VII.D Bipolar Plates

VII.D.1 Scale-Up of Carbon/Carbon Composite Bipolar Plates

David Haack
Porvair Advanced Materials, Inc.
700 Shepherd Street
Hendersonville, NC 28792
Phone: (800) 843-6105; Fax: (828) 697-7960; E-mail: dhaack@pamus.com

DOE Technology Development Manager: Donna Ho
Phone: (202) 586-8000; Fax: (202) 586-9811; E-mail: Donna.Ho@ee.doe.gov

DOE Project Officer: Reg Tyler
Phone: (303) 275-4929; Fax: (303) 275-4753; E-mail: Reginald.Tyler@go.doe.gov

Contract Number: DE-FC04-02AL67627

Subcontractor:
UTC Fuel Cells, Inc., South Windsor, CT

Start Date: May 2002
End Date: May 2005

Objectives

- Develop near-net and net-shape molded carbon/carbon bipolar plate materials that meet or exceed customer and DOE requirements
- Develop process for manufacturing materials with high consistency
- Evaluate the performance of the bipolar plate materials through fuel cell stack testing
- Develop, test and evaluate deliverable 10 kW fuel cell stack
- Develop comprehensive cost evaluation of material and process

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- Durability
- Cost
- Electrode Performance

Technical Targets

The DOE technical targets and Porvair's current status are shown in Table 1. The cost per kW shown as current status reflects current manufacturing capability (approximately 20,000 bipolar plate pairs per year). Product pricing is greatly influenced by the manufacturing rate. Bipolar plate cost projections over volume are provided in more detail in this report.

Table 1. DOE Property and Cost Targets and Current Status

Porvair Progress Toward Meeting DOE Bipolar Plate Property and Cost Targets			
	Units	**2010/2015 Targets**	**Current Status**
Cost	$/kW	6/4	200
Weight	kg/kW	<1	<1
H_2 Permeation Rate	cc/cm^2/sec (80°C, 3 atm)	2x10^{-6}	2x10^{-5}
Corrosion Resistance	mA/cm^2	<1	
Electrical Conductivity	S/cm	>100	>500
Resistivity	Ohm/cm^2	<0.01	
Flexural Strength	Mpa	>4 (crush)	>34 (flexural)
Flexibility	% deflection at mid-span	3-5	>2

Approach

Phase I

- Design, construct and install material forming, pressing and thermal treatment equipment
- Systematically investigate material forming techniques and composition ingredients
- Systematically investigate material processing variables and test material properties
- Perform fuel cell testing to evaluate plate performance at UTC Fuel Cells
- Investigate forming techniques aimed at rapid, low-cost production

Phase II

- Develop net-shape moldable materials for both porous and sealed applications
- Develop low-cost sealing method for sealed plates
- Develop bonding methods for both porous and sealed plates
- Investigate low-cost methods for plate wetting angle control
- Test performance of near-net and net-shape molded parts in fuel cell testing
- Manufacture 10 kW stack in cooperation with commercial partner and test for baseline performance
- Analyze process costs to assemble detailed product cost analysis

Accomplishments

- Designed and developed higher speed forming system to lower component forming costs Demonstrated rate of forming at approximately one plate per minute with this developmental system
- Developed moldable materials and process to achieve target tolerance requirements.
- Developed methods for wetting angle control
- Manufactured, tested and delivered plates for stack testing
- Developed low cost plate sealing methods
- Performed cost analysis to evaluate high volume potential of process

Future Directions

- This project was completed in May 2005.

- Porvair is continuing to develop this bipolar plate technology through the following near-term activities by:
  - Reducing molding times to minimize processing costs
  - Improving manufacturing stability and product uniformity characteristics
  - Evaluating tolerance control on new bipolar plate designs
  - Optimizing manufacturing systems for cost reduction and volume capacity increase

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Introduction

Bipolar plates are a key component in the construction of proton exchange membrane (PEM) fuel cells. In 2001, Porvair Fuel Cell Technology, Inc. (PFCT) licensed a promising carbon/carbon composite bipolar plate formation technology from Oak Ridge National Laboratory. The carbon/carbon material has specific advantages in PEM fuel cells in that the material is highly conductive, high strength and chemically stable. The goal of PFCT is to transfer this novel technology from the laboratory to full-scale, low-cost mass production to meet the emerging need of the rapidly developing fuel cell industry. The DOE-sponsored project is directed at moving the technology from the national lab to a manufacture-capable material that can meet the performance, durability and cost demands of the fuel cell industry. The project is further designed to demonstrate product performance in fuel cell testing, and to project the cost of the product when in high volume manufacture.

