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Reduction in Fabrication Costs of Gas Diffusion Layers

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Project ID # MN002

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Project Overview

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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)

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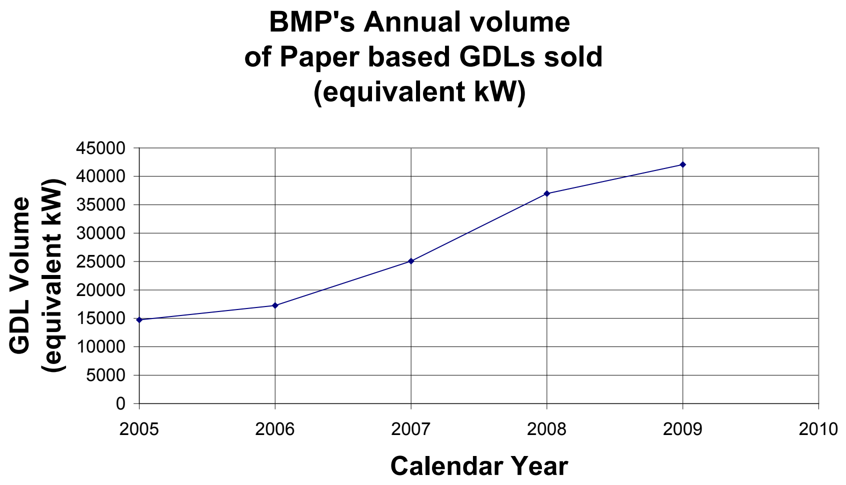
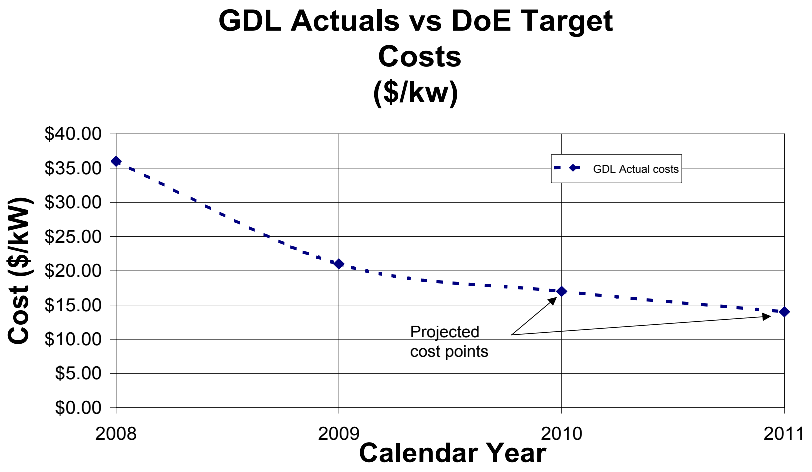
Project Objectives

- **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**





Project Relevance (2)

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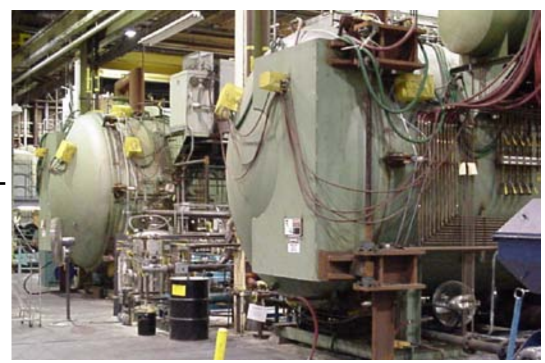
Low density Carbon Fiber Paper (Purchased)

Carbon Powder/Resin Coating

Roll-to-roll Heat Treatment (Oxidation)



Inspection

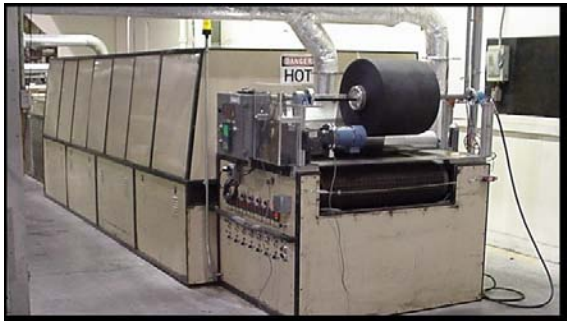
Batch Graphitization

Roll-to-Roll Heat Treatment (Carbonization)

Project Relevance (3)

PTFE Impregnation

Micro-porous layer Coatings



Continuous Sintering

Final Visual Inspection

Project Relevance (4)

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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)**

Project Approach (1)

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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

Total GDL cost ~$36/kW

Project Approach (2)

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- **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)

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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

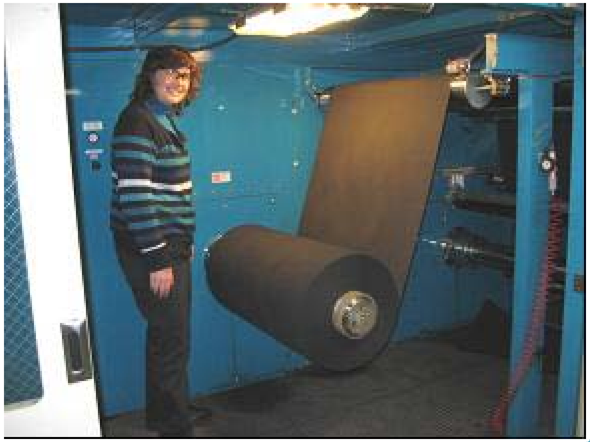
- All new equipment was designed, specified, purchased and received on time.
- Multilayer coating system has been installed and is functional.
- The majority of on-line tools (mass flow meters, viscometers, coating weight, thickness/surface topology) have been installed and tested.
- The in-line mixing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

