Development of Micro-Structural Mitigation Strategies for PEM Fuel Cells:
Morphological Simulations and Experimental Approaches

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Ballard Materials Products
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Project ID# FC049

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Overview

Timeline
- Start Date: January 2010
- End Date: March 2013
- Percent Complete: 38%

Barriers
A. Durability
   - Pt/carbon-supports/catalyst layer
B. Performance
C. Cost (indirect)

Budget
- Total Project: $6,010,181
  - $4,672,851 DOE + FFDRC
  - $1,337,330 Ballard
- Funding Received:
  - $1,835,000 (Total)
    - FY 2010: $1,435,000
    - FY 2011: $400K to date, $1M planned

Project Partners
- Georgia Institute of Technology
- Los Alamos National Laboratory
- Michigan Technological University
- Queen’s University
- University of New Mexico
Relevance

**Objective**
- Identify/Verify Catalyst Degradation Mechanisms
  - Pt dissolution, transport/plating, carbon-support oxidation and corrosion, and ionomic thinning and conductivity loss
  - Mechanism coupling, feedback, and acceleration
- Correlate Catalyst Performance & Structural Changes
  - Catalyst layer morphology and composition; operational conditions
  - Gas diffusion layer properties
- Develop Kinetic and Material Models for Aging
  - Macro-level unit cell degradation model, micro-scale catalyst layer degradation model, molecular dynamics degradation model of the platinum/carbon/ionomer interface
- Develop Durability Windows
  - Operational conditions, component structural morphologies and compositions

**Impact**
- Increasing catalyst durability
  - Based on understanding of the effect of structure and operating conditions
- Enabling achievement of DOE catalyst durability targets
  - Durability with cycling, i.e. ≤40% mass activity loss, <10% carbon support mass loss
Approach

MD Model of Pt/C/Ionomer
- 3-phase interface structure
- Pt dissolution/transport mechanism/rates

Micro-structural GDL Model
- Boundary conditions
- Effective properties

Microstructural Catalyst Layer Model
- Effective properties
- Mechanism rates
- Catalyst structure

Catalyst Powder /Ink Characterization

MEA/Components Characterization

Experimental Investigations

1D-Unit Cell Model
- Boundary conditions
- Effective properties

Deliverable
- 1D MEA degradation model
- BOL performance/degradation design curves

- Mechanism Understanding
- Degradation Design Curves
- Mitigation Windows for Catalyst Degradation
Go/No-Go Decision Point

- Validation of statistically generated BOL UC-Model performance curves against experimental results

  - Go: Model predictions are within the 95% statistical variability of the experimental data for the baseline MEA at standard conditions
Milestones 2010/2011

**Model Development**
- Molecular dynamic model of the Pt/C/ionomer system
  - Determined cohesive energy of Pt cluster and interaction with H₂O and O₂, C and ionomer interactions are in progress
- Micro-structural catalyst model expansion for liquid water
  - Implemented preliminary transient 2-phase flow
  - Extraction of effective properties vs. catalyst layer composition and simulation of catalyst performance vs. effective properties is in progress
- BOL MEA/Cell macro-model development and validation
  - Liquid water transport physics (from literature) has been added, under refinement
  - Interfacial transport resistance model derived, implementation is in progress
  - Statistical input modification and preliminary validation completed
  - Final validation of Beginning of Life (BOL) Model is in progress.

**Experimental Investigations**
- Operational and Structural Design Curves
  - Carbon type study: Performance degradation rates established
  - Ionomer content study: Performance degradation rates established
  - Pt/C ratio study is in progress
  - Upper Potential Limit study (two carbon supports) is completed
- Characterization
  - In-situ HRTEM Tool - planned
  - Quantitative changes of the Pt surface and carbon support: Cathode powder characterization and correlation development is in progress
1-D - Unit Cell MEA model was re-derived for statistical inputs

- Statistical inputs in geometry, transport/electrochemistry properties, and operational conditions
- Moved to modular format to allow ease of physics modifications
- Script based format allows automated parametric studies
Technical Progress – Modeling BOL Simulations

Statistical Sensitivity of Input Parameters

- Tested 1 – 10% variability in each input parameter.
  - Sensitive parameters are Tafel Slope, catalyst ionic resistance, catalyst thickness, $j_0$, ECSA, Pt loading, Pt:C ratio.
The average experimental results agree with model prediction to ~1.0A/cm² (1Std Dev)
  - Experimental dataset of 20 (different MEA batches and test stands)
  - Differences between predicted and experimental at high current densities likely caused by water sensitivity

