Long Term Innovative Technologies

DOE's Hydrogen and Fuel Cell Technologies, Fuel Cell Presolicitation Workshop

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With Input/Feedback from Rod Borup (LANL), Debbie Myers (ANL), DOE and others as noted in presentation

Lakewood, CO

March 16, 2010

Innovative/Long Term and RELEVANT

Mission of DOE

The Department of Energy (DOE) contributes to the future of the Nation by ensuring energy security, maintaining the safety, security and reliability of the nuclear weapons stockpile, cleaning up the environment from the legacy of the Cold War, and developing innovations in science and technology.

Mission of EERE (Applied Program)

The Office of Energy Efficiency and Renewable Energy (EERE) works to strengthen the United States' energy security, environmental quality, and economic vitality in public-private partnerships. It supports this goal through:

- **Enhancing energy efficiency and productivity;**
- **Bringing clean, reliable and affordable energy technologies to the marketplace; and**
- **Making a difference in the everyday lives of Americans by enhancing their energy choices and their quality of life.**

Mission of HFCT

To enable the widespread commercialization of hydrogen and fuel cells in diverse sectors of the economy—with emphasis on applications that will most effectively strengthen the nation's energy security and improve our stewardship of the environment—through research, development, and demonstration of critical improvements in the technologies, and through diverse activities to overcome economic and institutional obstacles to commercialization. This mission supports the Department of Energy's goals of reducing greenhouse gas emissions, petroleum use, and air pollution, and building a more diverse, secure, and efficient energy infrastructure.

Innovative/Long Term and RELEVANT

Should address high level Multi-Year Research, Development and Demonstration Plan Targets

Table 3.4.2 Technical Targets for Automotive Applications: 80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen [a]

Characteristic	Units	2003 Status	2005 Status	2010	2015
Energy efficiency [b] @ 25% of rated power	%	59	59	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W / L	440	500	650	650
Specific power	W / kg	420	470 [c]	650	650
Cost [d]	$ / kW$_e$	200	110 [e]	45	30
Transient response (time from 10% to 90% of rated power)	seconds	3	1.5	1	1
Cold start-up time to 50% of rated power					
@–20°C ambient temp	seconds	120	20	30	30
@+20°C ambient temp	seconds	60	<10	5	5
Start up and shut down energy [f]					
from -20°C ambient temp	MJ	N/A	7.5	5	5
from +20°C ambient temp	MJ	N/A	N/A	1	1
Durability with cycling	hours	N/A	~1,000 [g]	5,000 [h]	5,000 [h]
Unassisted start from low temperatures [i]	°C	N/A	-20	-40	-40

Table 3.4.7 Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)

Characteristic	Units	2005 Status [a, b]	2006	2010
Specific power	W / kg	20	30	100
Power density	W / L	20	30	100
Energy density	Wh / L	300	500	1,000
Cost	$ / W	40 [c]	5	3
Lifetime	hours	>500	1,000	5,000

Table 3.4.4 Technical Targets [a]: Integrated Stationary PEM Fuel Cell Power Systems (5-250kW) Operating on Reformate

Characteristic	Units	2003 Status	2005 Status	2011
Electrical energy efficiency [b] @ rated power	%	30	32	40
Combined Heat and Power (CHP) energy efficiency [c] @ rated power	%	70	75 [d]	80
Cost [e]	$ / kW$_e$	2,500	2,500	750
Transient response time (from 10% to 90% power)	seconds	<3	< 3	< 3
Cold start-up time (to rated power @ -20ºC ambient) Continuous use application	minutes	<20	<90	<30
Survivability (min and max ambient temperature)	ºC ºC	-25 +40	-25 +40	-35 +40
Durability @ <10% rated power degradation	hours	15,000	20,000	40,000
Noise	dB(A)	<65 @ 10 m	<60 @ 10 m	<55 @ 10 m
Emissions (combined NO_x, CO, SO_x, hydrocarbon, particulates)	g / 1000 kWh	<8	<8	<1.5

Table 3.4.8 Technical Targets: Auxiliary Power Units and Truck Refrigeration Units

Characteristic	Units	2003 Status (Stack)	2005 Status (System) [a]	2006	2010	2015
Specific power	W / kg	50 [b]	25 [b]	70	100	100
Power density	W / L	50 [b]	25 [b]	70	100	100
Efficiency @ rated power [c]	%LHV	20	15	25	35	40
Cost [d]	$ / kW$_e$	>2,000	>2,000	<800	400	400
Cycle capability (from cold start) over operating lifetime	number of cycles	10	5	40	150	250
Durability	hours	100	100	2,000	20,000	35,000
Start-up time	min	2-3 hours	60-90	30-45	15-30	15-30

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf

What is meant by Long-Term Innovative Technologies?