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

Half-Width Production Roll

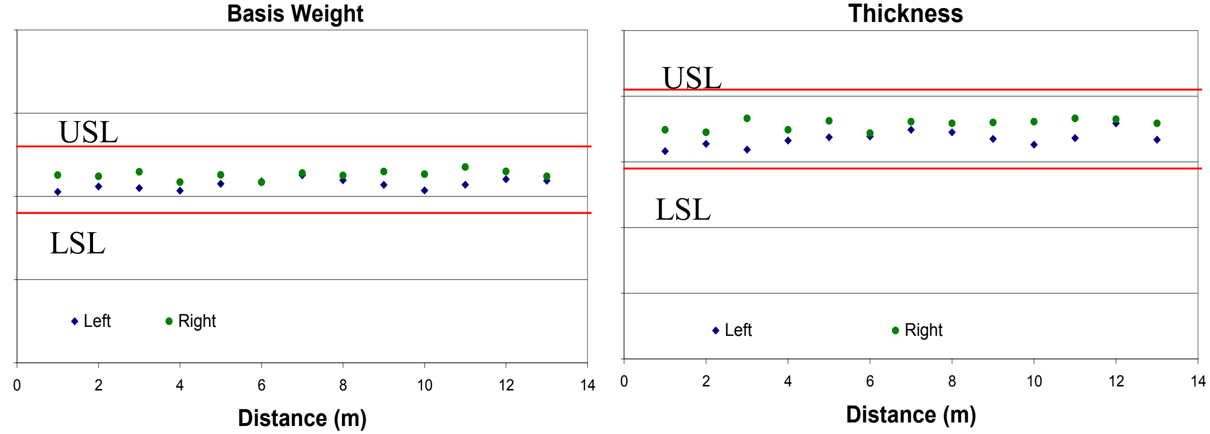
Full-Width Production Roll



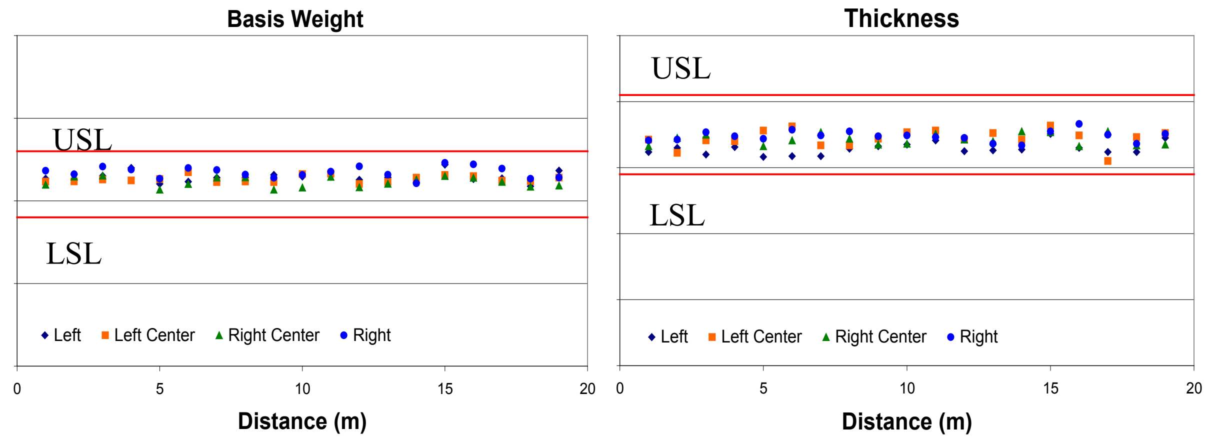
Technical Accomplishments and Progress (2)

- **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

Half-Width GDL



Full-Width GDL



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 venders 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

Technical Accomplishments and Progress (4)

- **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

Technical Accomplishments and Progress (5)

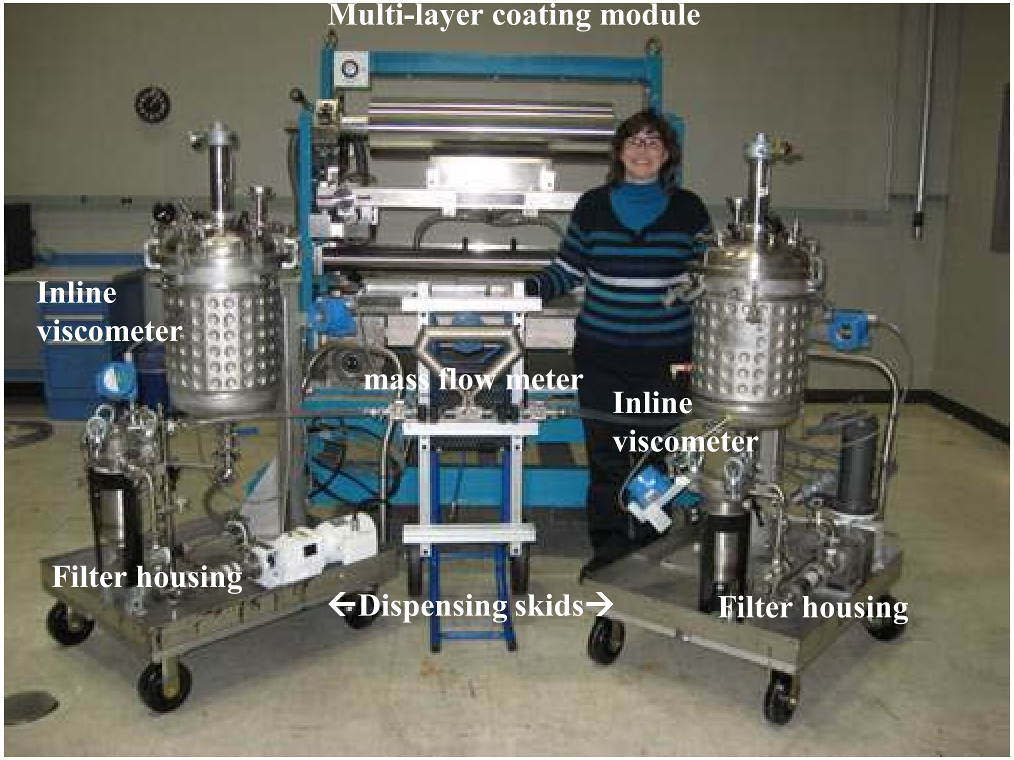
Multi-Layer Coating

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

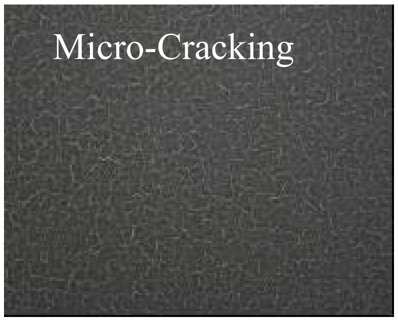


Control Tools associated

- 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

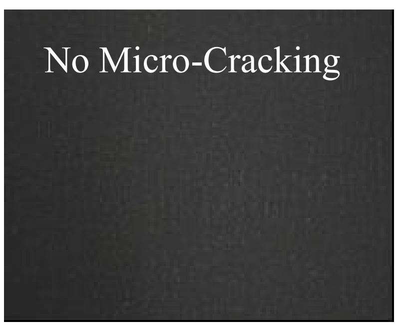
Technical Accomplishments and Progress (6)

