R&D for Automotive PEM Fuel Cell System
- Bipolar Plates -

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IEA Advanced Fuel Cells Annex 34
November 11, 2015
Why Hydrogen Fuel Cell Vehicles?

Hydrogen has been considered as a viable alternative fuel source in the long-term.

- Hydrogen fuel has the potential to diversify energy resources and improve energy security.
- Opportunity to improve vehicle’s energy efficiency
- Fuel cell power is one of the best ways to use hydrogen fuel for vehicle propulsion.
A Portfolio Approach for Sustainability

A portfolio approach to develop various kinds of powertrain technologies, including ICE improvement and electrification, has been taken for alternative fuel options.

ICE Improvement
- Gasoline Direct Injection
- “Downsizing & Boosting”

Electrification
Challenges for Fuel Cell Vehicle Commercialization

Hydrogen Infrastructure

• Immature H$_2$ Infrastructure
• Subsidized initial development for expansion

Carbon footprint

• CO$_2$ emission for production and delivery of H$_2$ Fuel
• Employ carbon sequestration or increased mix of renewable energy

Fuel cell technology
Ford Fuel Cell Vehicle Development

1999
P2000 HFC
Mk700 - CGH₂

2000
Ford Focus FC5
Mk901-Methanol

2000
Ford Focus FCV
Mk901-CGH₂

2001
Mazda Premacy
Mk901-Methanol

2005-2009 Focus FCEV
30 Vehicle Demonstration Program

2006-2009 DOE Technology
Demonstration Vehicle (TDV) Program
Fuel cell powertrain systems also use HV batteries for hybridization.

- Optimized in terms of Cost and Efficiency
- Transient performance
- Hotel power for start-up and shut-down
Durability and Cost are the primary challenges to fuel cell commercialization and must be met concurrently.
R&D drives cost reduction, but still gap.

Trend of cost reduction shows plateau for last 4 years in spite of significant R&D effort.

Further R&D is necessary to reduce cost while meeting durability targets.

see above
Opportunity for Cost Reduction

Sensitivity of Fuel Cell System Cost vs. Key Parameters

- Power Density
- Pt Loading
- Bipolar Plate Cost (incl. coating & welding)
- Membrane Cost
- Hydrogen Recirculation System Cost
- Compressor/Expander Efficiency
- Air Compressor Cost
- Balance of Air Compressor Cost
- GDL Cost
- Membrane Humidifier Cost

Performance at high current density and decreased mass transport overpotential

Higher ORR activity

Lower cost materials and components

USDRIVE Fuel Cell Technical Team Roadmap, p15 (June 2013)

Area Specific Power Density (Mass Transport), ORR catalyst performance and materials cost (Bipolar Plate, etc.) are high impact factors.
Technical Area for Further R&D Effort

- High impact for cost reduction
- Cost and Durability to be met concurrently.

**Materials**

**ORR Catalyst**
- High Mass Activity (catalyst powder)
  - Structure of Catalyst Layer
    - (oxygen and proton transfer resistance in catalyst layer)

**Bipolar Plate**
- bipolar plate materials and manufacturing process

**Attributes**

**Mass Transport Performance**
- High performance at high current densities

**Durability Study**
- degradation mechanism in MEA and fuel cell materials

**Analytical Methodology**

➢ Focus is shifting from previous accomplishments to updated priorities.
Cost Fraction of Fuel Cell Stack

Stack Cost - $25/kW

- Membranes: 12%
- MEA Gaskets: 15%
- Bipolar Plates: 21%
- Other: 6%
- Catalyst Ink & Application: 34%
- GDL: 12%

DTI, 2010 analysis, scaled to high volume production of 500,000 units/yr
Used $1100/Troy Ounce for Pt Cost
### Technical Targets (US DOE)

