NanoSonic, Inc.

Virginia Tech

Economical High Performance Thermoplastic Composite Bipolar Plates

2006 DOE Hydrogen Program Merit Review

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5/17/06

Project ID # FCP 38

Overview

Timeline

Start – May 2005
End – March 2006 (Phase II submitted)

Phase I 100% complete

Budget

Total project funding

- Fuel cell stack components $32.5M
- Total H_2 & FC $169.5M

Phase I funding - $100k

Barriers Addressed

- Bipolar plate/fuel cell cost
- Durability
  - Operating temperature range
  - Mechanical strength
  - High electrical conductivity
  - Low permeability

Bipolar Plate Targets:
$10/kW, >59 MPa, >100 S/cm

Partners

STTR partner: Virginia Tech

Corporate: Lockheed Martin

Objectives

OVERALL: Develop materials and processes to fabricate high performance bipolar plates that meet DoE performance metrics with a cost below $10/kW (below $6/kW by 2010)

Phase I (2005-2006)

- Fabricate bipolar plates using novel wet-lay materials
- Demonstrate superior performance metrics
- Preliminary process modeling for processing time/cost estimates

Phase II (Proposed 2006-2008)

- Downselect best material compositions
- Semi-continuous bipolar plate fabrication
- Full scale bipolar plate production cost analysis
- Fuel cell device integration, including hybrid system development

Approach

APPROACH: Novel wet-lay composite material suitable for compression molding

Wet-lay processing facilitates material integration unlike any other process:

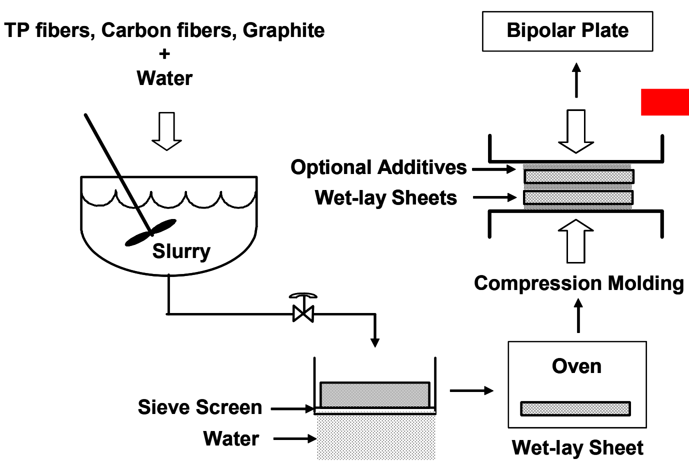
- Superior mechanical properties with high filler loading levels
- Reinforcement/matrix orientation
- Low-cost, environmentally friendly, fast processing times

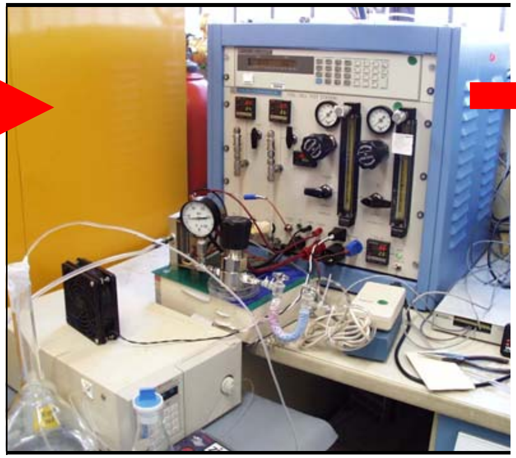
Phase I Technical Feasibility Assessment

Wet-lay material fabrication
Multiple compositions
Batch bipolar plate fabrication

Performance characterization

Process modeling
Time/cost estimates





Technical Accomplishments
Phase I Results

Novel wet-lay composites and associated bipolar plate processing have shown superior performance compared to other technologies:

[DoE targets in brackets]