- **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 subalyers 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

Technical Accomplishments and Progress (7)

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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

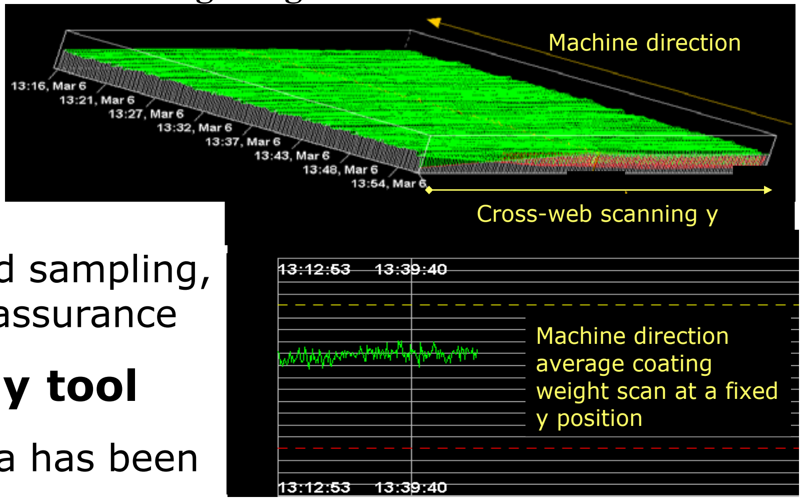
On-line thickness and surface topology tool

- 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

Coating Weight Tool – Shown Last Year



Thickness/Surface Topology Sensors

Technical Accomplishments and Progress (8)

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Online Tools

Mass Flow Meter

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

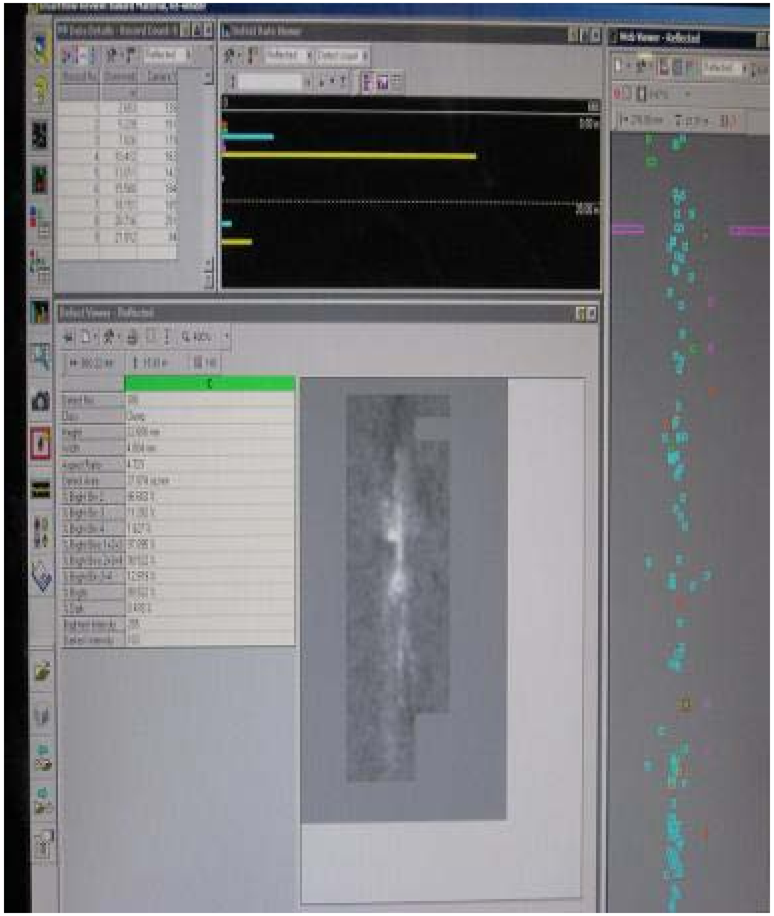
Online vision system for GDL inspection

- Equipment has been received and installed
- Operators have been trained on proper usage and programs have been set up to identify specific visual defect
- 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

Online Vision System for GDL Inspection



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

Dew Point Measurement System

Surface Tension Meter

Technical Accomplishments and Progress (10)

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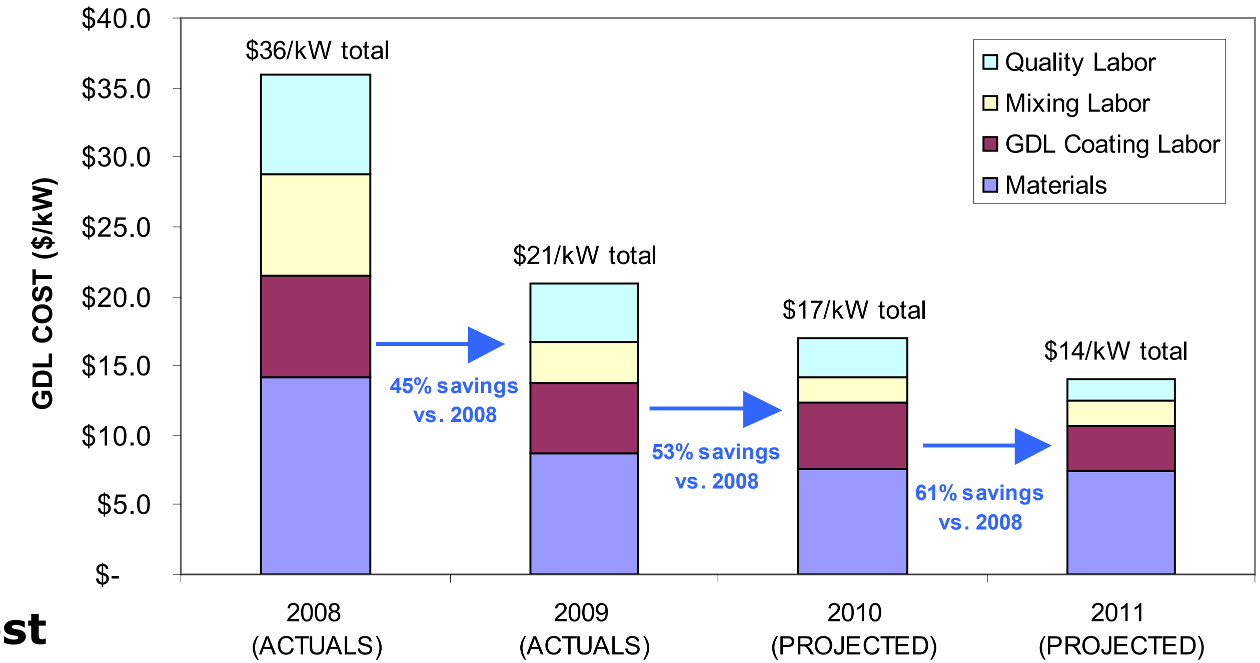
- **Relation of Process variables to final GDL Properties**
  - **Constructed database to track all known process variables that may have an impact final GDL properties**
    - Allows us to quickly group data based on specific final properties to look for process variables that may influence them
    - 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

