2005 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Development of Polybenzimidazole-based High Temperature Membrane and Electrode Assemblies for Stationary and Automotive Applications

May 23, 2005

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Project ID # FC8

SAFE HARBOR STATEMENT

This presentation contains forward-looking statements, including statements regarding the company's future plans and expectations regarding the development and commercialization of fuel cell technology. All forward-looking statements are subject to risks, uncertainties and assumptions that could cause actual results to differ materially from those projected. The forward-looking statements speak only as of the date of this presentation. The company expressly disclaims any obligation or undertaking to release publicly any updates or revisions to any such statements to reflect any change in the company's expectations or any change in the events, conditions or circumstances on which such statement is based.

OVERVIEW

Timeline

- Project start date Aug 2003
- Project end date July 2006
- Percent complete 50%

Barriers

- O. Stack material and manufacturing cost
- P. Durability

Budget

- Total project funding $7.29 M
  - DOE share $ 5.84 M
  - Plug share $1.46 M
- Funding received in FY04 $1.50 M
- Funding for FY05 $2.05 M

Subcontractors

- Rensselaer Polytechnic Institute (RPI)
  - Polymer Science Laboratory
  - Fuel Cell Center (approval in progress)
- PEMEAS
- Albany Nano Tech
- Entegris
- University of South Carolina

OBJECTIVES

- To identify and demonstrate an MEA based on a high-temperature polybenzimidazole (PBI) membrane that can achieve the performance, durability and cost targets required for both stationary and automotive fuel cell applications (original)

- In August 2004, the Department of Energy modified the objective to focus only on stationary applications

APPROACH

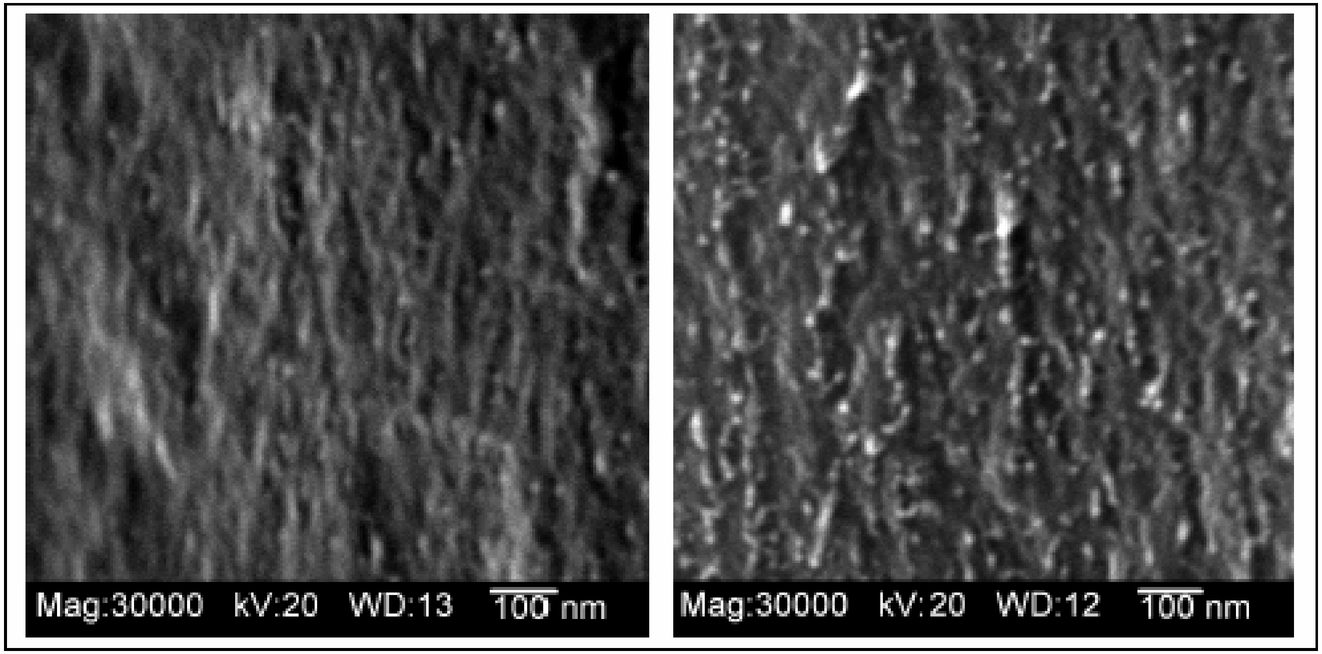
- ❖ Membrane (Task 1-4)
  - ✓ Formulate and characterize polymers
  - ✓ Improve membrane mechanical stability
  - • Scale up process and fabricate full size MEAs
- ❖ MEA (Task 5-8)
  - ✓ Conduct 50cm^2 screening tests at RPI
  - ✓ Conduct parametric tests to fully characterize MEA performance
  - • Assemble and test a full size short stack
- ❖ Stack (Task 9-12)
  - ✓ Characterize acid absorbing materials
  - ✓ Optimize flow fields and sealing
  - ✓ Develop novel electrodes using nanotechnology
  - • Cost assessment