Model is currently extended to include 2-phase flow

### Component Properties % Deviation (1 Std Dev)

<table>
<thead>
<tr>
<th>Component</th>
<th>% Deviation (1 Std Dev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst/Catalyst Layer</td>
<td>+/- 8%</td>
</tr>
<tr>
<td>Thickness (microns)</td>
<td></td>
</tr>
<tr>
<td>Weight Ratios (%)</td>
<td>+/- 1%</td>
</tr>
<tr>
<td>Pt:C</td>
<td>+/- 1%</td>
</tr>
<tr>
<td>(Pt:C):Ionomer</td>
<td>+/- 1%</td>
</tr>
<tr>
<td>Pt Loading [mg/cm²]</td>
<td>+/- 1.25 %</td>
</tr>
<tr>
<td>Pt size</td>
<td>+/- 10%</td>
</tr>
<tr>
<td>Tafel Slope [mV/dec]</td>
<td>fixed</td>
</tr>
<tr>
<td>Jo [A/cm² pt]</td>
<td>+/- 10%</td>
</tr>
<tr>
<td>GDL</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>fixed</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>+/- 3%</td>
</tr>
<tr>
<td>Thickness (microns)</td>
<td>+/- 4%</td>
</tr>
<tr>
<td>Membrane</td>
<td></td>
</tr>
<tr>
<td>Thickness (microns)</td>
<td>+/- 2%</td>
</tr>
</tbody>
</table>
Variation of Pt loading from 0.1 to 0.7mg/cm² in steps of 0.02mg/cm²

- For each loading 15 polarization curves were generated.
- Model was validated against commercial test hardware, loading dependency is similar between the hardware.
Technical Progress
Effect of Upper Potential Limit

**Degradation signature is similar for both catalysts**
- Pt dissolution is the dominating mechanism at low cycle number and low UPL resulting in agglomeration and PITM
- With increasing UPL and/or cycle number the dominant mechanism shifts to carbon corrosion

**Superimposed voltage spike does not cause significant degradation**
Pt Supported on Low/Medium Surface Area Carbon

**Pt Crystallite Size/PITM**
- EOT

**Pt in the Membrane (PITM)**
- EOT

**Pt-LSAC at 1.2V UPL**
- Cycle Number Study

- **Pt Agglomeration at EOT**
  - Both catalysts have similar agglomeration at UPL > 1.0V
  - Pt50 LSAC has slightly larger Pt size

- **PITM at EOT shows dependency on UPL**
  - Similar PITM concentration for both catalysts

- **Catalyst layer thickness at EOT is dramatically reduced for UPL > 1.2V**
  - Pt50-MSAC less corrosion resistant than LSAC

AST: Air/H2, 100% RH, 5 psig, 80°C, 0.6 V (30 sec) → UPL (60 sec), 4700 cycles
Water content at 0.6V increases to 100 Cycles, decreases from 100 cycles to EOT

- Performance loss is not observed until >250 cycles

- ECSA loss as observed in 50 cm² test hardware
Pt/C Catalyst Powders (50wt.%)

- Pt average crystallite size is similar for all non-heat treated Pt catalyst powders
- Heat treatment widens particle size distribution and increases average crystallite size
- EOT (1.2V UPL) crystallite size varies with carbon support structure
Technical Progress
Effect of Carbon Support Structure

- Catalysts supported on higher surface area carbons show in general improved performance but durability is greatly impacted.
- Carbon support surface area is not the only measure of durability, the carbon structure and morphology impacts durability.

**ECSA Breakdown @ EOT**

- **LSAC Pt50**
- **MSAC Pt50**
- **Vulcan Pt50**
- **HSAC2 Pt50**
- **HSAC1 Pt50**

**Air Performance, 0.67A/cm² (mV)**

**Increasing C Surface Area**

**AST:** Air/H2, 100% RH, 5 psig, 80°C, 0.6 V (30 sec) → 1.2 V (60 sec)
Effect of Carbon Support Structure

- Graphitic carbon content of catalyst support is one measure of durability
- Degradation decreases with increasing graphitic content
  - Voltage loss
  - Catalyst layer ionic voltage loss
  - ECSA, Pt dissolution
  - Carbon corrosion (cathode thickness change)

AST: Air/H₂, 100% RH, 5 psig, 80°C, 0.6 V (30 sec) → 1.2V (60 sec)
Technical Progress
Effect of Ionomer Loading

Low Surface Area Carbon Catalyst (Pt50-LSAC)

- Optimal performance for Nafion loading is ~30wt%.
- Increased ionomer content results in:
  - increased catalyst layer ionic conductivity
  - increased ECSA loss (Pt dissolution)
- Excessive ionomer (50wt%) results in greater mass transport and catalyst layer resistance losses.