Needs to address HFCT Program Office High Level Technical Targets (MYPP)

Tradeoffs of a focused program versus an exploratory program …

Materials focus (Novel Materials for Fuel Cells)

Revolutionary (game-changing) technologies

Longer-term consideration

Hard to define …

Funding Opportunity Announcement (2008)

Announcements_DE-PS36-08GO98009(10)

Topic 1	**Catalyst Studies**
Topic 1A	Ultra-low PGM Cathode Catalysts
Topic 1B	Non-PGM Catalysts
Topic 1C	Durable Anode Catalysts
Topic 2	**Innovative Concepts**
Topic 2A	Innovative Fuel Cell and System Materials
Topic 2B	Innovative Fuel Cell Component Structures
Topic 3	**Fuel Cell Degradation Studies**
Topic 3A	Cell Degradation Studies
Topic 3B	Accelerated Testing Validation
Topic 3C	System and Air Impurities Effects
Topic 4	**Transport within the PEM Stack**
Topic 4A	Transport Studies
Topic 4B	Freeze Effects
Topic 5	**Portable Power**
Topic 5A	Improved Materials for Portable Power (alternative-fuel fuel cells)
Topic 5B	Portable Electronics Balance of Plant and Packaging
Topic 6	**Fuel Cell System Demonstrations**
Topic 6A	Stationary PEM Power Systems
Topic 6B	Solid Oxide Fuel Cell Power Systems
Topic 7	**Market Transformation Activities**
Topic 7A	Emergency Backup Power Systems
Topic 7B	Fuel Cell-Powered Material Handling Equipment

C. Anticipated Award Size

The anticipated total DOE award size for projects under each Topic Area (i.e. for Topic 1, it is estimated that up to $40,000,000 of DOE funds will be split among up to 7 projects) in this announcement is:

Topic Area	Estimated Number of Awards	Estimated Total DOE Funding
Topic 1	up to 7	up to $40M
Topic 2	up to 3	up to $5M
Topic 3	up to 6	up to $20M
Topic 4	up to 6	up to $20M
Topic 5	up to 3	up to $7.5M
Topic 6*	up to 4	up to $10M
Topic 7*	up to 25	up to $28M
Total	up to 54	up to $130.5M

Funding Opportunity Announcement DE-PS36-08GO98009/10 (2008)

Topic 2 Innovative Concepts
Innovative concepts with the potential for radical improvements in performance, durability, cost, and/or manufacturing are of interest. The primary thrust of this topic is the development of new materials for fuel cells; however, new structures and/or morphologies which use existing materials will be considered if a strong case is made for their benefit.

Applications should clearly demonstrate the potential benefits of the proposed innovative concept in terms of durability, cost, and performance compared to conventional fuel cell technology for automotive or stationary applications. The application should clearly state the status of the applicant's current stack and/or component technology as it relates to the state-of-the-art and include a discussion of how any proposed development work will meet the DOE 2010 targets and/or have the potential to meet the appropriate DOE 2011/2015 targets. Applications which directly address the Hydrogen Program's technical goals and targets published in the Multi-Year Program Plan [1] (and some of which are included in this FOA) are strongly encouraged.

Teaming is encouraged and should include an organization with first-hand knowledge of fuel cell science and operation.

Topic 2A Innovative Fuel Cell and System Materials

Areas of research interest include (but are not limited to) low-cost durable materials suitable for long-term use in the fuel cell system environment. Specific examples of interesting materials concepts include (but are not limited to):

- Non-carbon supports with superior corrosion resistance and electrical and structural properties at least as good as carbon.
- Mixed-conduction (ionic/electronic) catalyst supports to reduce or eliminate the need for electrolyte in the catalyst layer.
- Non-carbon gas diffusion layer (GDL) with superior corrosion resistance; electrical and structural properties at least as good as carbon at comparable cost; and stable wetting properties and physical dimensions.
- Development of low-cost metallic bipolar plates that meet DOE requirements [1].
- Chemically and mechanically stable seal materials.
- Low-cost materials for compact, high performance membrane-based water transport exchangers. Materials must endure cycles and stresses imposed during automotive fuel cell operation.