✓ indicates in progress

TECHNICAL ACCOMPLISHMENTS MEMBRANE (TASK 1)

- RPI created five membrane compositions (Type 1, 2, 3, 4 & 5)
- Down-selected to primary composition based on performance characteristics (Type 2)
- Focused polymer membrane effort on mechanical stability
  - Four reinforcing fillers scaled up and under evaluation at various loadings (Type 6, 7, 8 & 9)
- Developed techniques for uniformly dispersing fillers

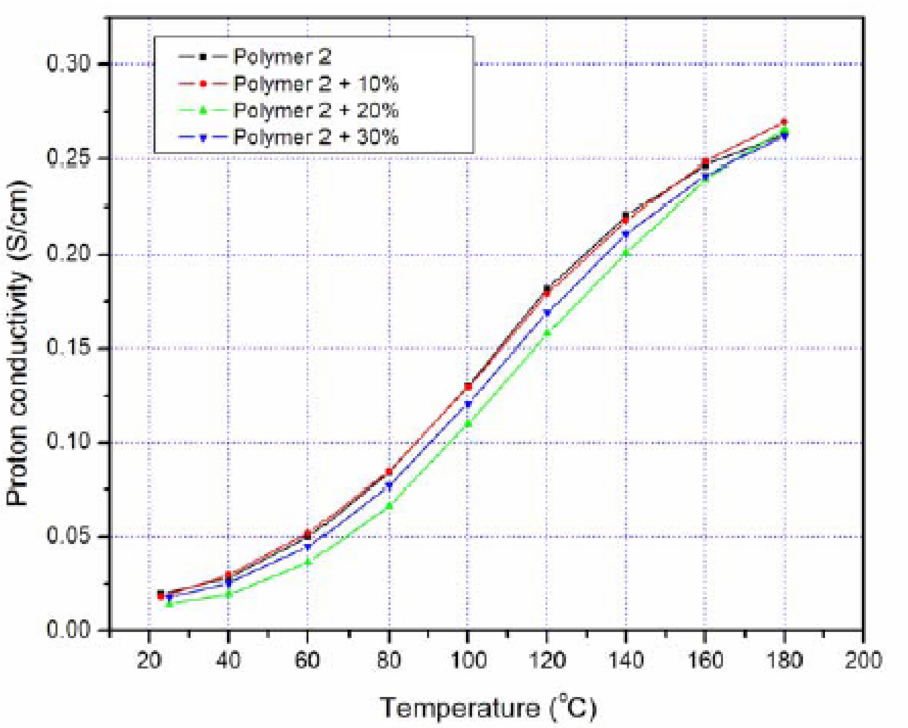
Without filler

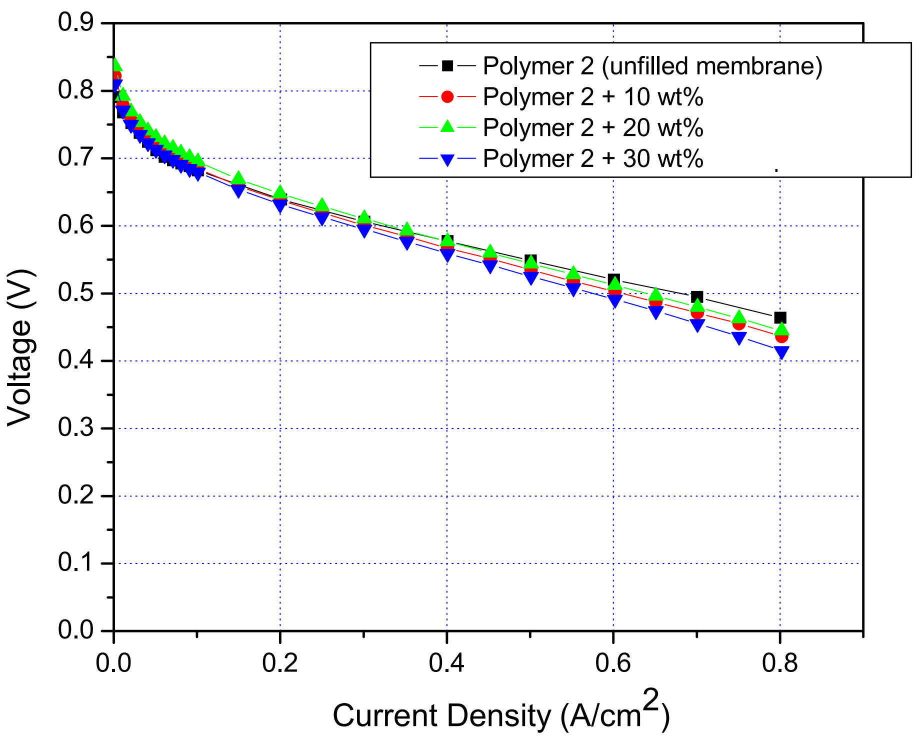


With filler

TECHNICAL ACCOMPLISHMENTS 50 CM² SCREENING (TASK 5)

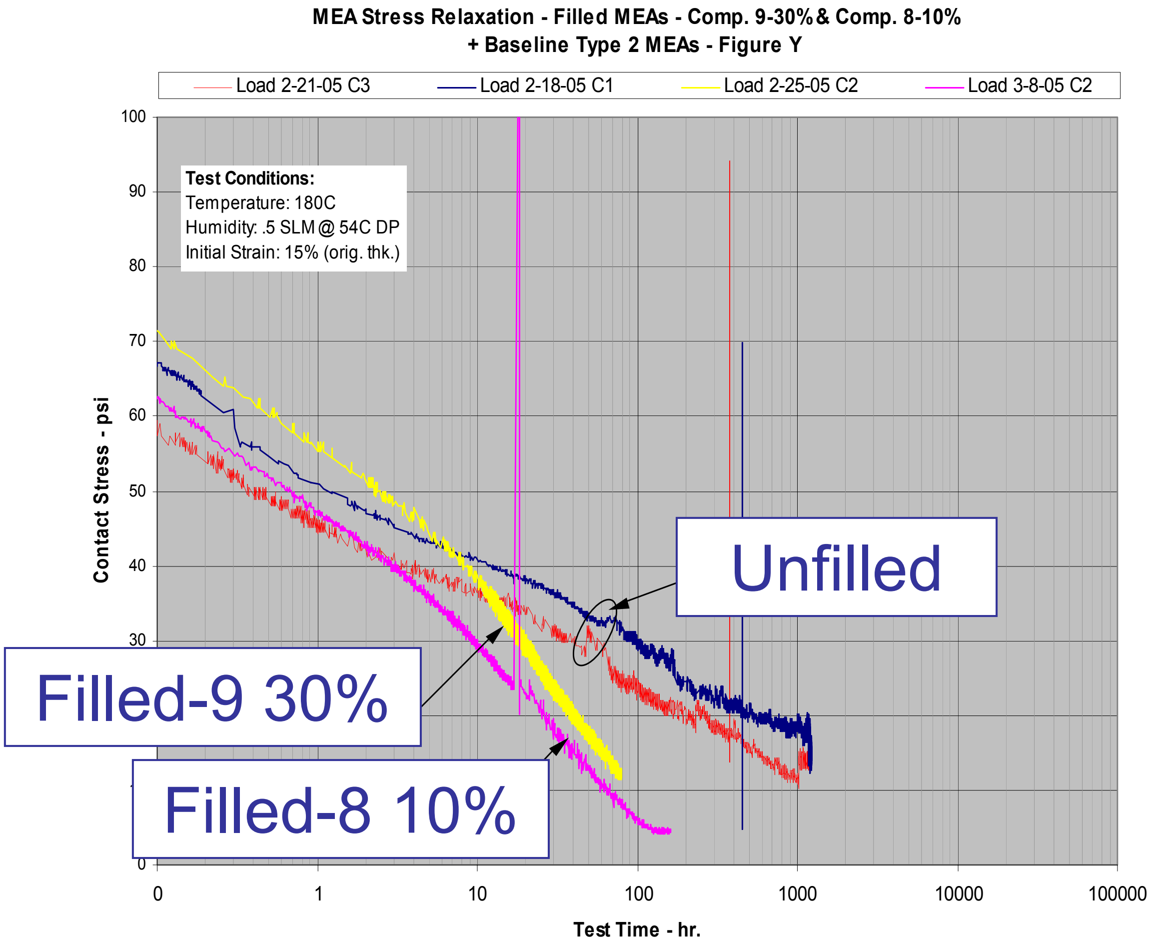
- Membrane conductivity of filled and un-filled membranes is similar
- MEA performance with filled and unfilled membranes is similar