AST: Air/H2, 100% RH, 5 psig, 80°C, 0.6 V (30 sec) → 1.2V (60 sec)
Organizations /Partners

- **Prime: Ballard Material Products / Ballard Power Systems**
  (S. Wessel, D. Harvey, V. Colbow)
  - Lead: Micro-structural/MEA/Unit Cell modeling, AST correlations, characterization, durability windows

- **Queen’s University – Fuel Cell Research Center (K. Karan, J. Pharoah)**
  - Micro-structural Catalyst Layer/Unit Cell modeling, catalyst characterization

- **Georgia Institute of Technology (S. S. Jang)**
  - Molecular modeling of 3-phase interface & Pt dissolution/transport

- **Los Alamos National Laboratory (R. Borup, R. Mukundan)**
  - Characterization of catalyst layer/GDL

- **Michigan Technological University (J. Allen, R. S. Yassar)**
  - Capillary pressure and interface characterization, catalyst layer capillary pressure tool development

- **University of New Mexico (P. Atanassov)**
  - Carbon corrosion mechanism, characterization of catalyst powder/layers
Plan Forward
Experimental/Characterization

**Molecular Dynamics Model**
- Completion of Pt/C/ionomer interface
- Molecular modeling of Pt dissolution

**Micro-structural Model**
- Completion of two-phase flow implementation
- Simulation of effective properties and performance with liquid water

**1D-MEA Model**
- Refinement of saturation model
- Validation of statistical 1D-MEA model with experiment
  - **Go/No-Go decision June 30, 2011**
- Integration of electrical contact resistance model
- Implementation of Multi-step ORR

**Experimental Investigations**
- **Carbon Types**
  - Investigate lower upper voltage limits
  - Correlate degradation with material properties
- Ionomer equivalent weight
- Pt/C ratio study
- Carbon corrosion (potential hold) study

**Material Characterization**
- GDL wettability and capillary pressure
- Interface characterization
- Property changes of aged GDLs and catalyst layers
Summary

Relevance
- Improve understanding of durability for fuel cell materials and components
- Provide recommendations for the mitigation of MEA degradation that facilitates achieving the stationary and automotive fuel cell targets

Approach
- Develop forward predictive MEA degradation model using a multi-scale approach
- Investigate degradation mechanisms and correlate degradation rates with catalyst microstructure and cell operational conditions

Technical Accomplishments and Progress to date
- Implemented statistical input option for macro model
- Quantified Pt/C catalyst performance degradation with UPL, carbon support type, ionomer loading
- Composition effects included in BOL MEA performance model and validated with experimental results

Collaborations
- Project team partners GIT, LANL, MTU, Queen’s, UNM
- Participation in DOE Durability Working Group

Proposed Future Research
- Validate 2-phase flow micro-structural model and expand to full catalyst layer thickness
- Complete MD model of Pt/C/ionomer, develop MD description of Pt dissolution
- Refinement of liquid water transport physics, validate statistical capability (Go/No-Go)
- Effect of the carbon ratio and ionomer type on AST degradation rates
Project Applicability to Industry

Model Predictions of Performance and Degradation are based on MEA Components, Composition, and Processing (Structure)

Component Properties and Structure

- **Catalyst Powder**
  - BET SA
  - Mass activity
  - ECA

- **Catalyst Ink**
  - Pt/C/Ionomer Vol. fractions

- **Catalyst Layer**
  - Mass activity
  - ECSA
  - Utilization
  - Thickness
  - Conductivity \((H^+, e^-, T)\)
  - Capillary pressure
  - Porosity

- **GDL**
  - Thickness
  - Tortuosity
  - Diffusivity
  - Porosity
  - Capillary Press.
  - Cond. \((e^-, T)\)