- High flexural strength 96 MPa [target 59 MPa]
- High tensile strength 57 MPa [target 41 MPa]
- Low gas permeability, estimated ~10^{-8} cm^3/cm^2*s [$<2x10^{-6}$]
- High conductivity, up to 271 S/cm [>100 S/cm]
- Rapidly moldable, no machining required
- Short processing times, projected <2 minutes/plate (TBD Phase II) – current state of the art thermoset at 8 minutes/plate
- Low materials cost (Cost/plate area TBD Phase II)

Comparison of NanoSonic/Virginia Tech Bipolar Plates to Other Technologies

<table>
<tr>
<td>Carbon composite

chemical vapor infusion
expensive processing</td>
<td>POCO graphite

poor mechanical properties
high machining costs
subject to corrosion</td>
<td>Vinyl Ester

require endplates, cannot handle clamping pressures
current state-of-the-art
~8 minutes to fabricate plate</td>
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<tr>
<td>Ticona LCP

no reported properties
LCP materials are generally brittle
>85% filled = questionable mechanical properties</td>
<td colspan="2">NanoSonic/VT Thermoplastic Composite

<u>advantages</u>
high mechanical strength
no endplates required .. can be directly clamped
lightweight
no machining required
inexpensive manufacturing method
< 5 minutes per plate, with potential for ~1-2 minutes
high chemical & corrosion resistance</td>
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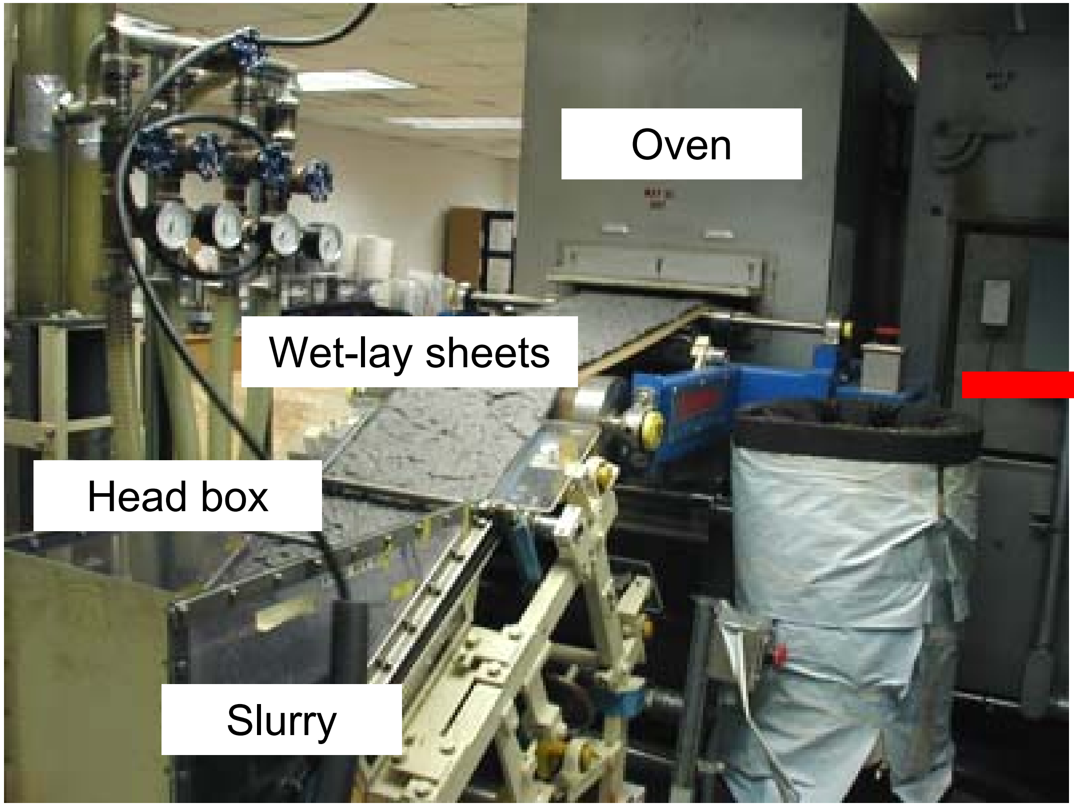
Comparison of NanoSonic/Virginia Tech Bipolar Plates to Other Technologies