TECHNICAL ACCOMPLISHMENTS
MEMBRANE MECHANICAL PROPERTIES (TASK 2)

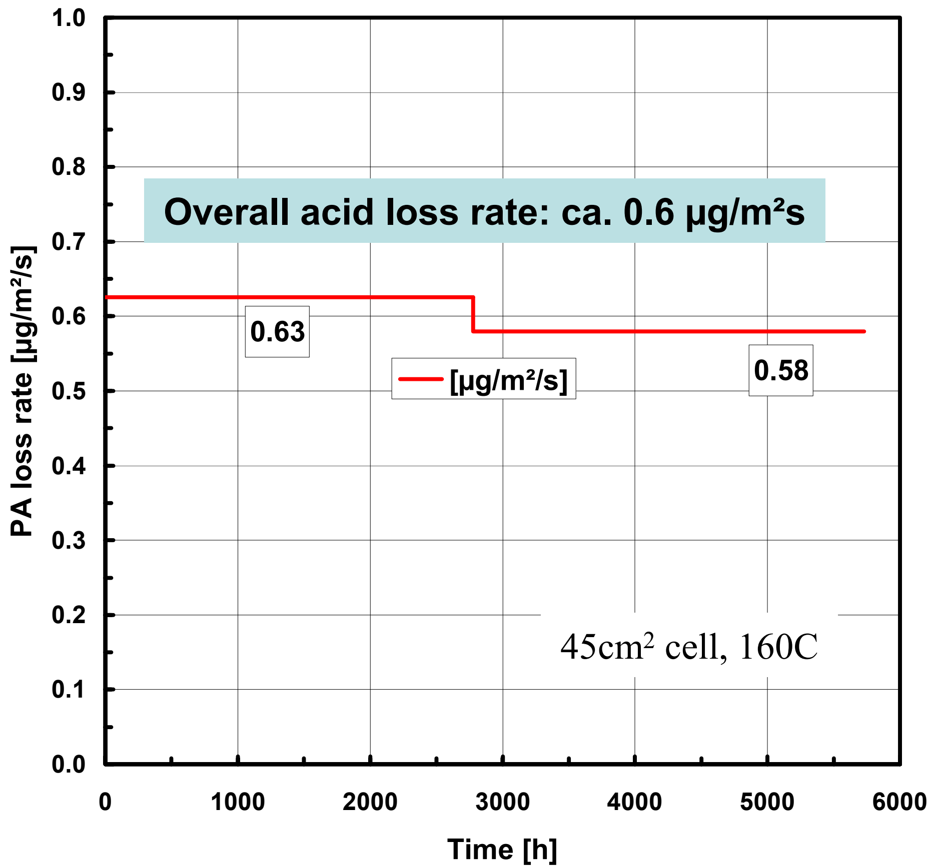
- Developed four mechanical test fixture to simulate fuel cell stack load conditions including temperature and humidity control
- Unexpectedly, the type 8 & 9 filled membranes showed a higher rate of stress relaxation than the unfilled membrane at 160°C, on different fixtures
- Further testing is underway to validate the effect with other fixtures
- Contact resistance needs to be investigated
- A mechanical model is under development at RPI to enable projection of 40,000 hour life



TECHNICAL ACCOMPLISHMENTS
ACID MANAGEMENT (TASK 9)

- Identified the factors that influence phosphoric acid loss:
  - Temperature
  - Reactant flow rates
  - Reactant water content
- Steady state phosphoric acid evaporation losses were studied on the types 1, 2, & 5 membrane and found to be less than theoretical.
- Acid loss remains unchanged during controlled startups and shutdowns.