Expected Outcomes:
The primary objective of Topic 2A is to fabricate and demonstrate the new concept through:

- Appropriate hardware (based on the materials developed) for independent testing:
  - an operating single cell MEA (active area ≥ 50 cm^2) or
  - an operating component based on the material developed
- Delivery of the hardware to DOE for third party testing.
- Formal cost estimate using commonly accepted methods.

Topic 2B Innovative Fuel Cell Component Structures

Possible concepts include, but are not limited to:

- Innovative in-cell thermal management to avoid excessive temperature gradients between reaction sites and cooling media, especially at very high current density.
- Graded (in three dimensions) cell component properties (chemical and morphological) to facilitate species transport as discussed in Topic 4.

As much as possible, the innovative fuel cell component structures should be generic and applicable to a wide segment of the fuel cell community.

Expected Outcomes:
The primary objective of Topic 2B is to fabricate and demonstrate the new concept through:

- Delivery of an operating fuel cell (active area ≥ 50 cm^2) to DOE for third party testing.
- Formal cost estimate using commonly accepted methods.

2009 FOA Awards

Innovative Concepts

Engineered Nano-scale Ceramic Supports for PEM Fuel Cells, Eric Brosha, LANL

Metallic Bipolar Plates with Composite Coatings, Jennifer Mawdsley, ANL

Resonance-Stabilized Anion Exchange Polymer Electrolytes, Yu Seung Kim, LANL

Low Cost PEM Fuel Cell Metal Bipolar Plates, Conghua Wang, TreadStone Technologies

Advanced Materials for Reversible Solid Oxide Fuel Cell (RSOFC), Dual Mode Operation with Low Degradation, Randy Petri, Versa Power Systems

Materials & Modules for Low-Cost, High Performance Fuel Cell Humidifiers, Will Johnson, W. L. Gore & Associates

http://www1.eere.energy.gov/hydrogenandfuelcells/2009_projects_meeting.html

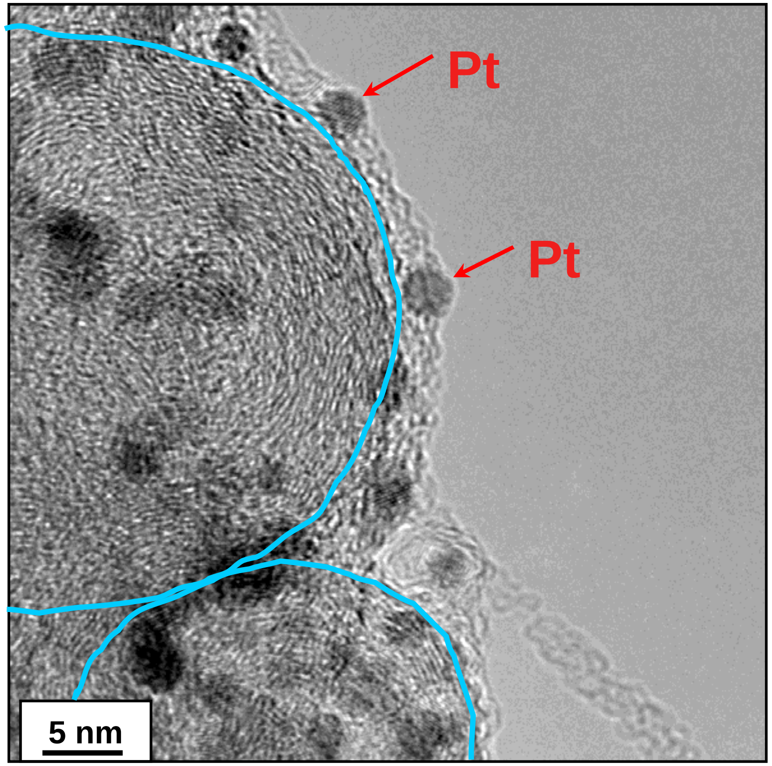
Examples of Innovative Concepts

- Electronics
  - Solid state transistor replacing vacuum tubes, subsequent evolution of microchips
- Televisions
  - CRT -> Plasma -> LCD -> LED
- Solar Devices
  - Crystalline Si, Amorphous Si, Dye Sensitized, CIGS, OPV
- Disruptive technology (in this case the disruptive technology has been chosen … fuel cells)