Approach

Porvair Advanced Materials is a specialty materials manufacturer whose goal is to manufacture materials for the emerging fuel cell industry. The activities associated with this project, were therefore directed toward the reliable and low-cost manufacture of carbon/carbon bipolar plates.

The taken approach in materials development utilized information fed back to Porvair by our customers following product property and fuel cell testing. Specific needs and concerns of our customers were evaluated relative to the current state of the product or process development to guide improvements leading toward a better bipolar plate. Internally, materials development efforts were guided through the performance of statistically designed experiments. Key product or process variables were evaluated in orthogonal arrays of experiments. Results were measured and analyzed to determine the degree of influence each variable has on the measured property. A statistical model was then built to aid in moving subsequent experiments into a near-optimum range of investigation.

Cost analysis and projections to large volume manufacture were made through an evaluation of the process and material, labor, energy, and overhead costs. Capitalization costs were not included in the cost study directly. A separate evaluation of the impact of capital equipment costs with the expected line lifetime was also completed.

Results

The past year has focused upon the Phase II activities and finalization of the project.

In Phase II, the material forming method of Phase I was evaluated critically and re-designed to eliminate material waste and to increase the processing rate. A new system design was created that significantly improved the forming process and the quality of the material produced. In the past year, process development and materials development activities designed to optimize the properties, uniformity and repeatability of the material and manufacturing process were undertaken, and a detailed cost analysis was completed, which evaluates product volume costing from today's low volumes to the future's ultra-high volumes.

Manufacturing System Optimization

Manufacturing stability directly impacts the achievement of a consistent product with consistent properties. A stable and capable process is defined as one where the process control limits are safely within the product specification limits for that particular process. For example, a key process measurement is the weight of the preform material that eventually becomes a bipolar plate in our process. This characteristic impacts directly the final properties of the bipolar plate material. Key properties impacted by variation in the preform weight include:

- Strength
- Conductivity
- Dimensional tolerances
- Permeability and bubble pressure (for porous plates)

The data is evaluated through statistical means examining the process capability parameters C_{pk} and P_{pk} relative to the process specification limits. The specification limits have been chosen to represent points beyond which acceptable product properties will not be achieved. The following charts (Figures 1, 2) represent the developed state of operational effectiveness for the following characteristics formed sheet weight and final plate thickness.