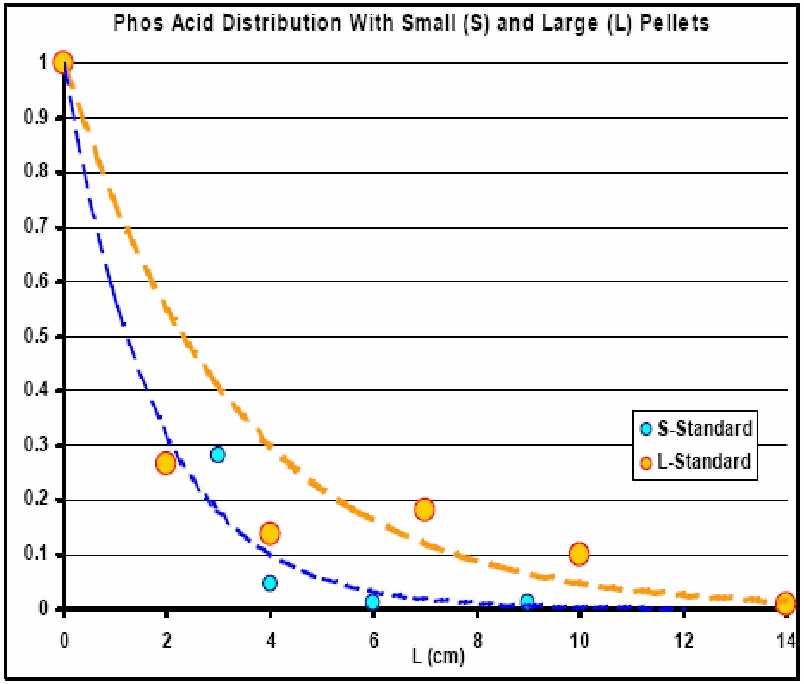
Acid Loss Rate Measurements



Projected cell life is 40,000 hours measured loss rate

TECHNICAL ACCOMPLISHMENTS
ACID MANAGEMENT (TASK 9)

Acid loss occurs through
- Diffusion
- Capillary transport
- Compression
- Evaporation



Acid Loss Calculation
- Measured rate 0.6 μg/ m^2sec
- At 160°C and reactant flows for 0.2 Amps/ cm^2
- A full size 5kw stack starts with 2100 g of acid
- Acid loss per year 83 g
- 4% loss/ year if running constant
- Sufficient acid is available for 40,000 hours

Acid Management Requirements
- Must prevent contamination of other system components
- Must have low service interval
- Must have low service cost

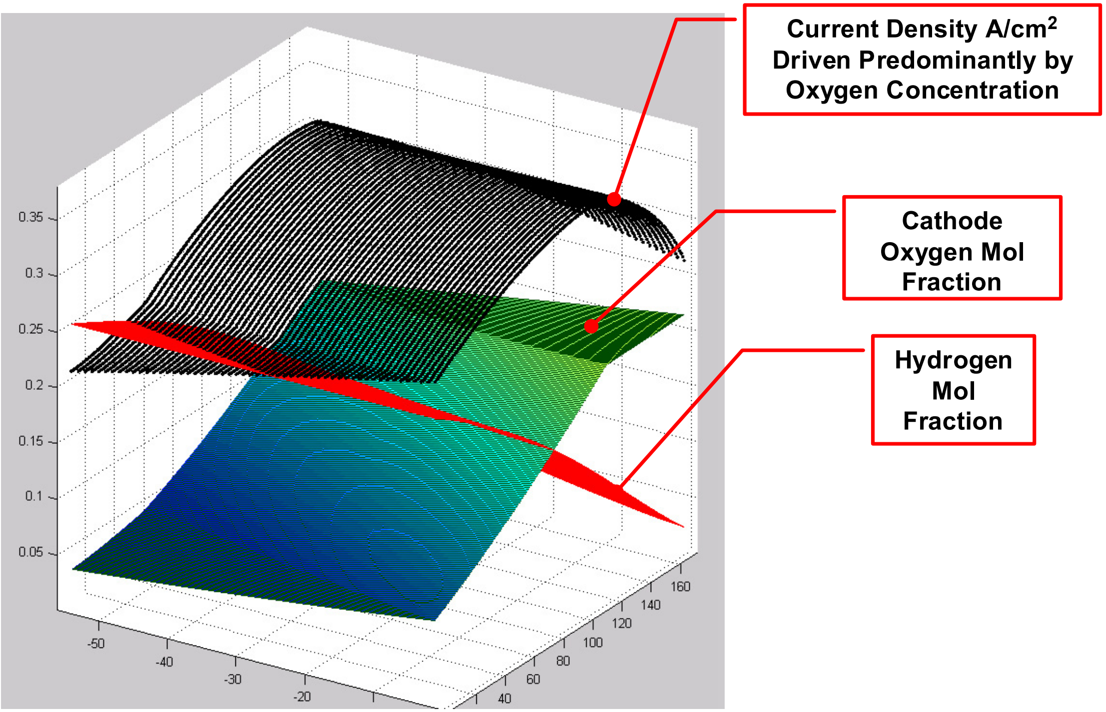
Acid Management Solution
- Stack exhaust (anode and cathode) are passed through a pelletized bed
- Sizing studies are underway to select best size.
- University of South Carolina engaged to develop an acid transport model