Past Innovative Fuel Cell Concepts

PEM Electrodes

- 'GE' style electrode: Pt black Teflon steam-bonded
- 1986: Raistrick (LANL): Impregnated catalyzed Prototech electrode (ELAT)
- 1990: Wilson (LANL): Intimately mixed ionomer/catalyst ink applied to membrane
- Mid 90's – Present: Nanostructured electrodes (3M, carbon nanotubes, Pt nanotubes)



HR-TEMs courtesy of Karren More, ORNL

Request for Information DE-FOA-0000225/ Agenda for Pre-solicitation Workshop

Technical Topic Areas for Scope of Work

Responses to these Topic Areas are limited to one page in length per Technical Topic Area. When more than one Technical Topic Area is addressed, submit separate one-page submissions to the e-mail address above.

Balance of Plant Component Development
- Transportation Systems (e.g., humidifier membranes, compressors)
- Stationary Systems
- Fuel processors for stationary systems (alternate fuels, durability, impurities)

Stack Component Integration
- Integration of state-of-the-art components into high-performance, low-cost stacks
- Integration of state-of-the-art components into high-performance, low-cost Membr Electrode Assemblies (MEAs)

Other Innovative Concepts
- Long-term technologies
- Alkaline fuel cells

Speed/Scale

March 17

8:30 Description of Breakout Groups Logistics and Purpose – Shawna McQueen, Energetics

8:45 Facilitated Breakout Groups (suggested) –
1) System BOP and Fuel Processors for Stationary Applications
2) System BOP for Automotive Applications
3) SOFC System BOP and Stack Component Integration for Stationary Applications
4) MEA/Stack Component Integration for PEM Systems
5) Long-Term Innovative Technologies (AFC, HT membranes, non-PGM catalysis, etc.)

Potential Long Term "Innovative" Topics

Alkaline Fuel Cells (precious metal requirements)

- Alkaline (anion exchange) membrane fuel cells
- Traditional alkaline

High Temperature Membranes (heat and water management)

Non-precious Catalysis (precious metal requirements)

Others (input from me and others)

- intermediate temperature conductors (ultra thin)
- regenerative proton-conducting fuel cells
- electrodes incorporating electron-conducting, proton-conducting, and catalytic functionalities in one material (non-composite electrodes)
- novel catalyst supports
- synthesis techniques (novel routes to materials)
- innovative processes for making or testing materials
- etc.

Alkaline Fuel Cell Potential Advantages (vs PEM)

Catalysis

- Non-precious catalysis
- Improved anode kinetics
- fuel choices, C-C bond electrochemistry?

System Issues

- Operating Temperatures
- Electro-osmotic drag in opposite direction
- Materials choices/ durability

Table 1: AFC catalyst combinations

AFC developer	Fuel system	Operating pressure (bar)	Anode catalyst	Cathode catalyst
Bacon*	H_2-O_2	45	Ni	NiO
UTC-Apollo	H_2-O_2	3.4	Ni	NiO
UTC-Orbiter	H_2-O_2	4	Pt/Pd	Au/Pt
Elenco	H_2-air	atmospheric	Pt	Pt
Siemens	H_2-O_2	2.2	Ni	Ag
DLR	H_2-air	atmospheric	Ni	Ag

* AFCs developed by FT Bacon at the University of Cambridge, UK, in the 1940s and 50s.

Guelzow, et al., Fuel Cell Review, 3, 2006.

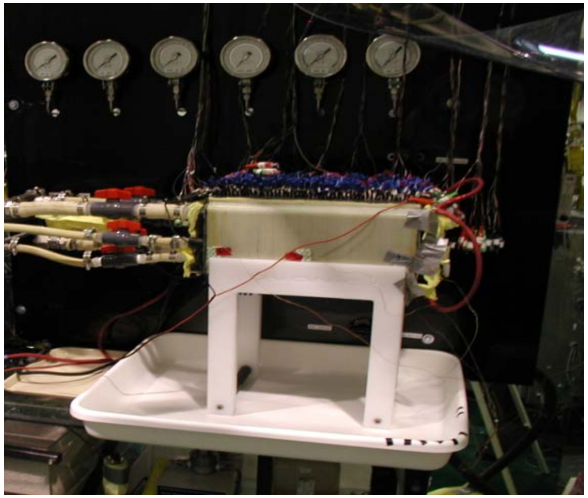
Nickel, silver, gold, cobalt, iron and other materials have been demonstrated in alkaline systems.