- **Plates**
  - Cond. \((e^-, T)\)
  - Geometry

- **Membrane**
  - EW
  - Thickness

- **MEA**

BOL Performance

- ECSA
- Exchange current density
- Tafel slope
- Mass activity
- HFR

Operating Conditions

1D Unit Cell Model

Parametric Performance Study

Predicted Voltage Degradation

Predicted ECSA Loss
Acknowledgement

Thank you:

- Financial support from the U.S. DOE-EERE Fuel Cells Technology Program
- Support from project managers/advisor Kathi Epping Martin, Jason Marcinkoski, David Peterson, and John Kopasz
- Project Collaborators

**Acronyms/Abbreviations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AST</td>
<td>Accelerated Stress Test</td>
</tr>
<tr>
<td>BOL = BOT</td>
<td>Beginning of Life = Beginning of Test</td>
</tr>
<tr>
<td>CB</td>
<td>Carbon Black</td>
</tr>
<tr>
<td>CCL</td>
<td>Cathode Catalyst Layer</td>
</tr>
<tr>
<td>CL</td>
<td>Catalyst Layer</td>
</tr>
<tr>
<td>Cond</td>
<td>Conductivity</td>
</tr>
<tr>
<td>CV</td>
<td>Cyclic Voltammetry</td>
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<tr>
<td>ECSA</td>
<td>Effective Catalyst Surface Area</td>
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<tr>
<td>EDX</td>
<td>Energy Dispersive X-ray Analysis</td>
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<tr>
<td>EIS</td>
<td>Electrode Impedance Spectroscopy</td>
</tr>
<tr>
<td>EOL = EOT</td>
<td>End of Life = End of Test</td>
</tr>
<tr>
<td>EPSA</td>
<td>Effective Pt Surface Area (cm² Pt/cm² geom)</td>
</tr>
<tr>
<td>EW</td>
<td>Equivalent Weight</td>
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<tr>
<td>FA</td>
<td>Failure Analysis</td>
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<tr>
<td>GDL</td>
<td>Gas Diffusion Layer</td>
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<tr>
<td>HFR</td>
<td>High Frequency Resistance</td>
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<tr>
<td>HRTEM</td>
<td>High Resolution Transmission Electron Microscopy</td>
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<tr>
<td>HSAC</td>
<td>High Surface Area Carbon</td>
</tr>
<tr>
<td>HSAC-HT</td>
<td>High Surface Area Carbon - Heat Treated</td>
</tr>
<tr>
<td>LSAC</td>
<td>Low Surface Area Carbon</td>
</tr>
<tr>
<td>MD</td>
<td>Molecular Dynamics</td>
</tr>
<tr>
<td>MEA</td>
<td>Membrane Electrode Assembly</td>
</tr>
<tr>
<td>MOL = MOT</td>
<td>Middle of Life = Middle of Test</td>
</tr>
<tr>
<td>MPL</td>
<td>Micro-porous Layer</td>
</tr>
<tr>
<td>MSAC</td>
<td>Mid-range Surface Area Carbon</td>
</tr>
<tr>
<td>NAA</td>
<td>Neutron Activated Analysis</td>
</tr>
<tr>
<td>OER</td>
<td>Oxygen Evolution Reaction</td>
</tr>
<tr>
<td>ORR</td>
<td>Oxygen Reduction Reaction</td>
</tr>
<tr>
<td>PSD</td>
<td>Particle Size Distribution</td>
</tr>
<tr>
<td>P/C</td>
<td>Platinum/Carbon Ratio</td>
</tr>
<tr>
<td>PITM</td>
<td>Platinum in the Membrane</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>SA</td>
<td>Surface Area</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
</tr>
<tr>
<td>UPL</td>
<td>Upper Potential Limit</td>
</tr>
<tr>
<td>XPS</td>
<td>X-ray Photoelectron Spectroscopy</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
</tr>
</tbody>
</table>
Technical Backup Slides
Approach

- **Model Development**
  - 3 scale modeling approach
    - Molecular dynamics model of the Pt/ carbon/ionomer interface, Pt dissolution and transport process
    - Microstructural catalyst layer model to simulate the effect of local operational conditions and effective properties on performance and degradation
    - Unit cell model predicting BOL performance and voltage degradation