TECHNICAL ACCOMPLISHMENTS
PBI SPECIFIC FLOW FIELD DESIGN (TASK 10)

- Initiated work with Entegris for stack sealing technology development
- Modeled full size flow field to improve system efficiency
- Worked with National Renewable Energy Lab (NREL) on optimizing coolant flow

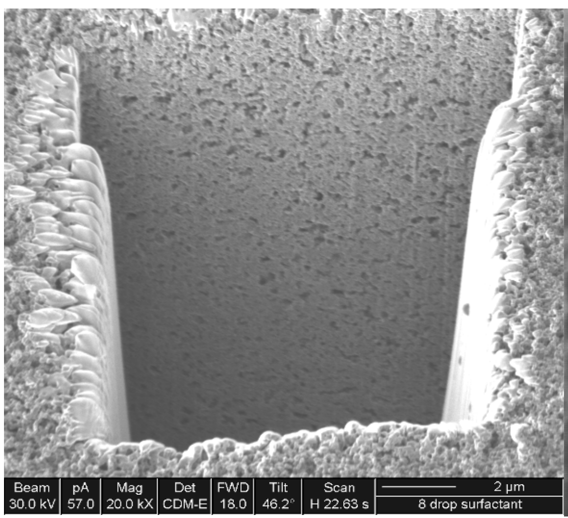
Flow field study

- 8 cathode / anode flow configuration modeled
- Co-flow vs. counter-flow and single vs. multi-pass high power vs. low power evaluated
- 2 configurations with the lowest variability and best mean performance will be built and tested to confirm model results

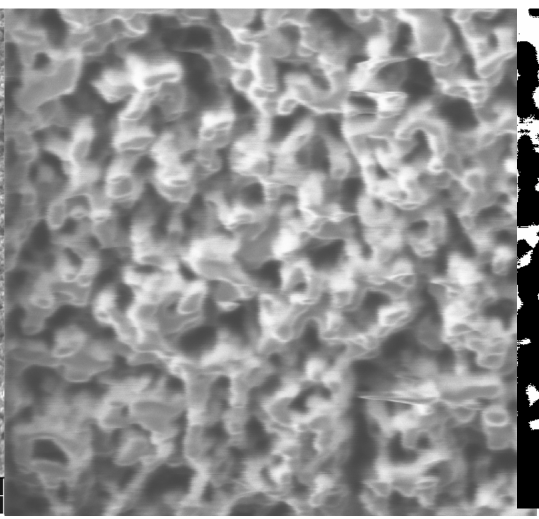


TECHNICAL ACCOMPLISHMENTS ELECTRODE (TASK 11)