Technical Accomplishments and Progress (11)

- **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)



Technical Accomplishments and Progress (12)

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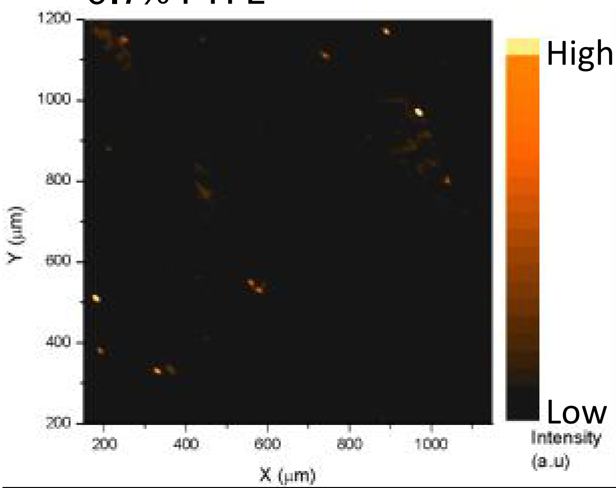
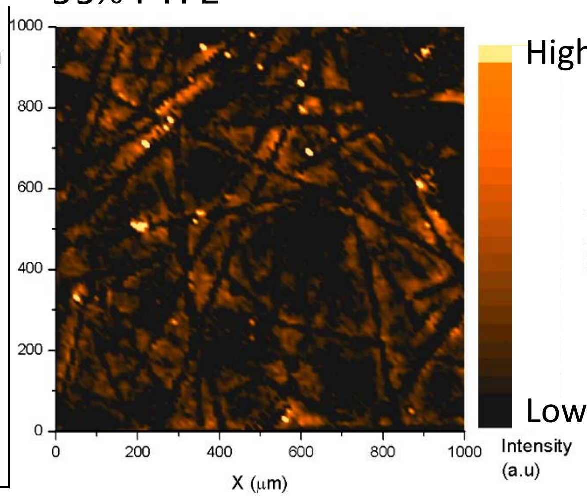
Confocal Raman scanning for PTFE distribution and concentration