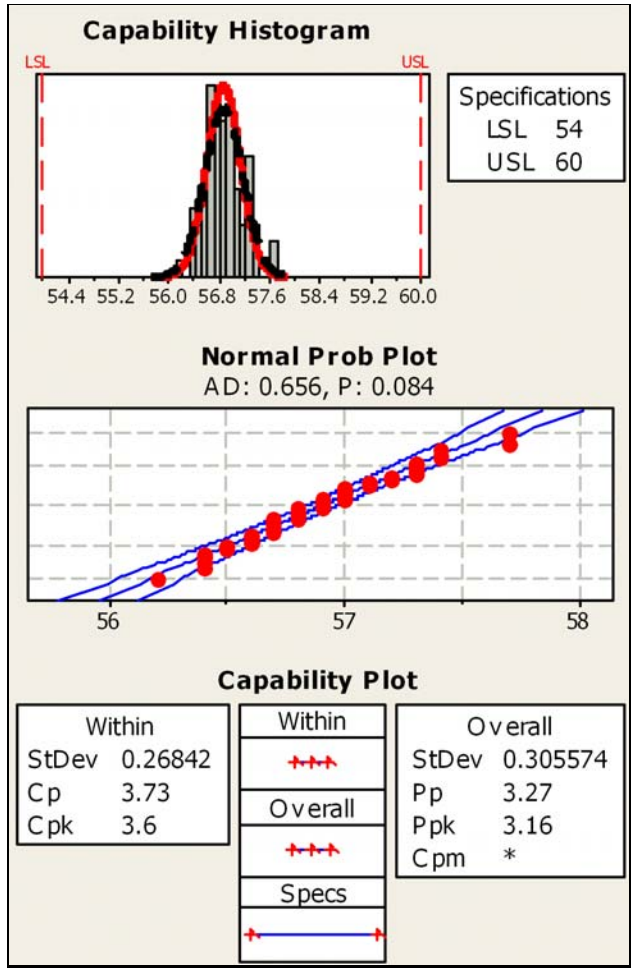

Figure 1. Cathode Formed Sheet Weight Stability

Plate Cost Analysis

As part of this contract, work has been done in estimating product cost over volumes projected to full fuel cell industry implementation for the transportation sector. The cost model evaluates materials costs and manufacturing costs. Assumptions have been made that presume continued product and process development that will be required to speed up key process steps and enable ultra-fast, automated production to be realized. The cost model does not include recovery of development and capital investment costs, but these costs have been estimated separately for each manufacturing phase shown below.

<u>Phase I – Near-term, volumes to 60,000 plate pairs per year.</u>

Assumptions:

- Current manufacturing method employed
- Two tooling sets required to achieve required molding rates
- 3-shift operation required
- Low capital investment required (<$500,000) to achieve 60,000 pairs annually

As can be seen in Figure 3, plate price begins at approximately $350/kW at low volume and drops rapidly to less than $100/kW at full scale low-volume production rates (60,000 pairs per year – sufficient to supply approximately 150 automotive fuel cell stacks per year). A sharp price reduction is realized at volumes approaching 20,000 annual units, where additional capital investment relieves a bottleneck step (part molding) and increases production rates. The capital investment requirement is relatively small ($500,000) and would add to the cost of the plates, depending upon the volume quantities and the capital payback period assumed.

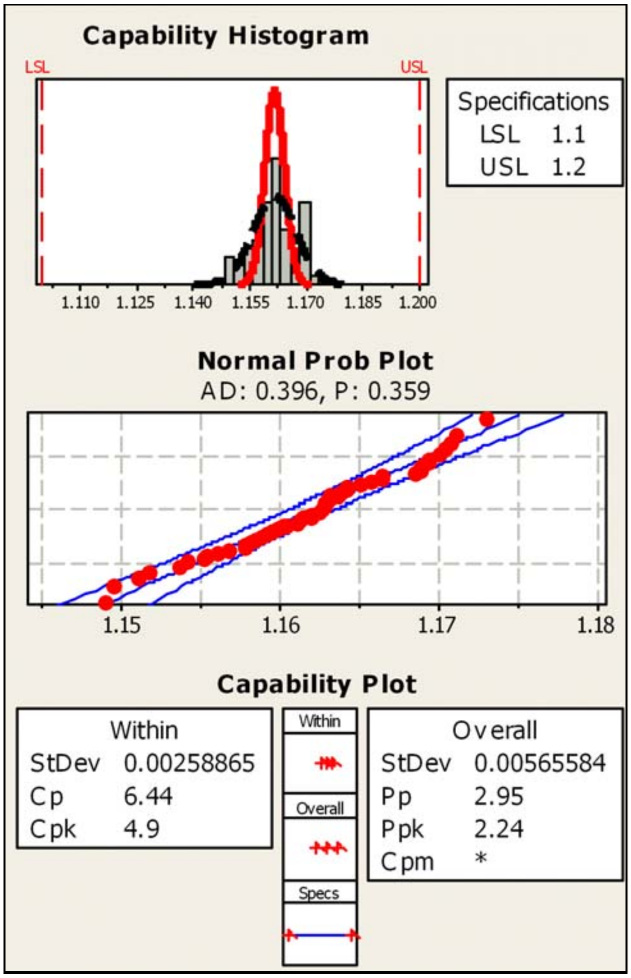

Figure 2. Cathode Thickness Stability

<u>Phase II – Intermediate volumes to 250,000 plate pairs per year</u>

Assumptions:

