Reduction in Fabrication Costs of Gas Diffusion Layers

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Project Overview

- **Timeline**
  - Start date: Sept. 1, 2008
  - End date: Aug. 31, 2011
  - **50% complete**

- **Barriers**
  - High material & manufacturing costs
  - Lack of high-volume membrane electrode assembly (GDL) processes
  - Low levels of quality control and inflexible processes

- **Budget**
  - Total project funding:
    - DOE share: $3,000,000
    - Contractor share: $1,617,949
  - Funding received in FY09: $999,994
  - Funding for FY10: $1,006,072

- **Partners**
  - The Pennsylvania State University – Dr. Mike Hickner
  - Ballard Power Systems
  - Ballard Material Products - Prime
Project Relevance (1)

Project Objectives

The overall objective of this project is to reduce the fabrication costs of Gas Diffusion Layer (GDL) products by:

- Improving product quality through the use of on-line tools
- Increasing the manufacturing efficiency by:
  - Reducing the number of process steps
  - Producing material at a wider width
- Reducing process losses by improving web handling equipment
- Eliminating scrap through improved product uniformity

Produce high performance GDLs at lower cost at high volumes in the near term

BMP's Annual volume of Paper based GDLs sold (equivalent kW)

GDL Actuals vs DoE Target Costs ($/kw)
Project Relevance (2)

- Low density Carbon Fiber Paper (Purchased)
- Carbon Powder/Resin Coating
- Roll-to-roll Heat Treatment (Oxidation)
- Inspection
- Batch Graphitization
- Roll-to-Roll Heat Treatment (Carbonization)
Project Relevance (3)

- PTFE Impregnation
- Micro-porous layer Coatings
- Final Visual Inspection
- Continuous Sintering
Project Relevance (4)

- **Project Objectives**
  - Improve the understanding of the relationship between process parameters and critical GDL properties by:
    - Understanding what process steps affect critical GDL properties
    - Implementing process controls steps and GDL screening at critical stages to improve quality yields
  - Identify GDL requirements for improved performance in various operating conditions
    - Optimize process conditions to maximize GDL performance for specific applications
  - Greenfield Design of a new production facility incorporating new GDL process technologies to meet automotive volume requirements at the DOE cost target of $30/kW for the fuel cell system (GDL cost target = $4/kW)
**Evaluation of GDL Costs**

- A breakdown of GDL manufacturing costs was performed during FY08 and it was found that the majority of the final product cost was due to labor.

- The best way to reduce GDL fabrication costs are to:
  - Reduce the number of manufacturing steps
  - Replace slow batch processes with faster continuous processes
  - Utilize modern on-line measurement tools to reduce the amount of ex-situ testing and improve product quality.

**2008 GDL Cost**

- Materials: 33%
- Quality labor: 17%
- Mixing Labor: 17%
- Heat treatment and coating labor: 33%

Total GDL cost ~$36/kW
Project Approach (2)

- **Develop New Process Technology**
  - Improve Substrate Processing
    - Eliminate slitting step after GDL Oxidation
      - Demonstrate product uniformity across web
      - Effectively doubles manufacturing capacity
      - Reduces losses due to startup/rewinding of rolls
  - In-Line Mixing
    - Reduce waste of raw materials
    - Increases production volume
    - Reduces energy costs
  - Multilayer Coating
    - Reduces number of process steps, increasing production volume
    - Reduces number of handling defects, improving product yields
    - Reduces losses due to startup/shutdown
  - In-line Process Controls
    - Improves product uniformity and quality
    - Reduces amount of ex-situ testing required for final product
Project Approach (3)

**Milestones (FY10)**

- 09/09 – All in-line mixing, multilayer coating, ink delivery system and on-line tools have been designed, specified, purchased and received
- 03/10 – All new equipment and online tools are installed and preliminary process capability metrics are established
- 09/10 – Assessment of process parameters and their effect on GDL properties is complete (in-line mixing and multilayer coating processes are done independently)
  **GO/NO-GO Decision Point**
- 09/10 – Demonstrate that performance of lower cost GDL produced with new technologies is equivalent to or better than baseline GDL material in single cell test stand.  **GO/NO-GO Decision point**

**Status Update**

- All new equipment was designed, specified, purchased and received on time.
- Multilayer coating system has been installed and is functional.
- The majority of on-line tools (mass flow meters, viscometers, coating weight, thickness/surface topology) have been installed and tested.
- The in-line mixing equipment has been installed and is in the process of being debugged.
Section 4