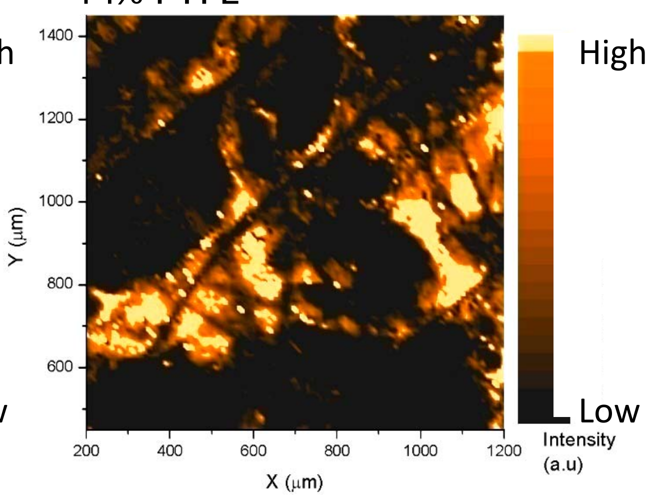
6.7% PTFE



33% PTFE

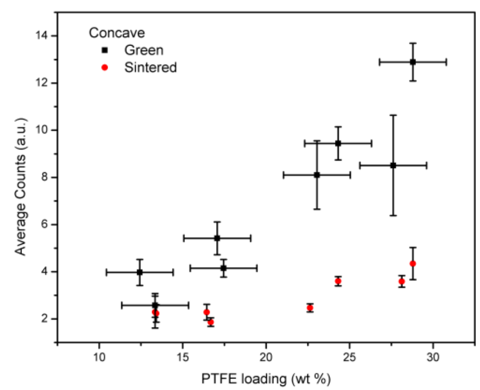


44% PTFE



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.**



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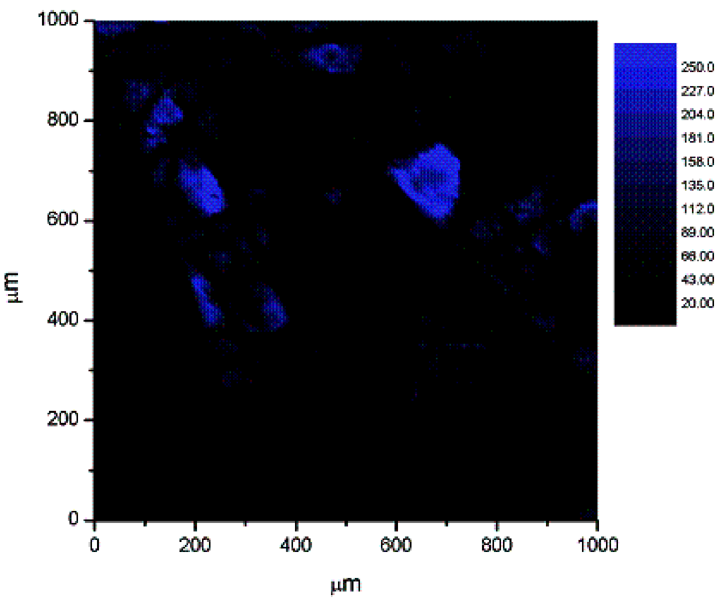
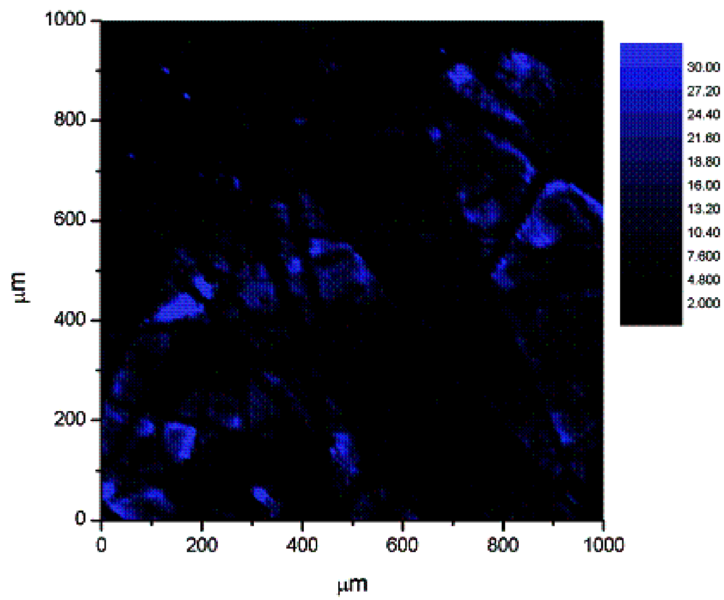
Technical Accomplishments and Progress (13)

PTFE distribution of green and sintered GDLs



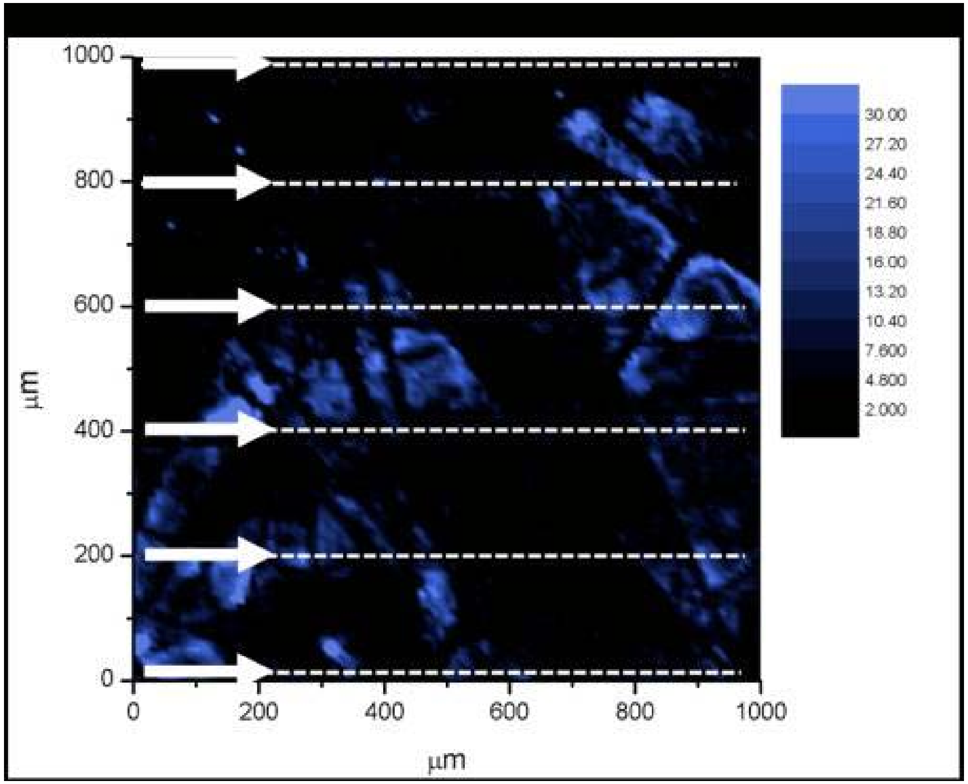


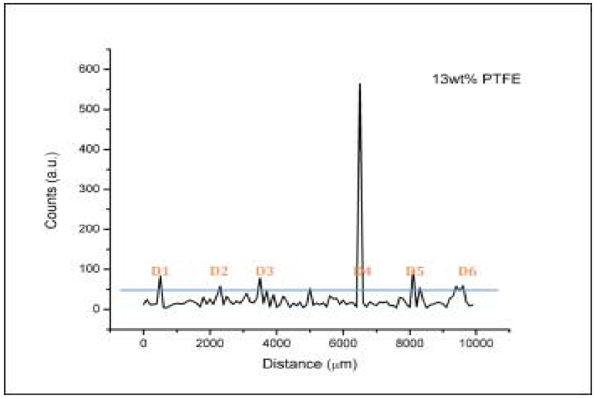
- PTFE Raman maps of green (left) and sintered (right) GDL with 28% PTFE. Note the range of PTFE counts next to each map. Counts are much lower in the sintered sample and aggregates appear much more spread out.