- Development effort required to eliminate molding time bottleneck
- Maximum production rate of one monopolar plate every 42 seconds
- Moderate capital investment required (approximately $3 million)
- Shift utilization optimized to eliminate down-time costs

In these volumes, plate pricing starts at less than $100/kW and drops to less than $50/kW at volumes of 100,000 pairs annually (Figure 4). This is sufficient to supply the manufacture of approximately 600 automotive fuel cell stacks per year. The key assumption in this phase of manufacture is that development activities lead directly to faster molding times, which in turn yield faster production rates with minimal increase in labor required. A moderate capital investment would be required to enable line operation. Equipment required would include forming, molding and carbonization equipment that can match the required production rates.

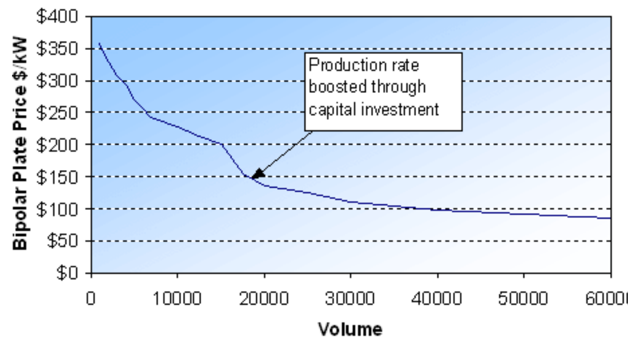

Figure 3. Low Volume Plate Pricing

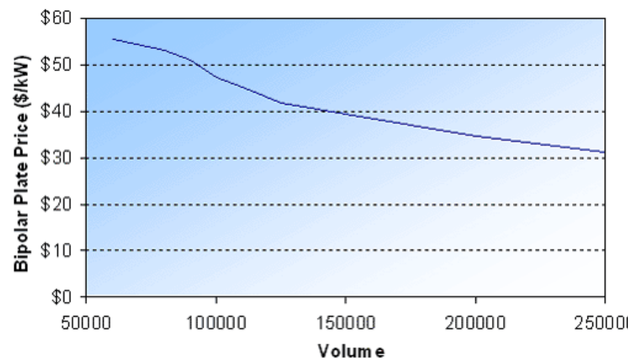

Figure 4. Intermediate Volume Plate Pricing

<u>Phase III – High volume manufacturing to 1 million bipolar plate pairs per year</u>

Assumptions:

- Significant development investment required to yield processes capable of yielding ultra-fast processing rates with minimal labor requirements
- High capital investment in equipment and infrastructure required per line ($15 million)
- Continued volume pricing reductions occur due to labor efficiency improvements and material volume pricing reductions.

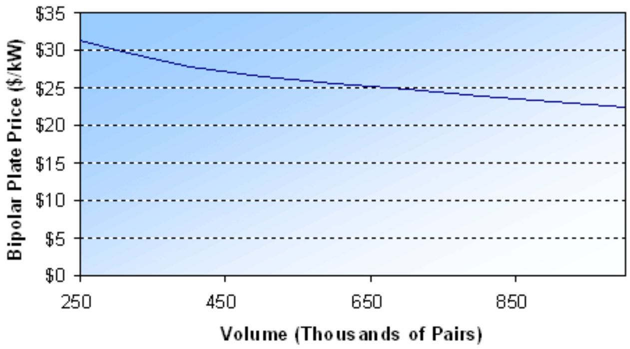

Figure 5. High Volume Plate Pricing

For these volumes, up to 1 million plate pairs per line (enough for approximately 2,500 vehicle power plants per year), the manufacturing time is less than 20 seconds per pair, and near full automation is utilized to minimize labor costs. The realization of this manufacturing concept will require significant development investment required to yield molding, carbonization and bonding rates that match the required production rate. These development breakthroughs will occur through material and process research and development activities. Additionally, a significant investment into the production line will be necessary to scale up to these manufacturing rates. It is estimated that each such production line will require approximately $15 million of equipment and infrastructure investment. However, the payback is a significant reduction in the price of the bipolar plates – expected to be near $20/kW at volumes of 1 million plate pairs annually (Figure 5).

