2007 DoE Hydrogen Program Review

Advanced Manufacturing Technologies for Renewable Energy Applications – a DoE/NCMS Partnership

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National Center for Manufacturing Sciences

Project ID # CCP 1

L E V E R A G I N G   E X C E L L E N C E

Overview

- **Timeline**
  - Project start date October 2004
  - Project end date July 2008
  - 75% Percent complete

- **Barriers**
  - Covered on next slide

- **Budget**
  - Total - $6,179,040
    - DOE - $**4,943,232**
    - In-Kind –
      - **$1,235,808 (contract)**
      - **$2,526,199 (projected)**
  - Funding received in
    - FY04 - $2,943,232
    - FY05 - $2,000,000

- **Partners**
  - Total: 22 Partners
  - Listed on project descriptions

Technical Barriers and Targets from the HFCIT Program Multi-year Program Plan

- **Technical Barriers**

  Fuel Cell Components

  O. Stack Material and Manufacturing Cost

  P. Durability

  Fuel-Flexible Fuel Processors

  N. Cost

  Hydrogen Storage Systems

  A. Cost

  B. Weight and Volume

  D. Durability

- **Technical Targets**

  Costs: Range from $10/kWe for fuel-flexible systems to $45/kWe for integrated systems operating on direct hydrogen; Storage system costs of $2/kWh net.

  Durability: Targets are all 5000 hours or greater. Portable storage systems equivalent to 300,000 miles.

  Weight and Volume: Target is 3 kWh/Kg net useful energy/maximum system mass

Objectives

- Working with DoE and the private sector, identify and develop critical manufacturing technology assessments vital to the *affordable manufacturing* of hydrogen-powered systems.

- Leverage technologies from other industrial sectors and work with the extensive industrial membership base of NCMS to do feasibility projects on those manufacturing technologies identified as key to reducing the cost of the targeted hydrogen-powered systems.

Approach

- Identify manufacturing hurdles to hydrogen-powered and storage systems (completed 2005)
- Rank as to impact for producing affordable structures (completed 2005)
- Institute collaborative development projects that address the manufacturing technology issues deemed of highest impact (ongoing)

NCMS/DoE Collaborative Projects

1. Affordable High-Rate Manufacturing of Vehicle Scale Carbon Composite High-Pressure Hydrogen Storage Cylinders
2. Manufacturable Chemical Hydride Fuel System Storage for Fuel Cell Systems
3. Novel Manufacturing Process for PEM Fuel Cell Stacks
4. Non-Destructive Testing and Evaluation Methods
5. Innovative Inkjet Printing for Low-Cost, High-Volume Fuel Cell Catalyst Coated Membrane (CCM) Manufacturing
6. Manufacture of Durable Seals for PEM Fuel Cells
7. Qualifying Low-Cost High-Volume Manufacturing Technologies for PEM Fuel Cell Power Systems
8. Develop Low Cost MEA3 Process

Affordable High-Rate Manufacturing of Vehicle Scale Carbon Composite High-Pressure Hydrogen Storage Cylinders

Collaborating Participants:

- Profile Composites - Project lead; process design and development; process demonstration
- Cincinnati Technologies - Production automation design
- A Leading Automotive OEM - Manufacturing process control requirements; vehicle-scale cylinder design parameters; prototype vehicle-scale cylinder evaluation

Background

Partial technology demonstration under another project achieved confidence in fatigue limits, carbon/resin compatibility and process control.