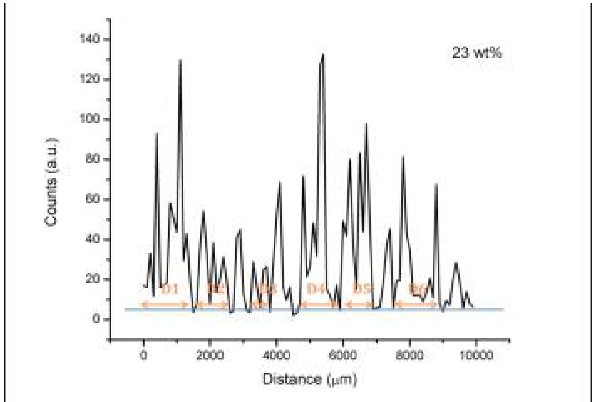
Technical Accomplishments and Progress (14)

- 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.**







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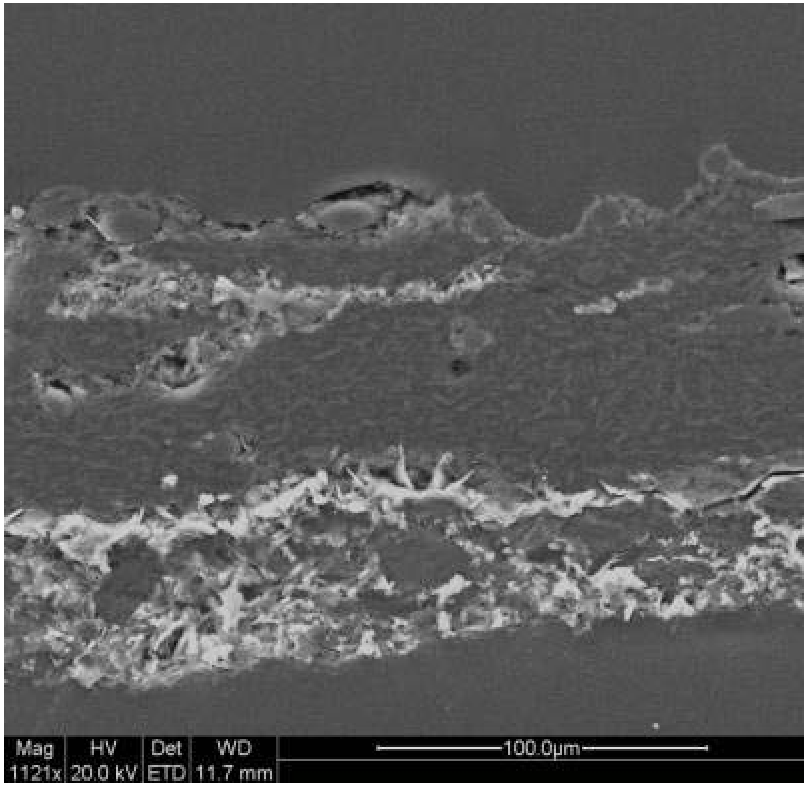
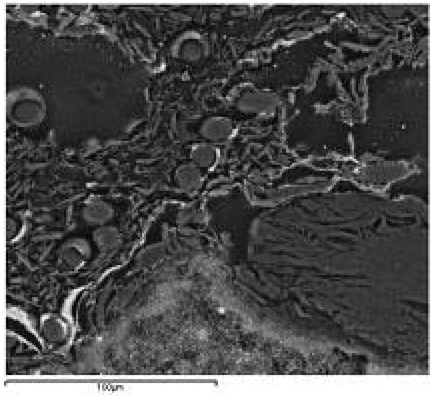
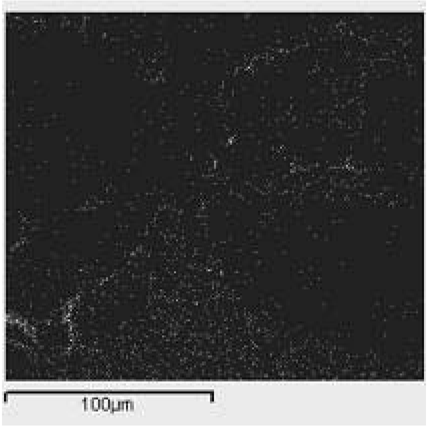
Technical Accomplishments and Progress (15)

- Detailed microscopic analysis of layered cross-sections.





SEM image



fluorine EDS image

- 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**
- **The Pennsylvania State University – Partner**
  - Dr. Michael Hickner is leading the effort to establish an in-line method for determining the chemical homogeneity of GDLs
- **Ballard Power Systems – Partner**
  - Perform stack testing and validation of GDLs manufactured with new technology
- **National Renewable Energy Lab – Collaborator**
  - 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)

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- **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**

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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)

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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

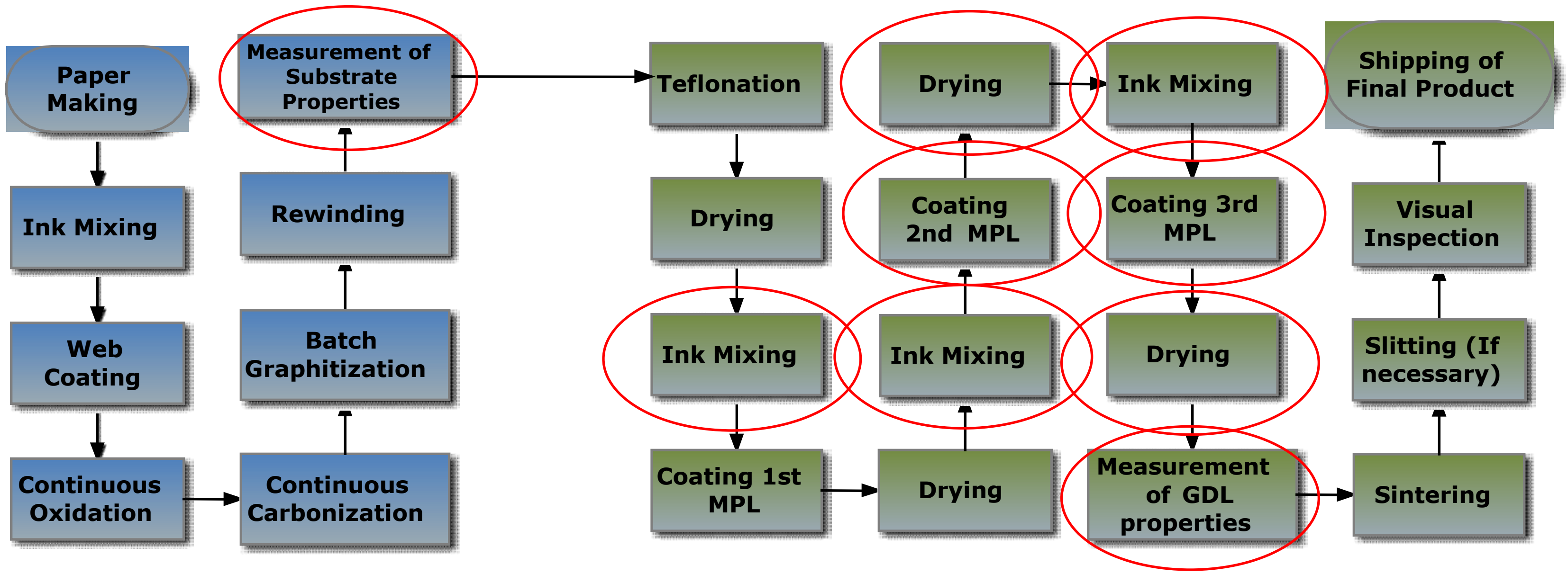
Process Improvements

- 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

Summary (3)