Polymer matrix composite bipolar plate comparisons

Manufacturer	Polymer	% Graphite + Fibers	Conductivity (S/cm)		Mechanical Strength		
			In-plane	Through-plane	Tensile (MPa)	Flexural (MPa)	Impact (ft-lb/in)
GE	PVDF	74	119			36.2	
GE	PVDF	64 + 16 CF	109			42.7	
LANL	Vinyl Ester	68	60		23.4	29.6	
Premix	Vinyl Ester	68	85		24.1	28.2	
BMC	Vinyl Ester	69	30		26.2	37.9	
Commercial			105		19.3	20.7	
BMC 940	Vinyl Ester		100	50	30.3	40.0	
Plug Power	Vinyl Ester	68	55	20	26.2	40.0	0.30
DuPont				25-33	25.1	53.1	0.14
SGL			100	20		40.0	
H_2Economy			67			29.4	
Virginia Tech	PET	65 + 7 GF	230	18-25	36.5	53.0	
This work(VT)	PPS	70 + 6 CF	271	19	57.5	95.8	1.56

Note: Process modifications have resulted in through-plane conductivities up to 209 S/cm on NanoSonic/VT materials

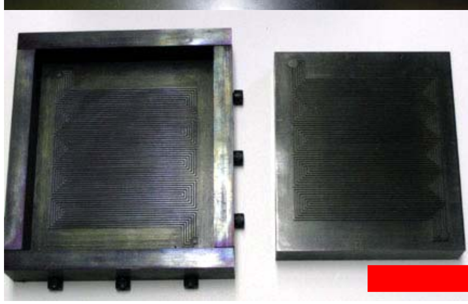
Technical Accomplishments
Wet-lay Composite Continuous Fabrication



Demonstrated continuous manufcaturing capability of wet-lay composites
Polyphenylenesulfide, polyethylene terephthalate, polyvinylidene fluoride

Technical Accomplishments
Batch Bipolar/Monopolar Plate Fabrication

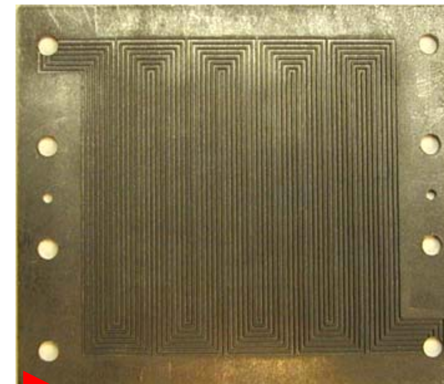
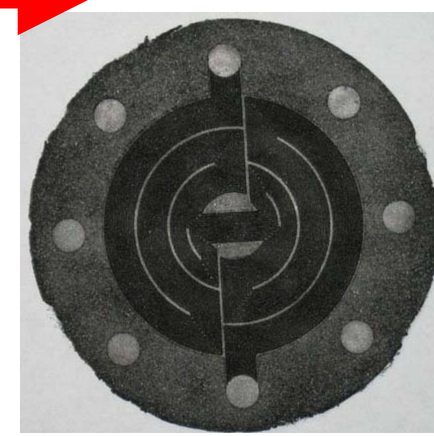
Specially designed molds
Plus wet-lay materials

+

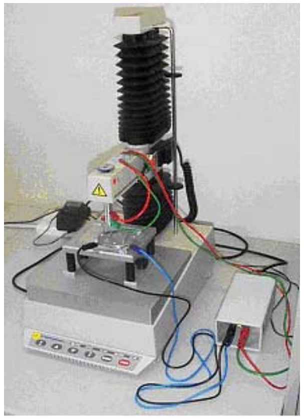
Compression mold (stamping)
Well-defined heat/cool cycle