**Table 6. Technical Targets for Bipolar Plates**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>Status</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate cost</td>
<td>$/kW</td>
<td>4&lt;sup&gt;b,c&lt;/sup&gt;</td>
<td>3</td>
</tr>
<tr>
<td>Plate weight</td>
<td>kg/kW</td>
<td>&lt;0.4&lt;sup&gt;c,d&lt;/sup&gt;</td>
<td>0.4</td>
</tr>
<tr>
<td>Plate H&lt;sub&gt;2&lt;/sub&gt; permeation</td>
<td>Std cm&lt;sup&gt;3&lt;/sup&gt;/(sec cm&lt;sup&gt;2&lt;/sup&gt; Pa) @ 80&lt;sup&gt;o&lt;/sup&gt;C, 3 atm 100% RH</td>
<td>&lt;2x10&lt;sup&gt;6&lt;/sup&gt;&lt;sup&gt;f&lt;/sup&gt;</td>
<td>1.3x10&lt;sup&gt;-14&lt;/sup&gt;</td>
</tr>
<tr>
<td>Corrosion anode&lt;sup&gt;g&lt;/sup&gt;</td>
<td>µA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>no active peak&lt;sup&gt;h&lt;/sup&gt;</td>
<td>1 and no active peak</td>
</tr>
<tr>
<td>Corrosion cathode&lt;sup&gt;i&lt;/sup&gt;</td>
<td>µA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>&lt;0.1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>S/cm</td>
<td>&gt;100&lt;sup&gt;i&lt;/sup&gt;</td>
<td>100</td>
</tr>
<tr>
<td>Areal specific resistance&lt;sup&gt;k&lt;/sup&gt;</td>
<td>Ohm cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.006&lt;sup&gt;h&lt;/sup&gt;</td>
<td>0.01</td>
</tr>
<tr>
<td>Flexural strength&lt;sup&gt;i&lt;/sup&gt;</td>
<td>MPa</td>
<td>&gt;34 (carbon plate)</td>
<td>25</td>
</tr>
<tr>
<td>Forming elongation&lt;sup&gt;m&lt;/sup&gt;</td>
<td>See note m</td>
<td>20-40&lt;sup&gt;n&lt;/sup&gt;</td>
<td>See note m</td>
</tr>
</tbody>
</table>

k: Measured across the bipolar plate; includes interfacial contact resistance (on as received and after potentiostatic test), measured both sides at 200 pounds per square inch (138 N/cm<sup>2</sup>), H. Wang, M. Sweikart, and J. Turner, “Stainless steel as bipolar plate material for polymer electrolyte membrane fuel cells,” Journal of Power Sources 115 (2003): 243-251.

m: 40%, per ASTM E8M-01: Standard Test Method for Tension Testing of Metallic Materials, or demonstrate ability to stamp generic channel design with width, depth, and radius.

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USDRIVE Fuel Cell Technical Team Roadmap, p10 (June 2013)
Performance Metric

Area Specific Resistance (GDL free)

Measured across the bipolar plate; includes interfacial contact resistance (on as received and after potentiostatic test), measured both sides at 200 pounds per square inch (138 N/cm²), H. Wang, M. Sweikart, and J. Turner, “Stainless steel as bipolar plate material for polymer electrolyte membrane fuel cells,” Journal of Power Sources 115 (2003): 243-251.
Corrosion Resistance

Corrosion Problem

- Retention of Electrical Conductivity under fuel cell operational conditions and cell environment.
- Mitigate effect of corrosion products
  - Proton conductivity in the ionomer
  - Catalyze formation of radicals that degrade the electrolyte polymer membrane

DOE Targets (Test Metrics)

- Anode; potentiodynamic 0.1mV/s, -0.4 to +0.6V (Ag/AgCl)
- Cathode; potentiostatic at 0.6V (Ag/AgCl) for >24 hours
- *Ex-situ* Corrosion Tests are guideline, not to be used as a pass/fail criterion

- Wide range of *ex-situ* corrosion tests (potentiodynamic, potentiostatic for both anodic and cathodic conditions) can help to understand material characteristics for real world conditions
- *In-situ* durability test is imperative to verify material’s durability.
Exposure of High Potentials

PEMFC operation during hydrogen and oxygen co-exist at the anode.

C + 2H₂O → CO₂ + 4H⁺ + 4e⁻
2H₂O → O₂ + 4H⁺ + 4e⁻
Pt → Pt²⁺ + 2e⁻
Pt + H₂O → PtO + 2H⁺ + 2e⁻
PtO + 2H⁺ → Pt²⁺ + H₂O
PtO + H₂O → PtO₂ + 2H⁺ + 2e⁻
PtO₂ + 4H⁺ + 4e⁻ → Pt²⁺ + 2H₂O

Exposure of High Potentials

Anode under hydrogen starvation

\[
\begin{align*}
C + H_2O & \rightarrow CO + 2H^+ + 2e^- \quad E_0 = 0.52V \\
C + 2H_2O & \rightarrow CO_2 + 4H^+ + 4e^- \quad E_0 = 0.21V \\
2H_2O & \rightarrow O_2 + 4H^+ + 4e^- \quad E_0 = 1.23V
\end{align*}
\]


This number varies depending on mag. of H₂ starvation and current drawn, ref. to O₂ electrode

Pratiti Mandal, et al., 3D Imaging of Fuel Cell Electrode Structure Degraded under Cell Reversal Conditions Using Nanoscale X-ray Computed Tomography, 228th ECS meeting in Phoenix, AZ
Nanometer scale thickness of Au coated stainless steel foil supplied by Daido Steel.