Technical Accomplishments and Progress (1)

- Substrate Improvements
  - Investigated Substrate Coating Process
    - Identified key process parameters that influence final GDL properties
    - Monitored and improved dryer settings
  - Studied the Oxidation Process
    - Examined how the oxidation parameters influence final GDL properties
  - Examined the Carbonization Process
    - Improved process controls to stabilize process and reduce cross-web variations enabling us to pursue full-width (80cm wide) production
    - Installed improved web handling equipment to allow us to process longer full-width rolls
Full-Width Validation

- GDL properties were measured across the web for a length of ~20 meters.
- Results showed no significant difference in measured values when compared to half-width material.
- Products are now being run full-width (80cm) from paper substrate through final MPL coating.
Technical Accomplishments and Progress (3)

In-Line Mixing Equipment

Preparatory work

- Performed assessment on current ink rheological properties to establish baseline
- Conducted lab-scale mixing trials at vendor to determine if the continuous mixer could successfully wet-out carbon black powder, supply adequate mixing time to make uniform mixtures, and mix ink at a rate that is beneficial to our process
- Performed trials at gravimetric feeder vendors to determine which technology was best suited for our application based on feed accuracy, versatility, and cost
- Performed pumping trials to determine how to best feed high viscosity fluids while minimizing flow pulsation, shear rates, and air entrainment at appropriate flow rates

Challenges

- Lumps found in ink made through continuous process
  - Found that controlling the process variables, mix speed, barrel temperature, % solids, etc. could minimize the agglomerate formation
- Pumping high-viscosity liquids to the mixer with minimal shear
  - Incorporated the use of sine pumps with pressurized tanks to help flow
In-Line Mixing Equipment

Installation of Equipment

- Two single-screw gravimetric feeders purchased and installed
- Three pump stations were designed, fabricated and installed
- Area above mixer inlet was enclosed to prevent air current from affecting powder delivery and provide the operators protection from airborne particulates
Multi-Layer Coating

Preparatory work
- Performed lab-scale multi-layer coating trials at vendor to determine capability
- Design two new coating skids to supply coating head with ink and accommodate control tools

Installation of Equipment
- Coating head was purchased and delivered and existing coating module modified
- Operators were trained to use the equipment
- Multiple trials were run

Control Tools associated
- Mass flow meter to ensure accurate ink loadings over long roll lengths for improved product quality
- On-line viscometers to monitor ink fluid properties and ensure proper coverage
- Filter housing to remove any particulate debris that may cause coating defects
Technical Accomplishments and Progress (6)

- Multi-Layer Coating
  - Challenges
    - Sublayer micro-cracking (undesired)
      - Initial trials showed micro-cracking in the top sublayer during multilayer coating trials
      - Sublayer inks and MPL drying conditions were adjusted offline to minimize this cracking
      - A screening experiment was performed on-line which varied the total loading of the sublayers with both modified and standard sublayer inks and with standard and improved drying profiles
    - How can we tell if the “Many At A Time” (MAAT) coating structure and the “One At A Time” (OAAT) coating structure are similar?
      - With the help of Penn State we are looking at cross-sections of the GDL structures and to determine the important characteristics of the structure to match
      - Characteristics being looked at are: Coating coverage, substrate penetration, mixing of sublayers
      - Dopants are being used in hand made samples to try to understand mixing and penetration and to delineate the different layers
Online Tools

Coating Weight Tool
- Allows for cross-web and machine direction coating weight measurement to provide real-time feedback to operators to ensure proper ink coverage
- The tool allows for longer run times, reduced sampling, improved product uniformity and customer assurance

On-line thickness and surface topology tool
- Equipment has been installed and initial data has been collected
- Major issue with the “fluttering” of our web
- Attempting to improve process measurement by placing sensors over roller to minimize flutter

On-line viscometers
- Oscillating piston viscometers were down selected
- Equipment is installed and initial values are consistent with expectations
Online Tools

Mass Flow Meter
- Equipment has been purchased and installed, and data is being collected

Online vision system for GDL inspection
- Equipment has been received and installed
- Operators have been trained on proper usage and programs have been set up to identify specific visual defects
- Benefits include faster material inspection, more accurate product map, improved quality control