Molded bipolar plate
High feature resolution

Technical Accomplishments
Mechanical Strength Evaluation

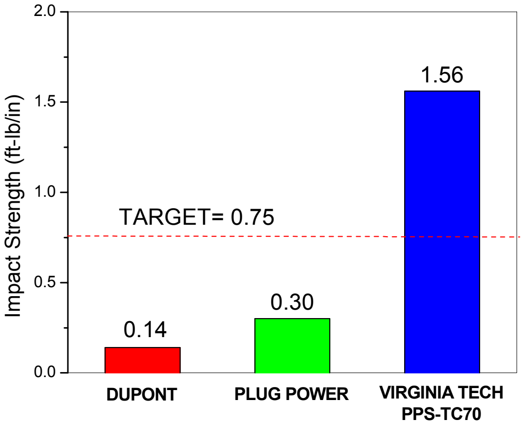
Flexural and Tensile Strength



Strength (MPa)		Modulus (GPa)		Maximum Strain (%)	
Average	Std Deviation	Average	Std Deviation	Average	Std Deviation
95.84	4.24	12.65	0.35	0.8	0.1

Tensile Strength : 57.5 MPa

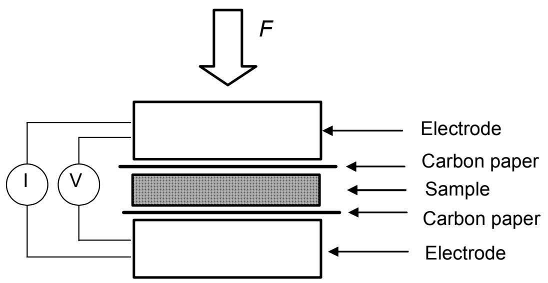
Impact Strength

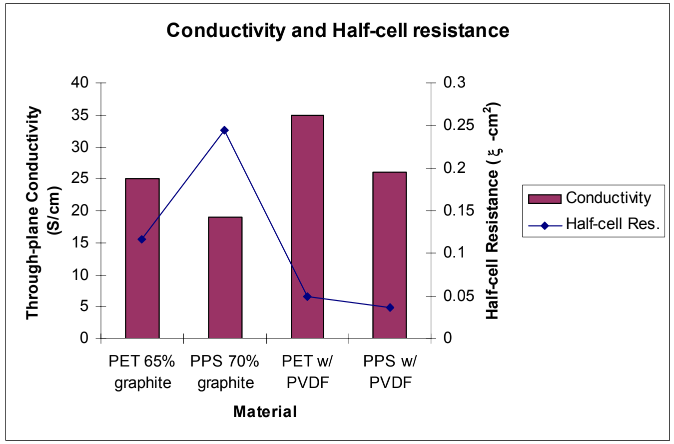


Mechanical strength far exceeds DoE targets

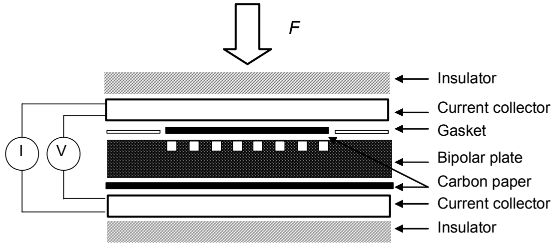
Technical Accomplishments
Electrical Conductivity/Resistivity Performance

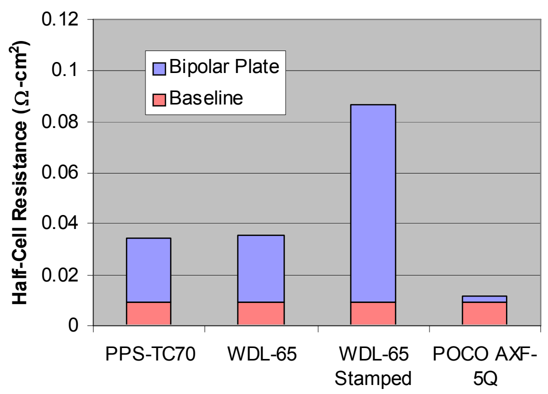
Through-plane conductivity





Half-cell resistance





- In plane conductivity 271 S/cm far exceeds DoE target (100 S/cm)
- Modified processing has resulted in through plane cond. of 209 S/cm

