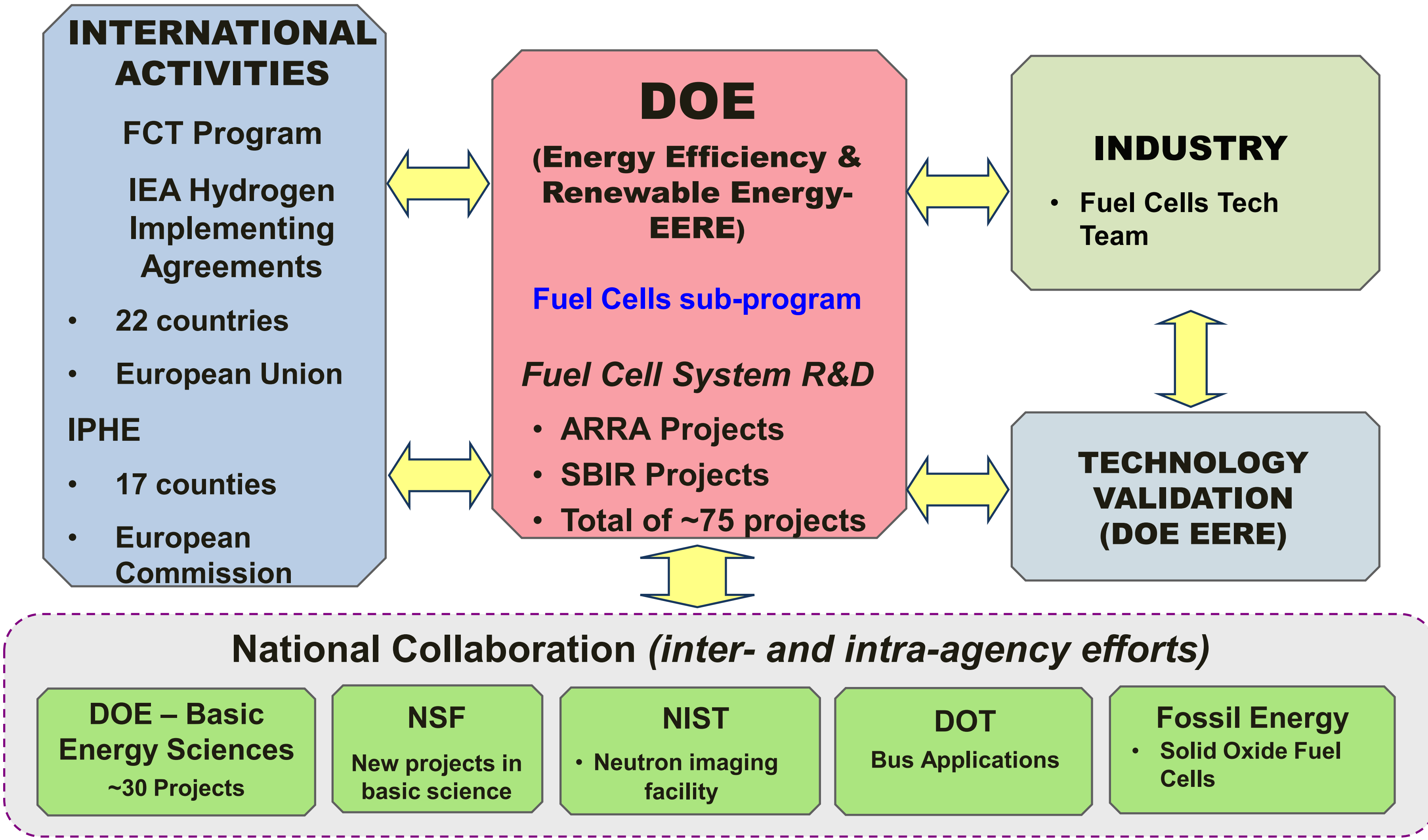
Questions may be addressed to: DOEFCBUSRFI@go.doe.gov

Proposed performance, durability, and cost targets for fuel cell transit buses

	Units	Current Status (Estimated)	Commercialization Target
Bus Lifetime	years/hours	TBD	12/36,000
Power Plant Lifetime[1]	years/hours	NA/8,000	6/18,000
Bus Availability	%	66	85
Fuel Fills[2]	per day	1	1(<10 min)
Bus Cost	$	2,300,000	1,000,000
Power Plant Cost[3]	$	TBD	TBD
Road Call Frequency (All/Powerplant)	miles between road calls	1,900/2,400	4,000/10,000
Operation Time	hours per day/ days per week	19/7	20/7
Operating Cost	$/mile (includes fuel)	TBD	1.16
Range	Miles	>300	300
Efficiency	%	TBD	TBD

[1] According to an appropriate duty cycle
[2] Time to fill is important (should be less than 10 min.)
[3] Includes cost of fuel cell system and battery system. Excludes power electronics.