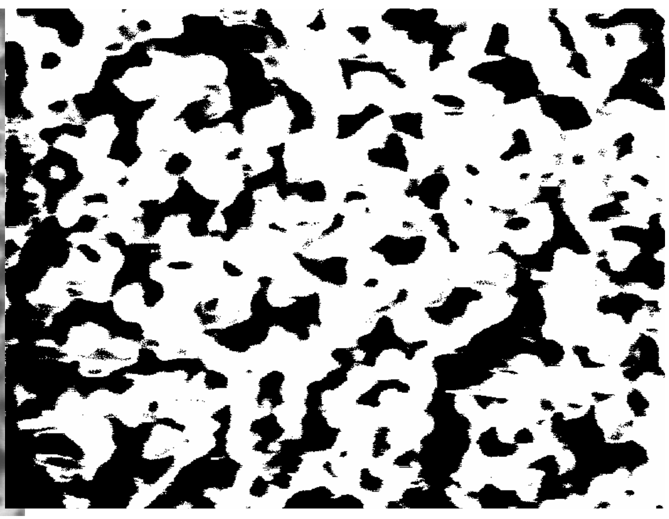
- Albany Nanotech subcontractor for nano-scale electrode development
- Investigated methods for measuring catalyst layer properties
  - Focus Ion Beam (FIB) used to look at pore structure and “connectedness” of pores below the electrode surface
- Investigating methods for creating low Pt loaded catalyst layers such as Pt sputter deposition
- RPI Fuel Cell Center added to program to explore alternate catalyst formulations to improve performance



FIB Trench



Original image



Black and white image model

TECHNICAL TARGETS- STATIONARY

Characteristics	Units	Calendar Year		
		2004 status	2005	2010
Membrane conductivity, operating temperature	Ohm-cm^2	0.1	0.1	0.1
Oxygen Crossover	mA/cm^2	5	5	2
Hydrogen Crossover	mA/cm^2	5	5	2
Cost	$/ kW		50	5
Operating temperature	^{o}C	160	160	170
Durability	Hours	5,000	>15,000	>40,000
Survivability	^{o}C	-20	-30	-40
Applicable to both stationary and automotive		Yes		
Operating Pressure	atm	0-3		

- **Conductivity:** Meets DOE target at 160^{o}C
- **Cross over:** Need to confirm with final membrane
- **Cost:** PEMEAS to provide cost estimate in 2006.
- **Temperature:** Routinely run at 180^{o}C
- **Durability:** 14,000 hours demonstrated by PEMEAS in 50cm^2 testing
- **Survivability:** Data available from PEMEAS

RESPONSES TO REVIEWERS' COMMENTS

- **" Application to stationary is clear- not sure how this can be used in automotive, specifically… freeze and thaw cycle"**
  - In August 2004, DOE modified program objective to focus on stationary applications
  - Limited freeze thaw data is available from PEMEAS
- **"… PBI has serious acid retention and mechanical stability", "... recommend speaking/ working with a PAFC developer who can help with acid management, flow field design, cathode catalyst …"**
  - Acid retention is not the issue, acid management is the issue- our solution is at this review. A PAFC consultant helped Plug Power and PEMEAS understand acid loss
  - Agree that mechanical stability is an issue and our focus has been around the membrane mechanical properties for the past 9 months
- **"… an electrode structure that will allow performance greater than state of the art materials eg. Nafion"**
  - We are adding a major program initiative to further address the electrode structure
  - Stack size is not critical for stationary applications, however cost is
  - PBI membranes are projected to be lower cost that Nafion event though the polar curve is lower

FUTURE WORK

Remainder 2005:

- ❖ Complete filled membrane characterization
- ❖ Select primary membrane for scale-up at RPI
- ❖ Build small scale prototypes and demonstrate stack sealing concept with Entegris
- ❖ Investigate failure modes associated with starts/stops and load cycling
- ❖ Test full-size flow field and quantify efficiency improvement
- ❖ ANT will build nano-scale electrodes for Plug Power test and quantify for Pt loading reduction & performance improvement

2006:

- ❖ Build and test a full size module with improved membrane, flow field and sealing concept
- ❖ PEMEAS will deliver price estimate for MEA
- ❖ Demonstrate 1,000 hours life with low degradation rate and project 40,000 hours life

PUBLICATIONS AND PRESENTATIONS

Publications (RPI-3)