- **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

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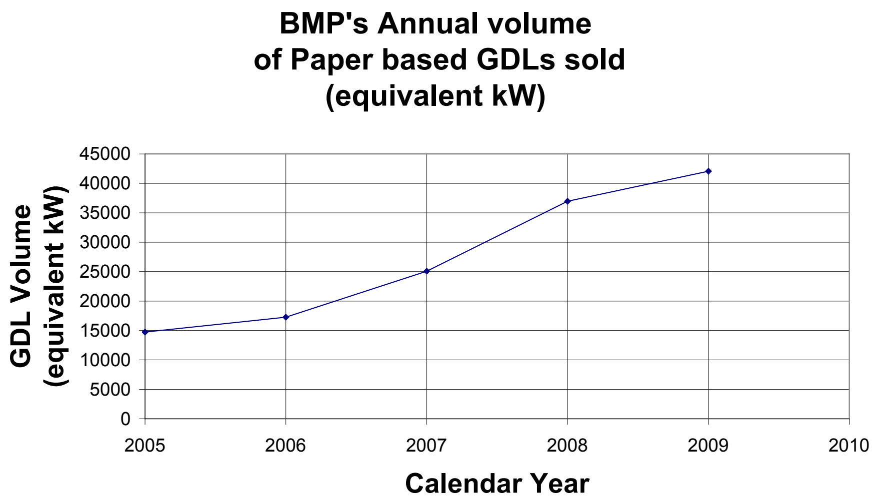
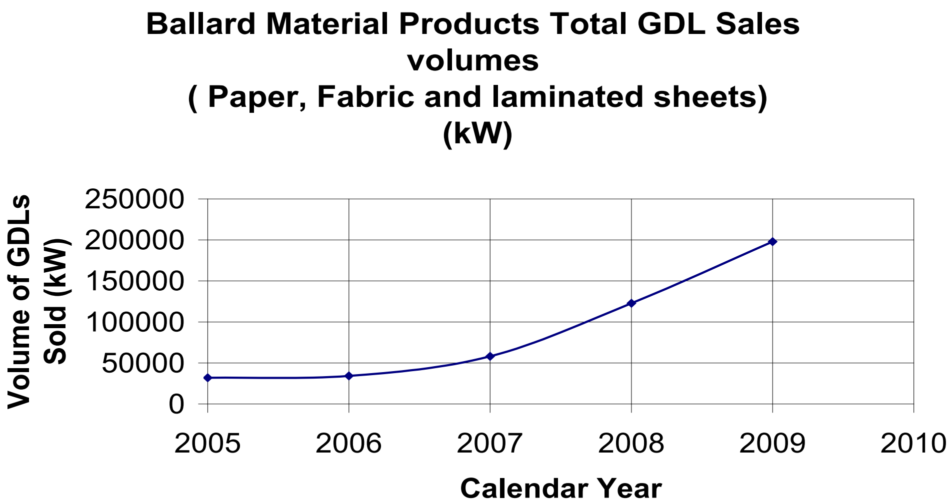
Supplemental Slides

Supplemental (3)

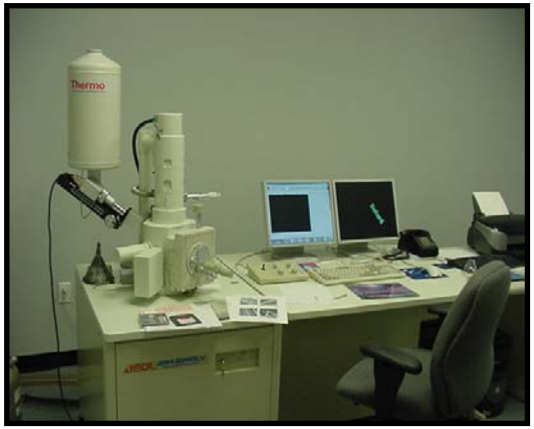
- **Sales Volumes**
  - Only includes GDL **paper** based sales
  - A typical PEM stack is comprised of between 2-5m^2 of GDL material
  - Additional GDL sales include:
    - Carbon Fabric
    - Molded Graphite Laminates (discrete sheets)
  - These additional materials are used in a variety of different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

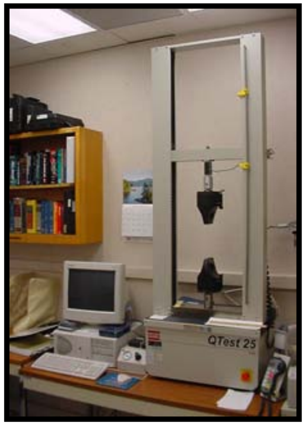




Supplemental (5)

- **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

Supplemental (6)