Technical and Business Goals and Objectives

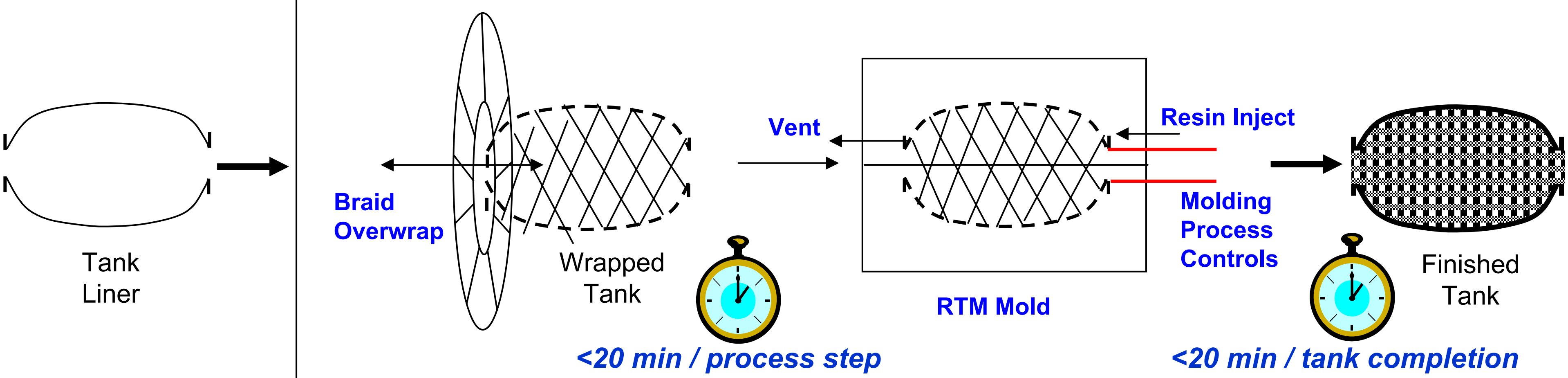
- Demonstrate carbon composite hydrogen cylinder production process providing compatibility with low-volume vehicle production
  - 20,000 units/year/tool
  - Requires 10-minute cycle time/stage
- Hydrogen storage pressure at 350 bar
  - Business objective would be to interest strategic partner for continued development/commercialization
    - Develop process to 700 bar capability
    - Accelerate to approximately 6-minute cycle time

Process Visualization

Advances in composite braiding and Resin Transfer Molding (RTM) technology

- Advanced fiber braid design
- Advanced braid application technology
- Production automation design

- Optimized resin system
- Advanced molding process control



- Production process control

Current Project Scope

Project Deliverables & Status

Deliverables:

- 350 bar vehicle-scale hydrogen cylinders
- Production automation specifications
- Individual process steps each demonstrated under 20-minute cycle times
- Manufacturing engineering study for achieving approximately 6-minute cycle times
- Materials qualification data to show capability to reach 700 bar with similar process

Status:

- Vehicle-scale tank/liner designs established
- RTM test cell press and infrastructure designed and in assembly
- Process flow controls and materials systems requirements for maximum automation in development
- Braid/RTM process development and control experiments underway

Manufacturable Chemical Hydride Fuel System Storage for Fuel Cell Systems

Objective:

- To develop a manufacturing process to produce cost effective flexible bladder and cartridge systems to manage the fuel and discharged fuel of a chemical hydride based hydrogen storage system.

  This hydrogen storage system is geared for portable power product applications in the industrial, military and consumer markets.

Team Members:

Millennium Cell (Technical Lead), Dow Chemical, Edison Welding Institute, and NextEnergy

Progress/Status

Project Task 1.1 Millennium Cell – Technical Lead

- Clearly define the present product and process so all participants are working from the same knowledge base, and to establish metrics for the manufacturing technologies that will provide a robust process and product. (Completed)

Project Task 1.2 Dow Chemical – Technical Lead

- Select four manufacturing-friendly plastic materials for each major component that will meet the product requirements. The tasks in this section are: select possible candidates (1.2.1), conduct materials testing (1.2.2), and finalize candidates (1.2.3). (Completed)

Task 3: Project Task 1.3

- Define and select the optimum manufacturing process for each bladder assembly component. The tasks in this section are: bladder sealing process study (1.3.1), membrane sealing process study (1.3.2), and fitment sealing process study (1.3.3). (Completed)

Accomplishments

- **Improved recyclability** - all bladder materials are of the same recycle stream except for one (the hydrogen membrane) representing a reduction from six materials, of which none were recyclable.
- **Improved overall quality** - subassembly fabrication scrap rate reduced from ~ 75% to less than 10%.
- **Reduced number of bladder assembly steps** by approximately 25% resulting in
  - reduced processing times – for some original process steps from 10-15 minutes to seconds
  - converting from a manual overall assembly process operation to one that is capable of high volume, lower-cost operations.
- **Reduced possible future volume costs** of this type of system by a factor of 8-10X

Novel Manufacturing Process for PEM Fuel Cell Stacks

Project

- Stack Manufacturability in 250-300 Watt Range
- Low-Cost Volume Compatible Process
- Compatible with Roll-to-Roll MEA (Scalable)
- Single Step Molding Eliminates Compressive Seals