Fuel Cell Collaborations



For More Information

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EERE Fellowship Program

U.S. DEPARTMENT OF ENERGY

- Fuel Cell Technologies Program Opportunities Available
  - Conduct applied research at universities, national laboratories, and other research facilities
  - Up to five positions are available in the areas of hydrogen production, hydrogen delivery, hydrogen storage, and fuel cells
    - ❑ Applications are due June 30, 2011
    - ❑ Winners will be announced mid-August
    - ❑ Fellowships will begin in mid-November 2011

www.eere.energy.gov/education/postdoctoral_fellowships/

Postdoctoral fellowships in hydrogen and fuel cell research ▸

Principal Participating Organizations

U.S. DEPARTMENT OF ENERGY

- **Testing and Technical Assessments**
  - LANL
  - Directed Technologies
  - TIAX
  - NREL
  - ANL
  - ORNL
  - NIST
- **Balance of Plant**
  - W. L. Gore & Associates
  - Stark State College
  - Dynalene
- **Bipolar Plates**
  - TreadStone Technologies
  - ORNL
  - ANL
- **Catalysts & Supports**
  - BNL
  - PNNL
  - 3M
  - UTC
  - LBNL
  - ANL
  - LANL
  - General Motors
  - Northeastern University
  - University of South Carolina
  - Illinois Institute of Technology
  - NREL
- **Durability**
  - Ballard
  - LANL
  - Plug Power
  - UTC
  - ANL
  - Nuvera Fuel Cells
  - University of Connecticut
- **Impurities and Fuel Processors**
  - NREL
  - University of Connecticut
  - Clemson University
  - University of Hawaii
  - DuPont
  - Rolls Royce
- **Membranes**
  - Giner Electrochemical Systems
  - Oak Ridge National Laboratory
  - FuelCell Energy
  - University of Central Florida
  - 3M
  - Vanderbilt University
  - Colorado School of Mines
  - Case Western Reserve University
  - LANL
  - Sandia National Laboratory
  - Ion Power
  - University of Southern Mississippi
  - Kettering University
- **Portable Power**
  - Arkema Inc.
  - University of North Florida
  - LANL
  - NREL
- **Stationary Power**
  - Intelligent Energy
  - Acumentrics
  - Versa Power Systems
  - UTC
  - University of Akron
  - Colorado School of Mines
  - Stark State College
- **Transport**
  - SNL
  - LBNL
  - Nuvera Fuel Cells
  - Giner Electrochemical Systems
  - General Motors
  - Rochester IT
  - LANL
  - CFD Research Corporation

Back up Slides

REVERSIBLE FUEL CELLS

Crystal City, Virginia, April 19, 2011

This workshop addressed reversible SOFC and reversible PEMFC in renewable electricity storage applications.

Workshop participants generally agreed that reversible technology is feasible for cost effective storage of renewable electricity, with further development required.

Issues requiring further study:

- New catalysis materials for air/oxygen electrode are needed to improve durability for both PEMFC and SOFC based systems.
- New stack designs and new approaches to heat management need to be investigated.
- Speed with which the systems can reverse directions and respond to variable inputs and loads is important for grid support.

Organized by:

U.S. DEPARTMENT OF ENERGY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2011 Fuel Cell R&D Workshops

U.S. DEPARTMENT OF ENERGY

2011 Alkaline Membrane Fuel Cell Workshop

2011 Alkaline Membrane Fuel Cell Workshop
on
May 8 - 9, 2011
Crystal Gateway Marriott,
Crystal City, VA

Objectives:

- Assess the state of alkaline membrane fuel cell technology, including quantifying status in various areas of performance for materials, and systems
- Identify limitations
- Performance potential
- Key R&D needs
- R&D timeframe/ level of effort

Specific areas addressed:

- Anion Exchange Membranes – Stability
- Anion Exchange Membranes – Transport/Conductivity
- Electrocatalysis in High pH (non-precious, complex fuels)
- MEA Issues (ionomer solutions, electrode performance/durability)
- System Issues (carbonate, specific materials, water management)

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