- **Experimental Investigations/Characterization**
  - Systematic evaluation of performance loss, catalyst layer structural and compositional changes of different catalyst layer structures/compositions under a variety of operational conditions
    - Carbon support type, Pt/C ratio, ionomer content, ionomer EW, catalyst loading
    - Potential, RH, O₂ partial pressure, temperature
    - Accelerated stress tests (ASTs) combined with in-situ/ex-situ techniques
    - Performance loss breakdown to determine component contribution
    - In-situ/ex-situ characterization to quantify effect of electrode structure and composition on performance and durability

- **DOE Working Group (Durability and Modeling)**
  - Interaction and data exchange with other projects
**Experimental Approach**

**In-situ diagnostics**
- **H₂/Air Polarization**
  - Performance
  - Limiting current
- **H₂/O₂ polarization**
  - V-loss break-down: Kinetic, Ohmic, Mass Transport
- **Cyclic Voltametry**
  - CO stripping
  - ECSA
  - Double layer charging current
  - H₂ cross-over
  - Pt surface understanding
- **Electrochemical Impedance Spectroscopy (EIS)**
  - Cell resistance
  - Ionomer resistance
  - Double layer charging current
- **Mass and specific activity**

**Ex-situ Diagnostics**
- **SEM**: Catalyst/membrane thickness
- **SEM/EDX**: Pt content in membrane and catalyst layer
- **XRD**: Pt crystallite size and orientation
- **BPS Diagnostic Tool**
  - Voltage Loss Breakdown (Kinetic Loss)
  - Limiting Current

**Selected MEA Components for Collaborators**

- **MEA**
  - Conditioning
  - BOT
  - MOT 1
  - MOT x
  - EOT

**AST Testing**

**Selected BOT/EOT Samples for Collaborators**

**Reference AST**: Air/H₂, 100% RH, 5 psig, 80°C, 0.6 V (30 sec) → 1.2V (60 sec), 4700 cycles

**Reference MEA**: 50:50 Pt/C, Nafion® ionomer, 0.4/0.1 mg/cm² (Cathode/anode), Ballard CCM, Nafion® NR211, BMP GDLs

**Ballard 1D Test Cell, 45cm² active area**
Experimental Approach
Voltage Loss Breakdown Method

- **Separation of voltage loss based on Air/O₂ and EIS**
  - Kinetic/ohmic/mass transport loss
  - Cathode catalyst layer ionic loss and estimated reaction penetration depth

- **Model validation of transport processes**
  - Kinetic rates for ORR
  - Component resistances
  - Mass transport losses at high and low current conditions

**Experimental Benchmarking**

**Compare degradation mechanisms for AST protocols**

<table>
<thead>
<tr>
<th>Oxidant</th>
<th>Failure Modes</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Pt Agglomeration, Carbon Surface Oxidation, Carbon Corrosion, PITM (?)</td>
<td>Under N\textsubscript{2}, membrane degradation is nominal, No product water effects</td>
<td>Platinum deposition occurs near the membrane/catalyst interface and is not separable from catalyst agglomeration.</td>
</tr>
<tr>
<td>Air</td>
<td>Pt Agglomeration, PITM, Carbon Surface Oxidation, Carbon Corrosion</td>
<td>More realistic to field data due to separable platinum in the membrane, Potential to capture effect of ionomer degradation</td>
<td>More difficult to control RH due to water production, Membrane degradation may occur at 1.0V UPL, More difficult to control/ setup equipment (potentiostat &amp; loadbank)</td>
</tr>
</tbody>
</table>

**Primary Protocol Differences (DOE vs. Ballard)**

- Triangular vs. square ramp
  - Square cycling profile enables better control/understanding of mechanisms
- \( N_2 \) vs. synthetic Air
  - Ability to quantify Pt in the membrane failure mode
  - Failure modes representative of products
- 1.0V vs. 1.2V upper potential limit (UPL)
  - 1.2V UPL enables better comparison with state-of-the-art catalysts
  - UPL will be investigated in operational and structural studies
## Experimental Benchmarking