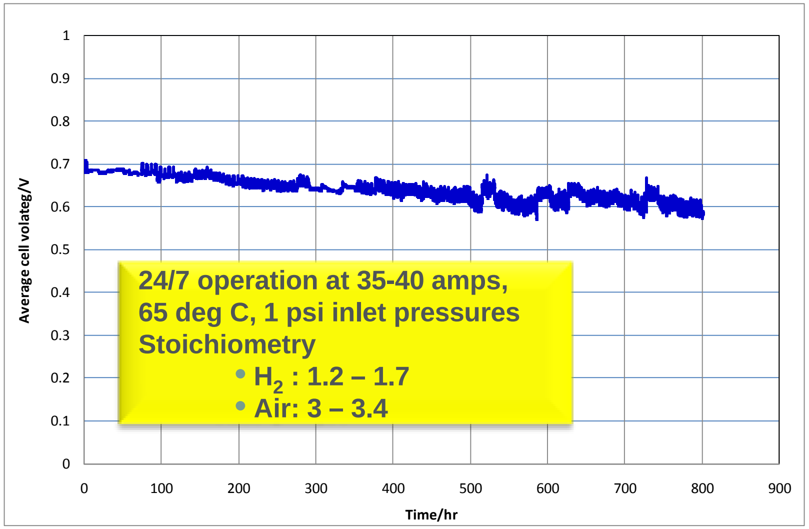
Ovonic – Enabling a practical fuel cell

2.5 kW stack durability demonstration

Stack Comparison	AFC	PEM FC
Power (Watts)	5500	5500
Specific Power (Watts/kg)	150	125
Power Density (Watts/L)	150	80
Cost estimate ($/kW)	$100 - $500	$2,000-5,000

AFC costs based on 100's to 10,000's stacks per year





Research need: Improvements in durability required on a stack level. Durability losses attributed to wetting characteristics of electrode/gas diffusion structures.

Input provided by Rob Privette, Ovonics

Anion Exchange Membrane Fuel Cells

Largely limited by membrane stability

- Better quantified recently
- Acceptable (?) for some applications

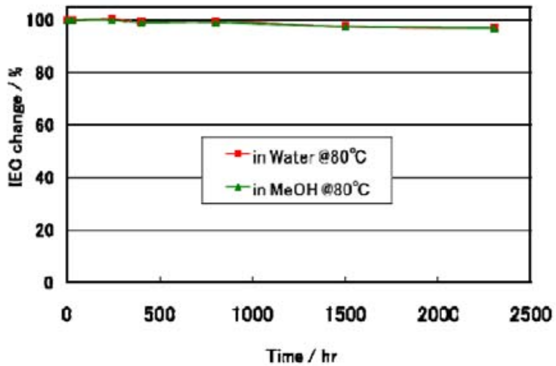
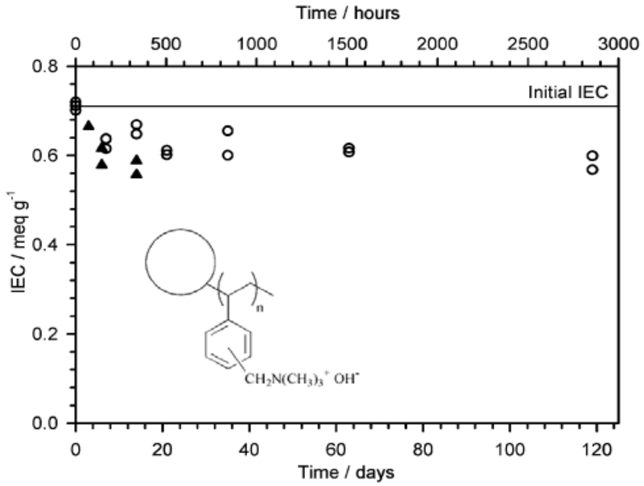
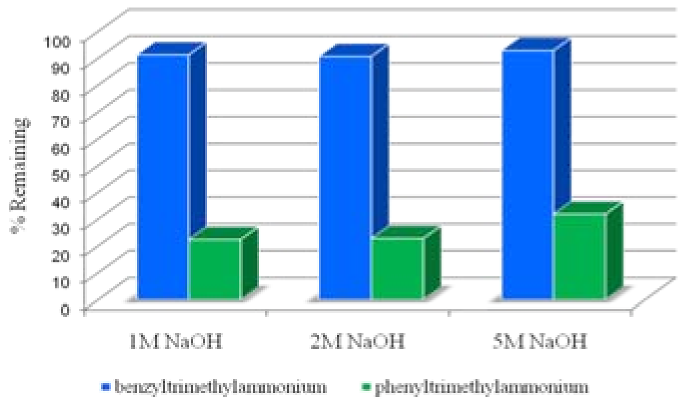