Protonex™

Partners:

- Protonex – Advanced Fuel Cell Technology
- Parker Hannifin – Volume Manufacturing Expertise

Parker

Project Objective & Team

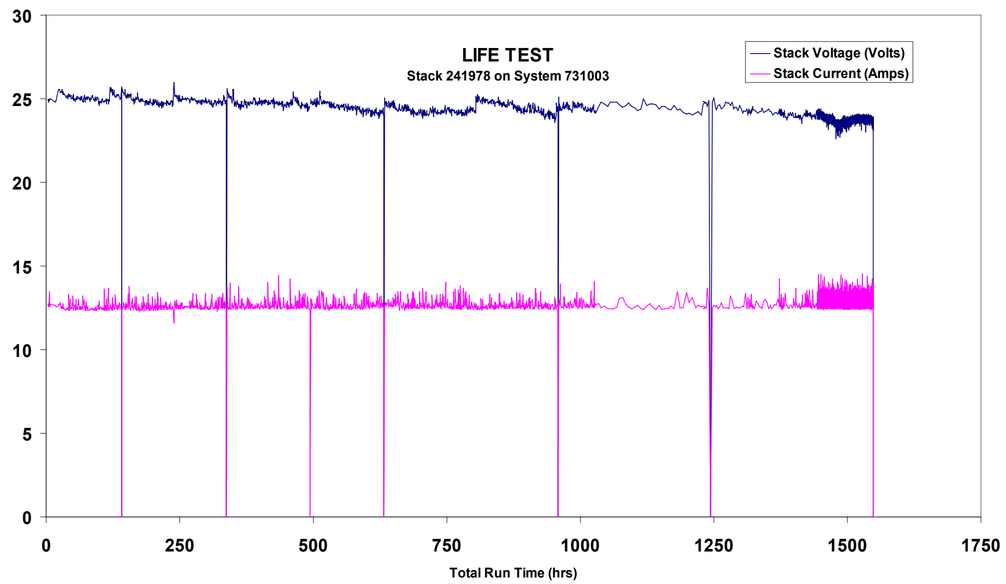
- **Project Objectives:**
  - Design and develop mass-producible stack architecture
  - Design and develop stack components and optimize the manifolded stack assembly
  - Develop and optimize one-step integral casing/sealing of stack assembly
  - Establish technical and cost benefits of one-step injection molding process
- **Business Goals:**
  - Reduced manufacturing cost
  - Improved fuel cell stack durability
- Protonex/Parker partnership combines agility of start-up with experienced high-volume manufacturer

Protonex™

Parker

Progress/Status

- Project substantially complete
- Exceeded technical targets
  - Power density target – 368 W/kg
  - Actual power density – 500 W/kg
- Optimization ongoing with Parker
- Stacks in life test Now – Preliminary results below

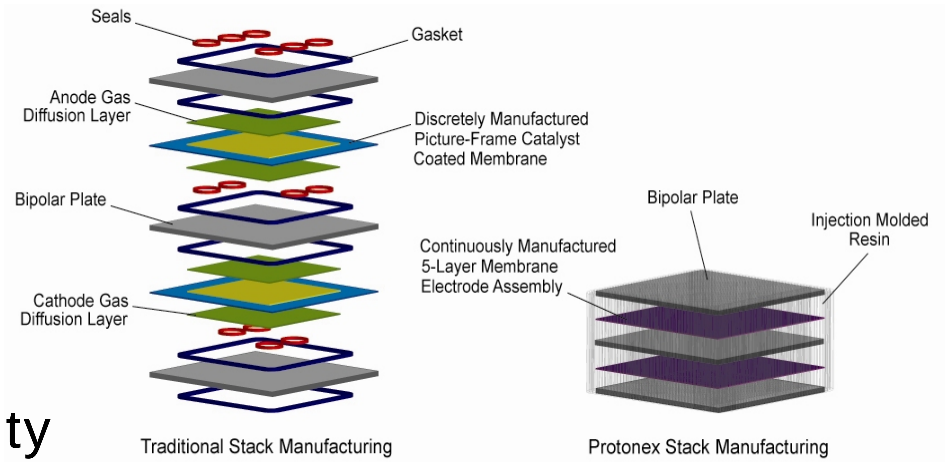


Accomplishments

- Demonstrated one-step resin molding process for commercial scale fuel cell stack manufacturing
- Established high-volume fabrication of stack components and MEA processing/sizing
- Manufacturing process optimized and validated for commercial scale production
- Throughput and yield of the manufacturing process demonstrated and adopted into production
- **100+ 250W stacks manufactured**