- Synthesis and Characterization of Pyridine-Based Polybenzimidazoles for High Temperature Polymer Electrolyte Membrane Fuel Cell Applications. Xiao, L.; Zhang, H.; Jana, T.; Scanlon, E.; Chen, R.; Choe, E.-W.; Ramanathan, L.S.; Yu, S.; Benicewicz, B.C. *Fuel Cells*, **2005**, xxxx.
- Synthesis, Characterization and Fuel Cell Performance of Poly(2,2'-(p-phenylene)-5,5'-bibenzimidazole) as a High Temperature Fuel Cell Membrane. Zhang, H.; Chen, R.; Ramanathan, L.S.; Scanlon, E.; Xiao, L.; Choe, E.-W.; Benicewicz, B.C. *Fuel Division Prepr.* **2004**, *49(2)*, 588-589.
- Polybenzimidazole Based Segmented Block Copolymers for High Temperature Fuel Cell Membranes. Scanlon, E.; Benicewicz, B.C. *Fuel Division Prepr.* **2004**, *49(2)*, 522-523.

Presentations/ Posters (RPI-20)

- Polybenzimidazole Based Polymers for High Temperature Fuel Cell Membranes. MACRO 2004, Paris, France, 7/6/04.
- Polybenzimidazole/Phosphoric Acid Polymer Gel Electrolytes for Fuel Cells, Novel Polbenzimidazole Membranes for High Temperature PEM Fuel Cells, Segmented Block Copolymers of Para-PBI and AB-PBI for Fuel Cell Membranes, Segmented Copolymers of Polybenzimidazole (PBI) for High Temperature Fuel Cells, Morphological Studies of PBI Membranes Made by the PPA Process. Gordon Conference on Fuel Cells, 7/25-29/04.
- Synthesis, Characterization and Fuel Cell Performance of Poly(2,2'-(p-phenylene)-5,5'-bibenzimidazole) as a High Temperature Fuel Cell Membrane, Polybenzimidazole Based Segmented Block Copolymers for High Temperature Fuel Cell Membranes. ACS Meeting, Fuel Division, Philadelphia, PA, 8/22/04.
- Advances in Polybenzimidazole Synthesis and Applications to Fuel Cells. Polycondensation 2004, Roanoke, VA, 9/28/04.
- NMR Studies of Mass Transport in High Acid Content Fuel Cell Membranes Based on PBI/Phosphoric Acid. 206th Electrochemical Society Meeting, 10/7/04.
- Polybenzimidazole Polymers for High Temperature Fuel Cells. Engelhard Corporation, Iselin, NJ, 1/11/05.
- Quantitative Investigation of Electrolyte Loss in Polymer Electrolyte Fuel Cell Membranes , Segmented Block Copolymers of Polybenzimidazole for High Temperature Fuel Cell Membranes, Segmented Block Copolymers of p-PBI and AB-PBI for Fuel Cell Membranes, Electrolyte Concentration Effects in Polybenzimidazole Fuel Cell Membranes. The Fifth New England Polymer Workshop, RPI, Troy, NY, 1/15/05.
- Electrolyte Concentration Effects in Polybenzimidazole Fuel Cell Membranes. Eastern NY ACS Undergraduate Research Symposium and 6th Robert A. Laudise Symposium, 2/5/05.
- Electrolyte Concentration Effects in Polybenzimidazole Fuel Cell Membranes. Advances in Materials for Proton Exchange Membrane Fuel Cell Systems 2005, 2/21/05.
- Quantification of Electrolyte Loss in a Phosphoric Acid/Polybenzimidazole Membrane Fuel Cell. Advances in Materials for Proton Exchange Membrane Fuel Cell Systems 2005, 2/21/05.
- Polybenzimidazole Segmented Block Copolymer Membranes for High Temperature Fuel Cells. Advances in Materials for Proton Exchange Membrane Fuel Cell Systems 2005, 2/21/05.
- Advances in Polybenzimidazole Synthesis and Applications to Fuel Cells. Advances in Materials for Proton Exchange Membrane Fuel Cell Systems 2005, 2/21/05.

HYDROGEN SAFETY

- The most significant hydrogen hazard associated with this project is:

  Hydrogen service to the lab space in order to perform the testing introduces hazards of pressurized gases, hydrogen leaks, which could serve as an ignitions source.

- Our approach to deal with this hazard is:
  - Annual safety training for every employee including hazard communication and general lab safety.
  - Lab design is expected to safe environment (100% outside ventilation, hydrogen sensors set at 18% and 25% LEL)
  - Safety reviews for all equipment prior to start-up

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