Fig. 1 Thermal durability of AEMs at 80 ℃
Membrane was ion-exchanged to OH⁻ form before durability test. □ is kept in water, △ is kept in Methanol

Yanagi and Fukuta, *ECS Trans.*, 16 (2), 257-262 (2008).



J.R. Varcoe, R.C.T. Slade, G.L. Wright and Y. Chen, *J. Phys. Chem. B*,**110**, 21041 (2006).
J.R. Varcoe and C.T. Slade, *Fuel Cells* **2005**, *5*, 187.



B.R. Einsla, S. Chempath, L.R. Pratt, J.M. Boncella, J. Rau, C. Macomber and B.S. Pivovar, *ECS Transactions*, 2007; v.11, no.1, p.1173-1180.

Alkaline Fuel Cell Challenges

General

- CO_2 and carbonate formation
- Power density limits applications
- Durability

Traditional AFCs

- Free (corrosive) electrolyte concerns
- Ohmic losses

Anion exchange membrane fuel cells

- Current AEMs lack stability at high pH
  - (largely developed for anion exchange applications)
- Lower conductivity than proton conducting systems
- MEA fabrication

High Temperature Membranes

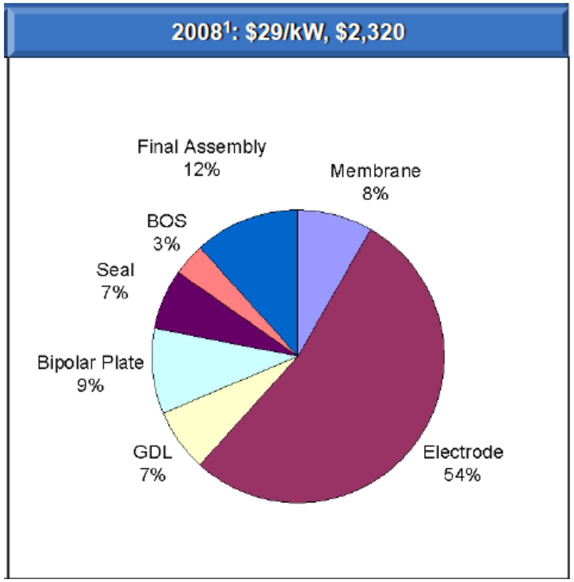
Humidification requirements increase system cost and are driven by proton conductivity of membranes

The ability to work hotter also requires drier operation. The higher temperatures allowable, the lower the radiator requirements.

DOE has had a large effort in this area, to date no material has met all the needs required simultaneously.