Project Impact

- Cost-effective, Adhesion Molded Design validated at commercial scale
  - Design enables simple low tolerance assembly/parts
  - Minimal part count
  - Fast build cycles
  - Easily automated
  - Low-cost roll MEA
  - No compression set issues
  - Component vendor flexibility



- Enabling 250W cost effective, reliable commercial fuel cell system

Non-Destructive Testing and Evaluation Methods

Objective:

- The investigation of non-destructive testing and evaluation methods to enable manufacturers to test and determine the integrity of their products at much reduced times and costs.

Team Members:

ASME Standards Technology, Digital Wave, Lincoln Composites, and TransCanada Pipelines

Project Status and Schedule

- Initial testing of four carbon fiber composite pressure vessels was completed on October 2006
- AE monitoring results of four pressure vessels; the vessels were tested to 15K psi
- A theoretical analysis of the knee-of-the-curve concept showed that when applied to virgin specimens (vessels) it could be a good QC tool
- Higher pressurizations lead to more frictional AE (FRAE)
- A frictional AE database has been created
- Higher pressurizations lead to more FRAE
- Several damage source types in composites were identified by their wave characteristics

Project Status and Schedule

- Three additional pressure vessels have been purchased to conduct additional additional testing in AE and FREA
  - The new tanks are also made of carbon fiber composites
- Testing is scheduled at Lincoln Composite, Lincoln Nebraska for April 23, 2007
- The testing for the 48”x40’ long vessels has been pushed back to the week of May 28 due to setbacks in the construction of the new TransCanada plant St John
- External sensors will be incorporated in the testing to take place on April 23 and May 28

Project Status and Schedule

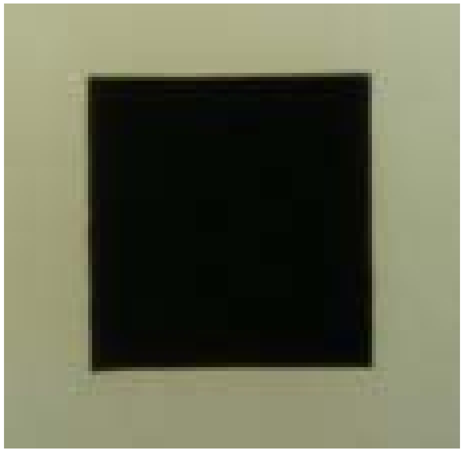
- An effort will be made to build in sensors within the pressure vessels in addition to the external sensors
- H2 Monitoring System – the additional scope of work has been approved by NCMS
- The kick off meeting for the H2 monitoring system was held May 8, 2007 in Orlando, FL

Innovative Ink-jet Printing for Low-Cost, High-Volume Fuel Cell Catalyst Coated Membrane Manufacturing

- **Objective**:
  - Provide innovative solutions for low-cost, high-performance, high-volume fuel cell CCM/MEA manufacturing to accelerate fuel cell commercialization.
- **Team**:
  - Cabot Corporation
  - MTI Micro

Progress/Status

- Cabot's low-cost, durable DMFC CCM/MEAs with low Pt content have presented an attractive path for DMFC commercialization.
- Cabot successfully developed advanced electrocatalyst inks with good stability and jettability for printing CCM.
- Cabot demonstrated inkjetting to make double-sided CCMs with inkjet printing platform.
- Cabot continues to improve the printing platform to advance the fuel cell CCM/MEA manufacturing.
- Cabot will expand this technology to the field of hydrogen air PEM fuel cells during Phase II project.



Cabot's Inkjet CCM

Accomplishments

- Cabot's low Pt loading CCM/MEAs have been demonstrated with excellent performance in DMFC using newly developed supported catalysts.
- Cabot developed a technology to advance Pt/C catalyst ink with reduced particle size. And related solvent and dispersant systems have been developed and optimized. The ink was demonstrated with good stability and ink-jettability.
- Cabot improved ink formulation to minimize the side effect of solvent and dispersant of the ink so that the DMFC MEA performance is maximized.
- Cabot successfully demonstrated inkjetting to make double-sided CCMs. Inkjet CCMs have been delivered to MTI for evaluation.
- Cabot developed accelerated durability testing protocol and demonstrated excellent durability with EOL > 80% BOL.