Online vision system for Coating line
- Equipment has been received and is being installed
- This will allow for real-time feedback for operators to make adjustments as an issue is detected
Technical Accomplishments and Progress (9)

On-Line Tools

Non-Contact Thermocouples

- Air cooled infrared thermocouple has been evaluated on coating line to measure and provide real-time feedback of actual web temperature throughout the drying process
- An additional 8 probes are being ordered

Dew point measurement

- Equipment has been purchased
- Multiple measure points have been installed in the drying oven
- Dew point study is underway to complete the characterization of drying in our ovens with the ultimate goal of future oven scale-up

Surface Tension Meter

- A multiple probe, maximum differential bubble pressure method surface tensiometer with full automation and a patented viscosity compensating design was down selected
Relation of Process variables to final GDL Properties

- Constructed database to track all known process variables that may have an impact final GDL properties
  - Allows us to quickly group data based on specific final properties to look for process variables that may influence them
  - Allows for better process analysis to monitor scrap rates, improve efficiency and monitor process changes

- Developed process model for controlling the effective diffusivity of a GDL
  - Empirical model was generated using over 100 rolls of GDL material made over the course of a year
  - The model allows us to make adjustments to coating conditions based on individual substrate roll properties
  - There has been a significant improvement in quality yields since the introduction of the model
  - The model is continuously being updated as more rolls of material are processed, allowing for continued optimization
  - Measurement of effective diffusivity is done using a proprietary instrument that was designed and implemented prior to this program
Cost Breakdown

2009 Cost Breakdown
- 2009 cost of ~$21/kW
- GDL cost reduction of ~45% from 2008 to 2009

2010 Projected Cost
- 2010 cost of ~$17/kW
- Expected GDL cost reduction of ~20% from 2009 cost (~53% from FY08)

2011 Projected Cost
- 2011 cost of ~$14/kW
- Expected GDL cost reduction of ~20% from 2010 cost (~61% from FY08)
Confocal Raman scanning for PTFE distribution and concentration

6.7% PTFE

33% PTFE

44% PTFE

Orange colors indicate high concentrations of PTFE.

- **Average PTFE peak intensity in Raman** is correlated to the bulk wt % PTFE in the sample.
- **PTFE signals** are higher in green GDLs versus sintered samples.
PTFE Raman maps of green (left) and sintered (right) GDL with 28% PTFE. Note the range of PTFE counts next to each map. Counts are much lower in the sintered sample and aggregates appear much more spread out.
Technical Accomplishments and Progress (14)

- Linear scanning for measuring the “size” of the PTFE aggregates without 2D information for size analysis.

- Peak within 1D intensity plots gives characteristic length scale of PTFE aggregates on the surface of GDL in process.

- Peak widths are clearly larger in the case of 23 wt % PTFE.

- Quantitative analysis is still ongoing.
Technical Accomplishments and Progress (15)

- Detailed microscopic analysis of layered cross-sections.

- Fluorine gives a weak signal in EDS, although some idea of the PTFE distribution in the cross-sectional analysis can be obtained.

- Currently using dopants with high contrast in EDS to more exactly distinguish the PTFE layer boundaries.
Collaborations (1)

- **Ballard Material Products – Prime**
  - Dr. Michael Hickner is leading the effort to establish an in-line method for determining the chemical homogeneity of GDLs

- **The Pennsylvania State University – Partner**
  - Perform stack testing and validation of GDLs manufactured with new technology

- **Ballard Power Systems – Partner**
  - Dr. Mike Ulsh and his team are working to determine what constitutes a GDL defect and how various GDL defects can influence cell performance
  - BMP is collecting representative defects and providing sample rolls to NREL for evaluation
Proposed Future Work (1)

- **Commissioning of process technology**
  - **In-line Mixing**
    - Complete commissioning of equipment
    - Develop procedures for production of more than 8 various ink formulations currently in use
    - Develop menu-driven, recipe-based control software
  - **MAAT coating (Many At A Time)**
    - Determine the optimum drying profile for MAAT coatings
    - Optimize/modify ink formulations to support MAAT coating
    - Examine GDL cross-sections to compare MAAT to OAAT coating layers
  - **On-line process controls**
    - Commission all equipment
    - Perform gauge capability studies as appropriate

- **Single Cell Evaluation**
  - Test GDL performance with new process techniques and compare to standard baseline material to verify functionality
Proposed Future Work (2)