See: http://www.hydrogen.energy.gov/annual_review09_fuelcells.html#membranes

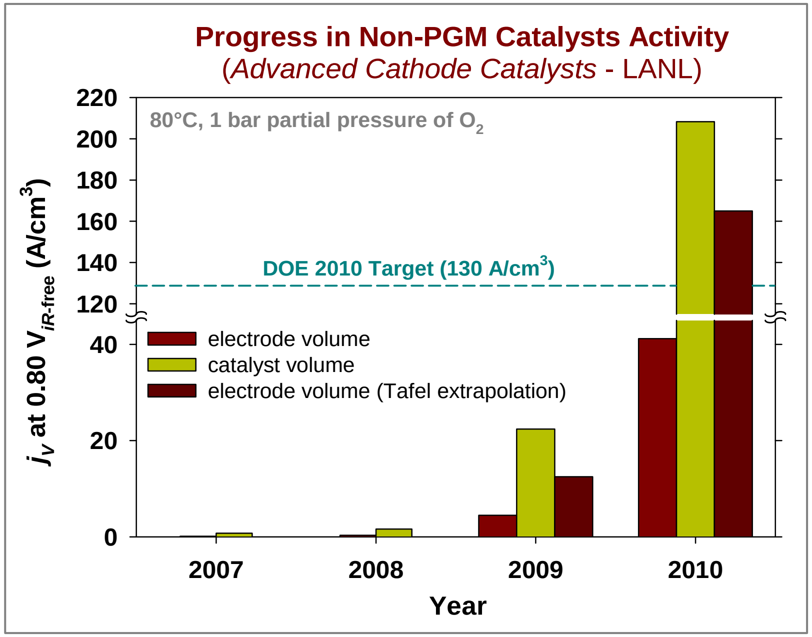
Non-Precious Catalysis



http://www.hydrogen.energy.gov/pdfs/review09/fc_31_sinha.pdf

In spite of dramatic advances with Pt based catalysts, catalyst cost still dominant in stack related costs. Non-precious metal catalysts represent an ideal solution.

Meaningful advances in performance using non-PGM catalysts have been shown. Although performance and durability (under acidic conditions) are still relatively low compared to state of the art Pt catalysts.



- **Research needs:**
  - *Further increases in catalyst activity*
  - *Increased durability at relevant potentials*
  - *Novel electrode layer designs*
  - *Tailored hydrophilic/hydrophobic properties of catalytic layers*
  - *Application of non-PGM catalysts in "alternative" fuel cells, e.g. alkaline*

Input provided by Piotr Zelenay, LANL

Limitations of liquid electrolyte systems

Membrane based system

- No free (liquid) electrolyte
  - Liquid water tolerance/ electrolyte migration
  - Differential pressures
  - Corrosion
  - System design simplification
- Thinner membrane (vs. liquid separator)

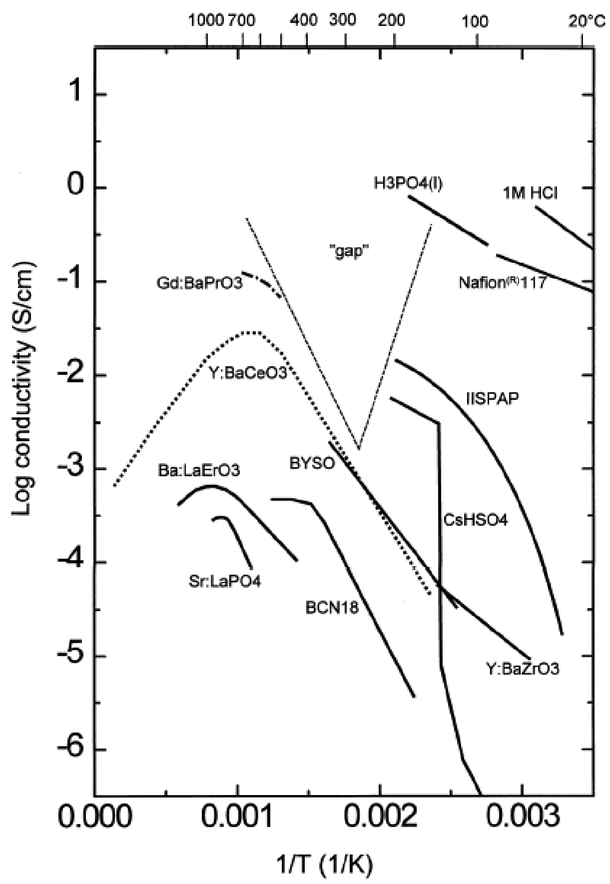
Alkaline

- Carbonate precipitation not possible

Phosphoric acid

- Anion absorption effects

“Norby Gap” Conductivities of known proton conductors as of 1999



Phosphoric acid has drawbacks:
- anion absorption
- corrosivity

But it has unique characteristics (stability, self-ionization, conductivity) as well. Any proposed upgrade needs to consider these issues as well.

From : T. Norby, *Solid State Ionics*, **125**, 1 (1999)

Novel Supports (currently funded)

Microwave aerosol-through-plasma (ATP) torch synthesis of (RE)B_6 and TiO_{2-x}

- Utilize flow of plasma gas through plasma to create high temperature/short contact times
- T > 3500K, t < 0.1 sec
- Plasma gas mixtures: Air, Ar, O_2, N_2 and H_2

Polymer assisted deposition (PAD) for (RE)B_6 and nitrides.