### Ranking of Stressors

<table>
<thead>
<tr>
<th>Operational Stressor</th>
<th>Range Studied</th>
<th>Mechanism Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPL</td>
<td>0.8&gt;&gt;&gt;1.2V</td>
<td>&gt;1.2V</td>
</tr>
<tr>
<td></td>
<td>0.8&gt;&gt;&gt;1.3V</td>
<td>&gt;1.2V</td>
</tr>
<tr>
<td></td>
<td>0.8&gt;&gt;&gt;1.5V</td>
<td>&gt;1.2V</td>
</tr>
<tr>
<td>Dwell Time</td>
<td>30-5000sec</td>
<td></td>
</tr>
<tr>
<td>Cycle #</td>
<td>(10,000-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cycle)</td>
<td></td>
</tr>
<tr>
<td>Temp (UPL 1.3V)</td>
<td>60&gt;&gt;&gt;80C</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Temp (UPL 1.2V)</td>
<td>60&gt;&gt;&gt;80C</td>
<td>&gt;75</td>
</tr>
<tr>
<td>RH</td>
<td>50&gt;&gt;&gt;120%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>LPL</td>
<td>0.5&gt;&gt;&gt;0.8V</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Structural Stressor</th>
<th>Impact on Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Support Type</td>
<td>High</td>
</tr>
<tr>
<td>Pt/C Ratio</td>
<td>High</td>
</tr>
<tr>
<td>Ionomer loading</td>
<td>Medium</td>
</tr>
<tr>
<td>Pt Particle size</td>
<td>Medium</td>
</tr>
<tr>
<td>Membrane</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Pt Loading</td>
<td>Low</td>
</tr>
<tr>
<td>GDL Type</td>
<td>Low</td>
</tr>
</tbody>
</table>

*Based on literature and experimental results  
*Relative Ranking

### Catalyst Samples Being Investigated

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample Specifics</th>
</tr>
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<tbody>
<tr>
<td>Carbon</td>
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<tr>
<td>Vulcan</td>
<td>Vulcan</td>
</tr>
<tr>
<td>LSAC</td>
<td>Low Surface Area Carbon</td>
</tr>
<tr>
<td>MSAC</td>
<td>Mid-range Surface Area Carbon</td>
</tr>
<tr>
<td>HSAC #1</td>
<td>High Surface Area Carbon #1</td>
</tr>
<tr>
<td>HASC #2</td>
<td>High Surface Area Carbon #2</td>
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<tr>
<td>Catalysts</td>
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<tr>
<td>Pt50-Vulcan</td>
<td>50/50 Pt/Vulcan</td>
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<tr>
<td>Pt50-LSAC</td>
<td>50/50 Pt/Low Surface Area Carbon</td>
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<tr>
<td>Pt50-MSAC</td>
<td>50/50 Pt/Mid-range Surface Area Carbon</td>
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<tr>
<td>Pt50-HSAC #1</td>
<td>50/50 Pt/High Surface Area Carbon #1</td>
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<tr>
<td>PT50-HSAC#1-HT</td>
<td>50/50 Pt/High Surface Area Carbon #1 -Heat Treated</td>
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<tr>
<td>Pt50-HSAC #2</td>
<td>50/50 Pt/High Surface Area Carbon #2</td>
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<tr>
<td>Pt50-HSAC #2 HT</td>
<td>50/50 Pt/High Surface Area Carbon #2 - Heat Treated</td>
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<tr>
<td>Pt30-LSAC</td>
<td>30/70 Pt/Low surface Area Carbon</td>
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<tr>
<td>Pt40-LSAC</td>
<td>40/60 Pt/Low surface Area Carbon</td>
</tr>
<tr>
<td>Pt60-LSAC</td>
<td>60/40 Pt/Low surface Area Carbon</td>
</tr>
<tr>
<td>Pt80-LSAC</td>
<td>80/20 Pt/Low surface Area Carbon</td>
</tr>
</tbody>
</table>

*Based on LSAC  
Results funded by Natural Resources Canada, Project ID: 414-CETC-526/823

### Mechanism Shift Range Studied

- **Operational**
  - UPL
  - Dwell Time (Cycle #)
  - Temp (UPL 1.3V)
  - Temp (UPL 1.2V)
  - RH
  - LPL

- **Structural**
  - Carbon Support Type
  - Pt/C Ratio
  - Ionomer loading
  - Pt Particle size
  - Membrane
  - Pt Loading
  - GDL Type

### Legend

- **Negligible Effect:** No Significant Change
- **Small Effect:** 2 to 5 times increase in deg. rate
- **Medium Effect:** 5 to 10 times increase in deg. rate
- **Large Effect:** >10X increase in deg. rate

*Based on LSAC