Cathodic CV Test – Au Clad®

Electrolyte: H₂SO₄, pH3
Temperature: 80 °C
Stirring: No
Purging gas: Air, 100 ml/min

Au Nanoclad w/SS316L

DOE ex-situ Target
Bipolar Plate Material – Au Dot Coating

Basic Function
Collect electric current
Provide reactant gas flow field
Mechanical Support

Basic Requirement
Electric conductivity
Corrosion resistance
Formability

Substrate Metal

Corrosion resistant alloy w/ a poor conductive surface layer
Electrically conductive dots

US Department of Energy Agreement # 09EE0000463, PI CH Wang, TreadStone
**Ex-situ Corrosion Resistance Tests**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Metric</th>
<th>Unit</th>
<th>2015 DOE Target</th>
<th>Ford Data on Au-Nanoclad®</th>
<th>Ford Data on Au-Dots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion anode</td>
<td>Current density at active peak in CV</td>
<td>µA/cm²</td>
<td>&lt;1</td>
<td>No active peak</td>
<td>No active peak</td>
</tr>
<tr>
<td>Corrosion cathode</td>
<td>Current density at 0.8 V&lt;sub&gt;NHE&lt;/sub&gt; in potentiostatic expt.</td>
<td>µA/cm²</td>
<td>&lt;1</td>
<td>~1.0</td>
<td>~0.1</td>
</tr>
</tbody>
</table>

**Robustness; Potentiostatic - High Potential Anodic and Cathodic**

1.6 V<sub>NHE</sub> (Air) / 0.5 V<sub>NHE</sub> (H₂) Potentiostatic
In-situ Durability Test

- Two short stacks were assembled with Au-nanoclad and Au-Dots baseline materials.
- Ford designed metallic bipolar plate with 300 cm$^2$ active area.
- Durability Cycle:
  - The stack is being tested for durability utilizing durability cycle (which includes FTP cycle along with others) mimicking real world operating conditions.

Short stack on the test stand at Ford

Metal bipolar plate with Daido Au-nanoclad®

Metal bipolar plate with TreadStone Au-Dot Baseline Material
• No significant increase in plate area specific resistance was observed during in-situ durability test.

• Post analysis revealed no significant corrosion issues. Metal cations in the stack effluent water (anode, cathode, and coolant) were below the detectable limit of Inductively Coupled Plasma (ICP) analyzer (~ppm).
Anodic passivation characteristic of Au Nanoclad® allows it to be applied prior to fabricating (stamping) metallic bipolar plates (pre-coat process).
TreadStone Au-dot coating

• TreadStone (Princeton, NJ) developed Au-dot coating metallic bipolar plate materials (USP7309540).

• Stainless steel substrate is covered by corrosion resistance coating (e.g. TiO₂) and Au-dots sprayed on the surface and penetrated through corrosion resistance layer to provide electrical conductivity.

• Post-coating process).
**Manufacturing Process – Formability**


### Fuel Cell Performance Comparison

<table>
<thead>
<tr>
<th>Current Density (Amps/cm²)</th>
<th>Mean Cell Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>0.80</td>
<td>0.20</td>
</tr>
<tr>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

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#### Stack 1 vs. Stack 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Substrate</th>
<th>Channel Span</th>
<th>GDL Material</th>
<th>GDL Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack 1</td>
<td>SS 316 L</td>
<td>1.5 mm</td>
<td>Stiff-Type</td>
<td>4.09/5.59 GPa</td>
</tr>
<tr>
<td>Stack 2</td>
<td>SS 301</td>
<td>0.8 mm</td>
<td>Roll Good-Type</td>
<td>1.15/1.18 GPa</td>
</tr>
</tbody>
</table>
Summary

1. Cost of bipolar plates are one of the largest fraction in the fuel cell stack. Cost reduction of materials/process are still required.
2. Retention of electrical conductivity under the fuel cell operational conditions is a key performance metric.
3. Wide range of ex-situ corrosion tests (potentiodynamic, potentiostatic for both anodic and cathodic conditions) can help to understand material characteristics for real world conditions. In-situ stack level durability test is imperative to verify material’s durability.
4. Flow field design configuration is an effective factor to the fuel cell performance. Formability is an important attribute to the design space.
“Improved sustainable performance is not just a requirement, but a tremendous business opportunity.”

- Bill Ford