Project Impact

- **Impact upon manufacturing costs and processes**

  The conventional technologies for CCM manufacturing needs significant investment for the fuel cell CCM production application with a complex manufacturing process. The new CCM printing platform uses existing printer systems is a fundamental change to the conventional manufacturing approaches without significant capital investment which can expedite fuel cell commercialization.

- **The potential to other industries**

  This technology can be easily applied to other areas by printing catalysts on substrates for other industries, e.g., membrane reactors, gas separation membranes coated with selective catalysts, other type fuel cells (like SOFC), electrolyzers, ultracapacitors, batteries, etc.

- **Potential benefits to the U.S. manufacturing base.**

  This new technology will accelerate the fuel cell commercialization. The application of fuel cells in vehicles will change the U.S. manufacturing base from traditional automotive manufacturing mode to an environmentally-friendly, high efficient manufacturing mode with less environment pollution, less noise and high fuel utilizations. It will also allow the U.S. less dependent upon the oil import from foreign countries.

Low Cost, High Reliability Seals for PEM Fuel Cells

- **Objective**: The objective of this project is to produce a durable seal to be manufactured in high volumes for use in Polymer Electrolyte Membrane (PEM) fuel cell applications. The advanced seal design will have a thin cross section, large plan view foot print elastomer molded onto a thin carrier film with short cycle times.

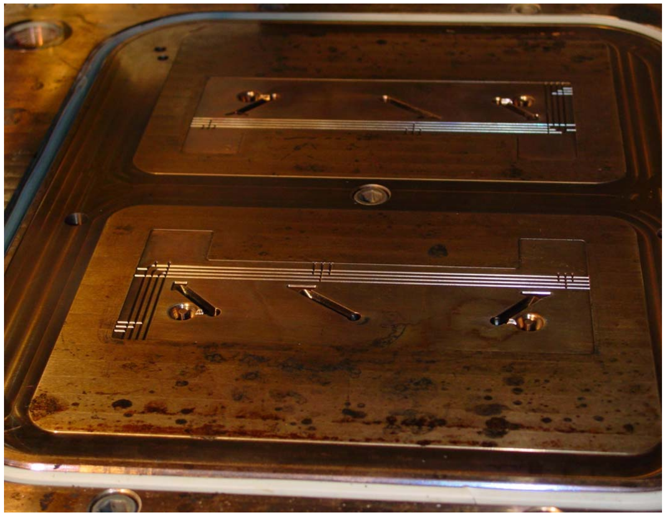
- **Team**: UTC Power engineering and Freudenberg engineering

Progress/Status

- Milestone 1: Material property selection and seal design
  - Property selections complete
  - Design Complete and forwarded to Freudenberg for tool design
- Milestone 2: Tool design and fabrication
  - Tool design complete
  - Tool Fabrication complete
- Milestone 3: Molding and fabrication process optimization
  - Process started, molding optimization near finalization.
  - Fabrication of final part optimization begun.
- Milestone 4: Cell Stack Verifcation
  - Not yet started.

Accomplishments

- UTC Power and Freudenberg have successfully collaborated on a low-cost manufacturable and extended durability seal for PEM Fuel Cells. Seal Design has been developed into tooling and first pieces are currently in progress.



Installed Tooling

Uncut First Piece Off Tool

Project Impact

- PEM Fuel Cells require robust and low-cost sealing technologies to physically separate hydrogen, air and coolant systems. Freudenberg and UTC Power have collaborated to specify the best design to meet both the durability and low-cost characteristics necessary for successful application of fuel cells for bus/fleet transportation drive train power.

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

- **Objective**:
  - Utilize low-cost, high-volume manufacturing processes for PEM Fuel cell power plants
- **Project dates**: 3/2006 – 6/2007
- **Project Partners:**
  - UTC Power
  - Lawrence Berkeley National Labs (LBNL), Berkeley, CA
  - General Pattern, Blaine, MN

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

LBNL Contributions:

- Leachate testing complete on:
  - Virgin polypropylene from APS Water Services ®
  - Banjo® glass-filled black polypropylene
  - Rubber Fab EPDM lined hose
- Mechanical properties testing complete on:
  - Virgin polypropylene
  - Polyone® black polypropylene
- Results
  - List of contaminants identified
  - Team is reviewing list to determine if quantities and types of contamination are a concern to PEM fuel cell