- PAD precursor routes to produce ceramic materials with high surface area.
- Films (CVs), powders (bulk catalysts, MEA prep)

Theory/Modeling support to aid experimental effort to provide data on stability in absence of Pt particles

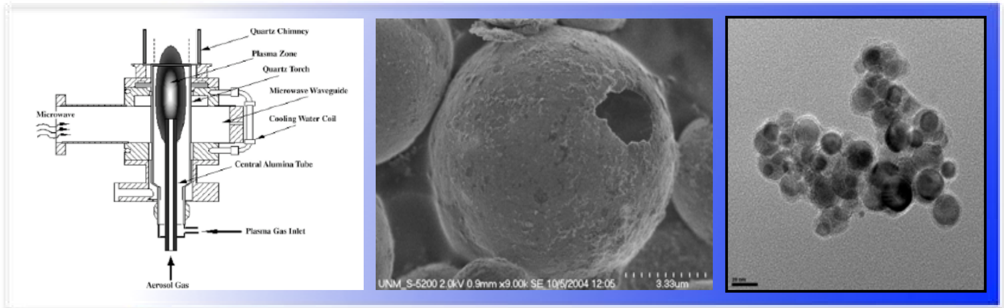
- Surface/cluster models useful to predict effects of particle size reduction, conductivity.
- Study nature of Pt binding sites, interaction energy, etc.

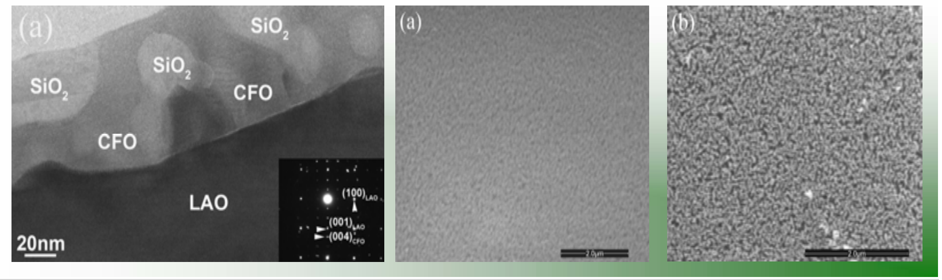
Conductive NbO_2 and RuO_2 supports (UNM)

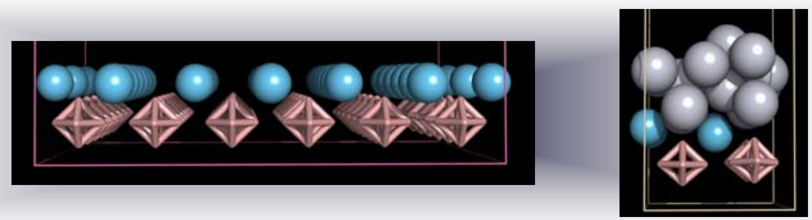
- Spray pyrolysis methods to prepared conductive metal oxide supports.

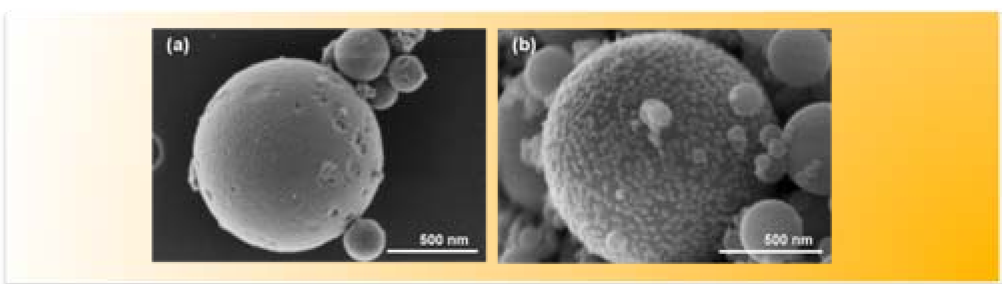
Mechanism to improved performance/durability and relaxed start-stop concerns

Input provided by Eric Brosha, LANL









Concluding Thoughts

RELEVANCY (timeframe, mission, targets)

Projects outside scope of production and delivery, storage, manufacturing, BES, etc.

Time frame for impact (10 yrs?)

Innovative concepts can provide an indirect pathway for taking on current limitations

- HT membranes (humidifier/radiator needs)
- Improved catalysts/supports (start/stop, compressor needs)
- Alkaline systems (catalysis, system issues)

Talk is meant to serve as a starting point for discussions