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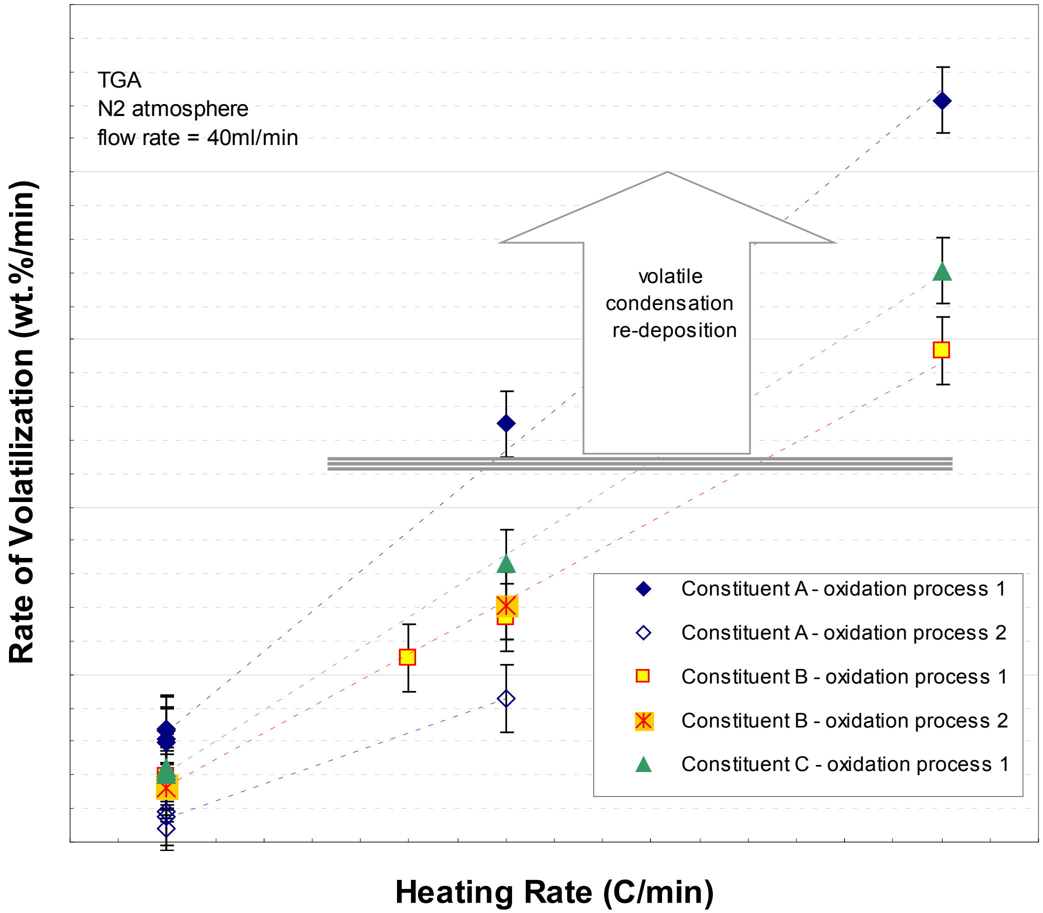
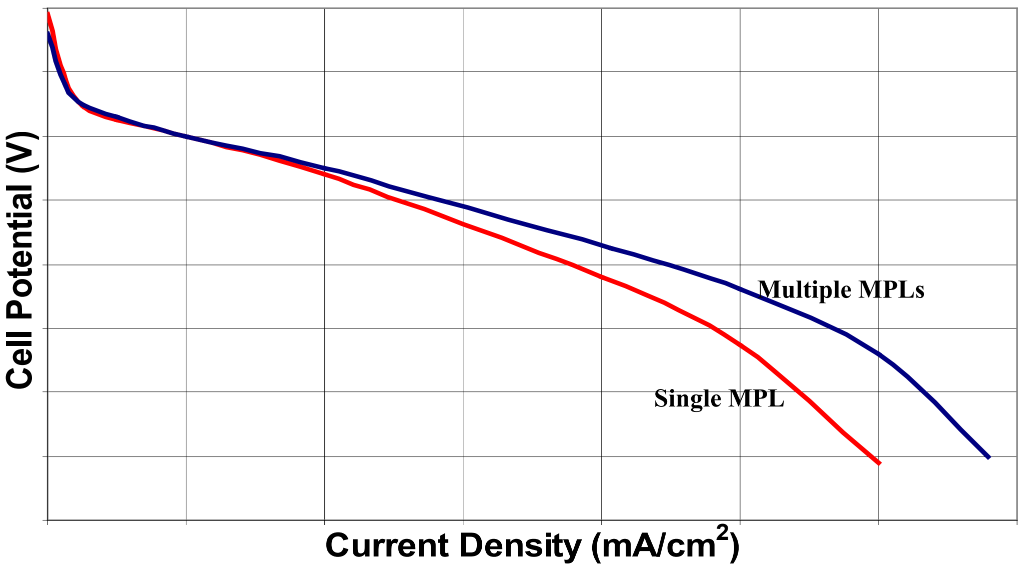
Carbonization Process Study – Presented Last Year

- 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



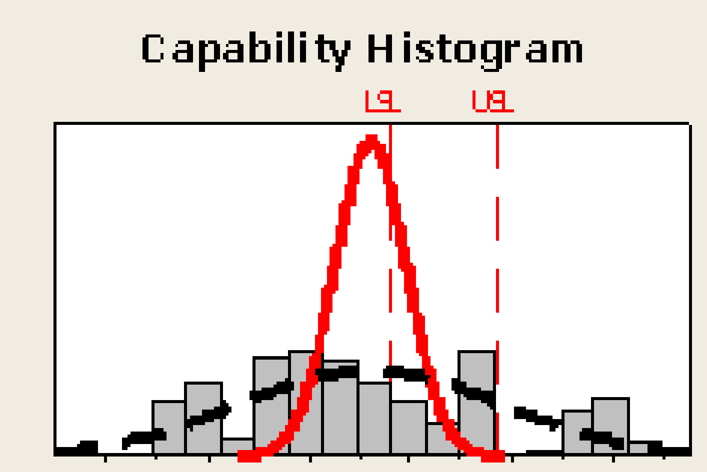
Supplemental (7)

- **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

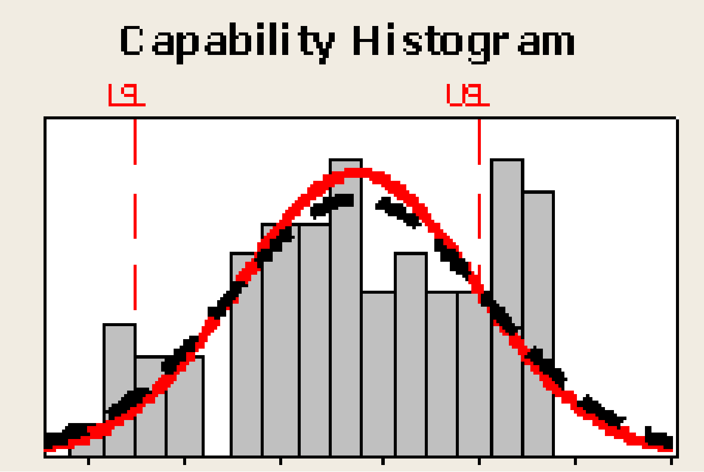


Supplemental (8)

- **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