- **Short Roll Uniformity Studies**
  - Make multiple short rolls (50-100m)
    - Baseline reference roll (all standard processes)
    - Multilayer coating with standard substrate and ink
    - Standard coating and substrate with in-line ink
    - Multilayer coating with standard substrate and in-line ink

- **Relate Process Variables to Performance**
  - Relate single cell performance to different process variables to look for trends
  - Utilize statistical analysis (JMP) to screen for potential relationships
  - Make/evaluate samples specifically targeting key variables

- **Manufacture full-scale demonstration roll utilizing all new process technologies**
  - Single cell validation
  - Stack validation
  - Determine manufacturing capability with a goal of achieving 6 sigma standards
**Summary (1)**

- **Evaluated manufacturing process**
  - Determined high labor costs and low product yields were keeping GDL cost high
  - Initial focus was on substrate manufacturing to allow for full-width production
  - Now focused on three key areas:
    - Improve process understanding
    - Reduction of processing steps
    - Implementation of on-line measurement techniques to improve product quality and reduce process scrap

- **Process Improvements**
  - Substrate manufacturing adjustments have allowed us to move to full-width production providing a cost savings of ~40% (FY08 to FY09)
  - Introduction of in-line mixing will allow for reduced scrap and increased capacity with a projected cost savings of ~6% (FY09 to FY011)
  - Introduction of MAAT coating reduces the number of process steps, increases capacity, reduces labor costs with a projected cost savings of ~10% (FY09 to FY011)
  - On-line process control tools will enable longer run times with reduced sampling, reduce ex-situ testing, improve product quality with a projected cost savings of ~13% (FY09 to FY011)
Summary (2)

Program Benefits to Date

- Reduced the cost by ~40% from FY08 to FY09 with help from this program
  - In addition to the funding for this program Ballard made a significant investment in new production equipment in 2009
- Anticipate further reductions in cost (~20%) from FY09 through the rest of the FY10
- Nearly doubled plant capacity from FY08 to FY09 by moving to full-width production and improving product yields
- Ample plant capacity to support near-term market demand

Planned Work FY10

- Commission of all process equipment
- Short-Roll Uniformity Studies
- Single Cell Testing
- Screen process parameters for effects on final GDL properties

Planned Work FY11

- Stack Testing
- Verify product performance
- Provide conceptual design for Greenfield facility for production of GDL to meet the 2015 DOE cost target and identify obstacles to achieving the target cost
Current GDL Manufacturing

- Ink mixing and quality control steps contribute significant cost to the final product.
- Multiple drying and coating steps are capacity-limiting, labor-intensive and costly.

Future GDL Manufacturing

- New GDL process will greatly reduce the number of manufacturing and quality steps.
Supplemental Slides
Sales Volumes

- Only includes GDL paper based sales
- A typical PEM stack is comprised of between 2-5m² of GDL material
- Additional GDL sales include:
  - Carbon Fabric
  - Molded Graphite Laminates (discrete sheets)
- These additional materials are used in a variety of different fuel cell applications varying from PEM to PAFC from 1-400kW making stack estimations difficult
Supplemental (5)

- **Ex-situ testing Capabilities**
  - Density
  - Areal Weight
  - Taber Stiffness
  - Gurley Air Permeability
  - Tensile
  - Force Compression
  - Trough plan electrical resistivity
  - Surface roughness

- **Additional Capabilities**
  - SEM
  - Carbon Analyzer
  - 1 kW test stands
Carbonization Process Study – Presented Last Year

- Higher carbonization heating rates can be utilized with optimized oxidation process

- Translation of experimental conditions to local furnace process conditions to determine maximum heating rate at onset of volatile condensation & re-deposition

- Improving oxidation and carbonization process controls and web-handling equipment allows material to be processed at full-width
What are the advantages of multiple sublayers?

- Allows for improved control of final GDL structure
  - Controlled pore size
  - Improved mechanical properties
- Allows for use of different types and sizes of particles in the sublayers
  - Impacts adhesion
  - Thermal resistance
  - Electrical resistance
  - Water transport properties

![Graph showing current density vs. cell potential for single and multiple MPLs.](image)
Supplemental (8)

- **Before implementation of process model to control diffusivity**
  - Values do not follow a normal distribution
  - Many values are outside of specification limits

- **After implementation of process model to control diffusivity**
  - Values follow a normal distribution centered on the specification limits

Prior to application of model

After application of model