Phase IV – Mass production to 50 million plates per line

Assumptions:

- Continued development investment required to further reduce processing times
- Sub-second processing times per plate pair
- Complete automation and minimal labor required
- Materials costs dominate product cost
- Significant capital investment required to build plant and line suitable of these quantities
- Approximately 16 lines in multiple facilities required to supply demand of 1 million fuel cell vehicles annually

At these high volumes, plate pricing realizes the 2010 DOE goal of $6/kW with the potential for closely approaching the 2015 $4/kW goal at higher volumes (Figure 6). The manufacturing at this stage would require significant investments in capital and infrastructure, and would require careful planning and integration with material suppliers, transportation companies and the end-user, to ensure seamless material supply and plate deliveries.
A complete evaluation of capital investment requirements has not been done, but an estimate might be $100 million per plant, each plant housing four production lines of this capability.

Evaluation of Capital and Development Investment Requirements by Phase

As indicated above, to enable the achievement of ultra-low cost plates, significant development and capital investment will be required over the course of industry-wide fuel cell development and commercial adoption. In the estimates shown in Table 2, capital payback will occur within a 3 year period for Phases I, II and III, and over a 7 year period for Phase IV. The short capital payback periods for Phases I, II and III reflect the quick-changing nature of the fuel cell

Table 2. Evaluation of impact of development and capital costs.

Phase	I	II	III	IV
Annual R&D Costs ($ millions)	1.5	2	4	10
Average sales (# of plate pairs)	40,000	150,000	600,000	25,000,000
R&D Cost Impact ($/kW)	96	34	17	1
Capital Investment ($ millions)	0.5	3	15	25 (per line)
Payback period (years)	3	3	3	7
Capital Cost Impact ($/kW)	11	18	21	0.4
Net Impact ($/kW)	107	52	38	1.4
Impact as % of Pricing Above	100%	85%	150%	18%

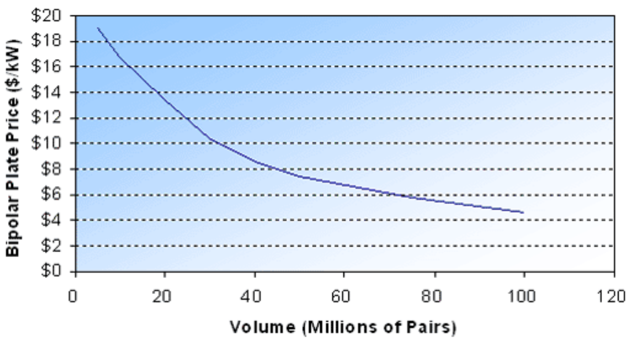

Figure 6. Mass Production Plate Pricing

industry and the continuing requirement for steady improvement, innovation and product cost reduction. As can be seen, the development and capital requirements will add significantly to the total product cost until the time when mass production of bipolar plates is realized.

Conclusions

Porvair has completed this development project. Through the execution of this project, Porvair has significantly improved materials properties, reduced product cost and constructed a small-volume demonstration production line that has demonstrated excellent process stability and control. All of the key project goals and milestones have been completed, and Porvair is continuing development activities aimed at commercialization of this unique bipolar plate technology. Detailed cost analysis shows that Porvair bipolar plate pricing can be attractive to fuel cell developers in both the near and long-terms. Eventual manufacturing rates will require manufacturing lines that are completely automated and that run at high rates of speed with exceptional process control and stability. Significant investment in plant and capital will be required to meet this opportunity. Further, continued process development will be required in at least four stages to enable ever faster production rates, as world-wide fuel cell commercialization occurs over the next ten years.

FY2005 Publications/Presentations

1. Scale-up of Carbon/Carbon Bipolar Plates, presented at the 2005 DOE Hydrogen Fuel Cells and Infrastructure Technologies Program Review, Crystal City, VA, May 2005.