Technical Accomplishments
Permeability Estimates

Van Krevelen Permeability Analysis

P=DS

$$D = D_o \exp\left(\frac{-E_D}{R_g T}\right)$$

$$\log D_o = \frac{E_D * 10^{-3}}{R_g} - 5.0$$

$$10^{-3}\frac{E_D}{R_g} = \left(\frac{\sigma_x}{\sigma_{N_2}}\right)^2 \left[7.5 - 2.5 * 10^{-4}\left(T_g - 298\right)^{\frac{3}{2}}\right]$$

$$S = S_o \exp\left(\frac{-\Delta H_s}{R_g T}\right)$$

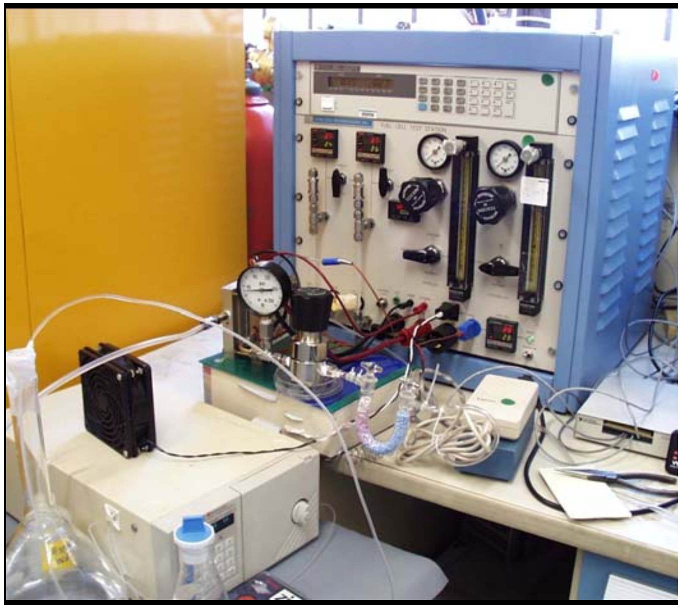
$$\log S_o = -6.65 - 0.005\frac{\varepsilon}{k}$$

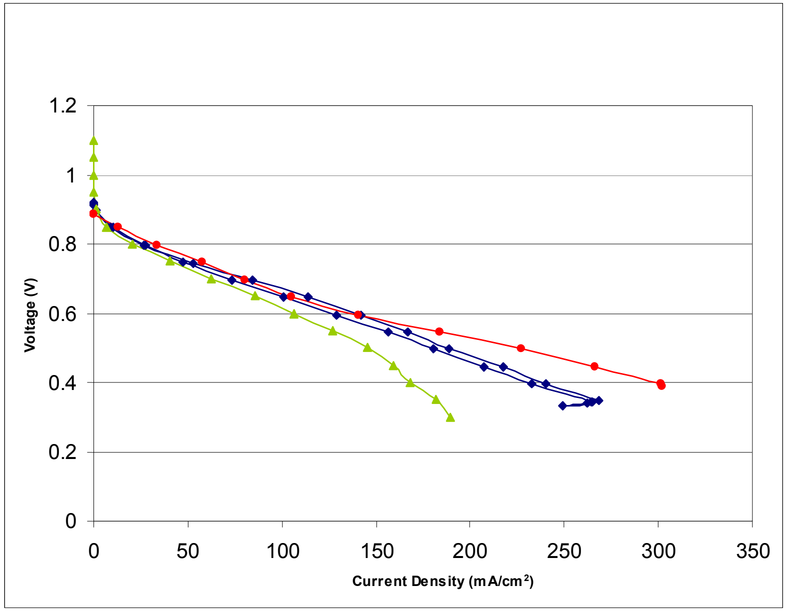
$$10^{-3}\frac{\Delta H_s}{R_g} = 0.5 - 0.01\frac{\varepsilon}{k}$$