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

- Remaining work at LBNL:
  - Perform mechanical tests on components subjected to leaching
  - Determine which identified contaminants will be added to Nafion membranes
    - Measure impact on membrane conductivity
    - Evaluate any mechanical degradation associated with exposure to contaminants
  - Perform leachate analysis on new parts provided by UTC Power
  - Generate a test plan for determining compatibility of materials with PEM Fuel Cell Power plants

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

General Pattern contributions:

- Polyone® polypropylene injection-molded Cathode Exit elbow prototypes delivered to UTC Power
  - Attempts to mold without mold release were unsuccessful
    - Future parts will use a Teflon-based mold release
  - A post-molding machining step was required to meet flatness requirement
    - Tool modifications and experiments with 20% glass-filled polypropylene planned to improve part quality
- HDPE (high density polyethylene) injection-molded Air Inlet Manifold
  - Part design modified for injection molding
  - Tooling fabrication kicked off

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

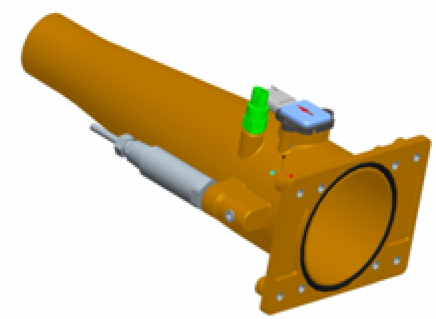
GENERAL PATTERN

Cathode Exit Elbow injection molded in Polyone®
black polypropylene

Cost is 1/15th the price of current 316L stainless steel part

Low-Cost, High-Volume Manufacturing for PEM Fuel Cell Power Plants

- General Pattern remaining work
  - HDPE injection-molded Air Inlet Manifold
    - Complete tooling fabrication
    - Deliver molded parts in May 2007
    - Expected cost is 1/25th cost of welded stainless steel assembly



  - HDPE injection-molded Cathode Inlet elbow
    - Assist UTC Power in modifying part design for injection molding
    - Design & Fabricate tooling
    - Deliver molded parts in June 2007

Develop Low Cost MEA3 Process

- **Objective:**
  - Develop low cost MEA3 process - "feasibility assessment of high throughput screen printing processes"
  - Develop product by process transfer functions – relationships between MEA manufacturing control points and performance of MEA`s Stacks
- **Team**:
  - DuPont Fuel Cells and Smart Fuel Cells (SFC)

Progress/Status

- Completed feasibility of two coating processes: automated printing and roll-to-roll coating processes.
- Selected low cost/high throughput coating process to drive cost down and meet current market needs.
- Demonstrated MEA performance with the customer using new electrode chemistry and process technology

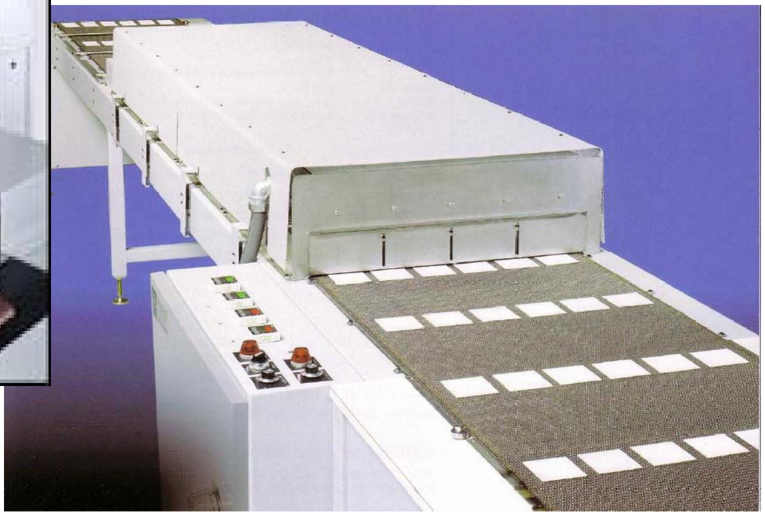
Accomplishments

- High throughput, high productivity coating process

PC Controlled Pinter

High Speed Automation

Conveyor/Dryer



Project Impact

- Potential to reduce cost of manufacturing by 25% at without compromising performance