For H_2 @ 3atm, 80°C, P ≈ 1.2-2.5x10^{-8} cm^3/cm^2*s

Far exceeding DoE target of 2x10^{-6} cm^3/cm^2*s

Technical Accomplishments
Fuel Cell Test Station, Polarization Curves





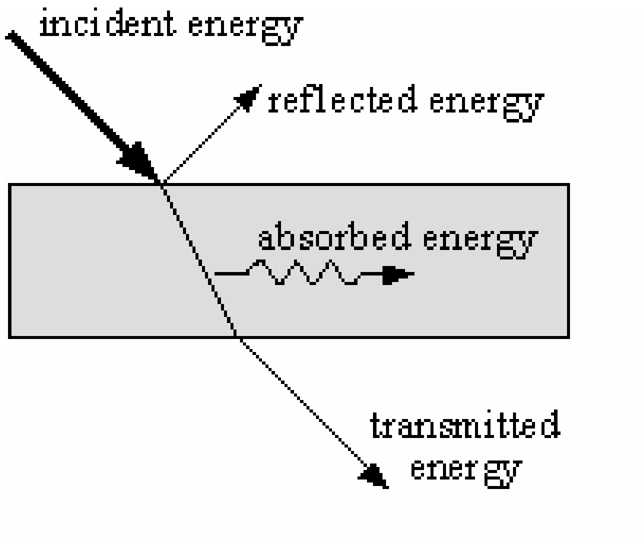
Polyphenylenesulfide based plates developed here performed comparably to POCO graphite plates

Technical Accomplishments
Cost/Process Model Development

Bipolar plate cost primarily dictated by processing time
Heating/cooling cycle of the stamping process

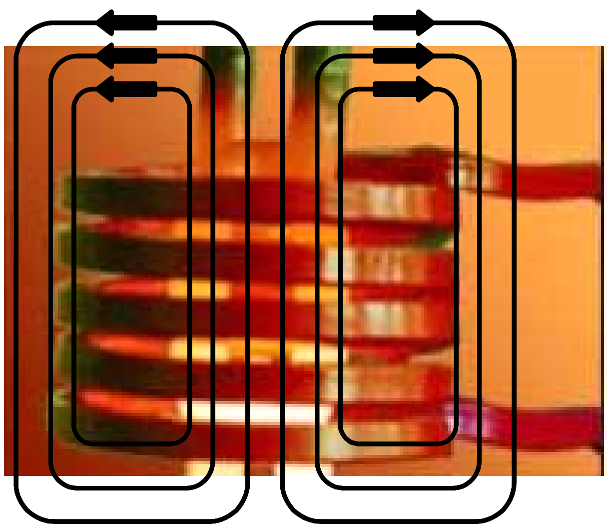
Two heating mechanisms modeled during Phase I for continuous mfg.

Radiation Heating



47 second heating cycled
Total estimated process time <2 min.

Induction Heating



10 second heating time for 7 kW heater
Total estimated process time 30-60 s

Future Work
Phase II Work Plan (FY06 - FY08)

- Downselect most appropriate material composition
  - Investigate PVDF/PPS skin/core bipolar plates
- Semi-continuous bipolar plate fabrication
  - Experimentally compare radiation and induction heating to Phase I model estimates
  - Cost analysis
- Fuel cell integration
  - Performance comparison to current "baseline" bipolar plates
  - Hybrid fuel cell system development
  - Test platform integration, both in-house and with corporate collaborators, to practically evaluate:
    - Durability
    - Weight savings
    - Performance

Project Summary

Relevance: Identification of low cost, high-performance bipolar plate materials and fabrication processes.

Approach: Compression molding, or stamping, of wet-lay thermoplastic composite material mats.

Technical Progress and Accomplishments: Proposed bipolar plate technology has exceeded DoE performance requirements, and requires significantly lower estimated processing energy and time compared to current state-of-the-art, corresponding to significantly reduced total cost.

Collaborations: NanoSonic and Virginia Tech have teamed to develop the technology. NanoSonic has active collaboration with Lockheed Martin and other Fortune 500 collaborators for design input, platform insertion, marketing, and commercialization.

Proposed Future Work: Continuous bipolar plate manufacturing for cost analysis. Fuel cell integration for performance characterization compared to "baseline" and current state-of-the-art bipolar plate technologies.