PEM Electrolyzer
Incorporating an Advanced Low Cost Membrane

Monjid Hamdan
Giner Electrochemical Systems, LLC
May 11, 2011

This presentation does not contain any proprietary or confidential information
Overview

Timeline
- Project Start: May 2008
- Project End: April 2011
- Percent Complete: 74%

Budget
- Total Project Budget: $2.49M
  - DOE Share: $1.99M
  - Cost Share: $0.51M
- FY10 Funding
  - DOE: $550K
- FY11 Funding
  - DOE: $550K

Barriers
Hydrogen Generation by Water Electrolysis
- G. Capital Cost
- H. System Efficiency

DOE Targets: Distributed Water Electrolysis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Cost ($/kg-H₂)</td>
<td>4.80</td>
<td>3.70</td>
<td>2.00 - 4.00</td>
<td>4.66</td>
</tr>
<tr>
<td>Electrolyzer Cap. Cost ($/kg-H₂)</td>
<td>1.20</td>
<td>0.70</td>
<td>0.30</td>
<td>0.60</td>
</tr>
<tr>
<td>Electrolyzer Efficiency (%LHV)</td>
<td>62 (73)</td>
<td>69 (82)</td>
<td>74 (87)</td>
<td>75.1 (88.8)</td>
</tr>
</tbody>
</table>

Partners
- Parker Hannifin Corporation (Industry) – System Development
- Virginia Tech University (Academic) – Membrane Development

Collaborations
- 3M Fuel Cell Components Program – NSTF Catalyst & Membrane
- Entegris – Carbon Cell Separators
- Tokuyama – Low-Cost Membrane
- Prof. R. Zalosh (WPI) – Hydrogen Safety Codes
Relevance/Project Objectives

Overall Project Objectives
- Develop and demonstrate advanced low-cost, moderate-pressure PEM water electrolyzer system to meet DOE targets for distributed electrolysis.
  - Develop high efficiency, low cost membrane
  - Develop long-life cell-separator
  - Develop lower-cost prototype electrolyzer stack & system

Relevance
- Successfully developing a low-cost hydrogen generator will enable early adoption of fuel cell vehicles

FY 2010-11 Objectives
- Fabricate scaled-up stack components (DSM, cell-separators)
- Assembly electrolyzer stack/system
- Install electrolyzer stack into system & evaluate
- Deliver and Demonstrate prototype electrolyzer system at NREL
## Milestones

<table>
<thead>
<tr>
<th>Go/No Go Decision Points</th>
<th>Progress Notes</th>
<th>%Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Membrane</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate DSM membrane performance comparable to or better than that of Nafion®1135 at 80°C</td>
<td>Performance DSM &gt; Nafion®1135 = Nafion®112, Completed 1000 hrs @ 80°C.</td>
<td>100% (Mar-09)</td>
</tr>
<tr>
<td>Demonstrate electrolyzer lifetime with DSM membrane (80°C ≥ 1000 hrs)</td>
<td>Testing indicates low membrane degradation rate, high life expectancy</td>
<td>100% (Mar-09)</td>
</tr>
<tr>
<td>Scale-up DSM membrane to 290cm² &amp; Evaluate in short stack for 1000 hours</td>
<td>Operated 5-cell for 1000-hours, Single-cell; &gt; 2800+ hours. Use of chemically-etched DSM supports for further cost reduction.</td>
<td>100% (Dec-10)</td>
</tr>
<tr>
<td>Identify new low-cost membranes for PEM-based electrolyzers, new low-cost catalysts</td>
<td>Tokuyama hydrocarbon membranes under evaluation, 3M catalyst evaluated</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Cell Separator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstrate performance comparable to dual-layer Ti separator</td>
<td>Operated 290-cm² cell-separators in 5-cell for 1000-hours. H₂-embrittlement testing confirms longevity of Carbon/Titanium cell-separators</td>
<td>100% (Dec-10)</td>
</tr>
<tr>
<td>Scale-up Carbon/Ti cell-separator to 290-cm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate in short stack for 1000 hours.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify &amp; evaluate new low-cost Carbon materials for cell-separators</td>
<td>Initiated investigation of low-cost carbon for future cost reductions</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Stack/System Development</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete preliminary design review</td>
<td>Completed: P&amp;ID, PFD, control diagrams, safety review, FMEA, system layout and packaging drawings</td>
<td>100% (Dec-09)</td>
</tr>
<tr>
<td>Complete Stack &amp; System assembly</td>
<td>Electrolyzer stack fabricated. System near completion.</td>
<td>25%</td>
</tr>
<tr>
<td>Evaluate efficiency of Stack &amp; System</td>
<td>Thin frames fabricated and tested in 160-cm² hardware.</td>
<td></td>
</tr>
<tr>
<td>Complete critical design review of system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate thin frame design for further cost reduction of electrolyzer Stack.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Membrane Development Approach

**DSM Membrane-GES**
- PFSA ionomer incorporated in an engineering plastic support
  - High-strength
  - High-efficiency
  - No x-y dimensional changes upon wet/dry or freeze-thaw cycling
  - Superior to PTFE based supports

**Bi-Phenyl Sulfone Membrane-VT**
- Hydrocarbon Membranes
  - Inexpensive starting materials
  - Trade-off between conductivity and mechanical properties

**Alternative Membranes**
- PFSA (850EW) Membrane-3M
- Hydrocarbon Membrane- Tokuyama

*Approach is to optimize membrane ionomer EW and thickness, scale-up fabrication methods and techniques, and improve costs*
High Durability Cell-Separator Approach

- Requirements
  - Gas-impermeable (separates $\text{H}_2$ and $\text{O}_2$ compartments)
  - High electrical conductivity and high surface conductivity
  - Resistant to hydrogen embrittlement
  - Stable in oxidizing environment
  - Low-Cost

- Legacy Design
  - Multi-Layer piece consisting of Zr on hydrogen side and Nb on oxygen side

- Single or Dual-Layer Ti separators
  - Ti subject to hydrogen embrittlement
  - Lifetime limited to <5000 hours, depending on pressure and operating conditions

- Approach
  - Develop a new low-cost dual-layer structure
    - Evaluate methods of bonding dissimilar metal films
    - Evaluate non-metal substrate with conductive coating
Designing Low Cost Electrolyzer Stack and System

- **Objectives**
  - Reduce BOP capital cost
  - Reduce BOP power consumption
  - Increase stack active area
  - Improve safety and reliability
  - Design for high-volume manufacturing

- **Approach**
  - Team with large volume commercial manufacturer (Domnick Hunter Group of Parker-Hannifin)
  - Redesign stack & system to eliminate or replace costly components
  - Laboratory evaluation of lower-cost components and subsystems
    - Design & test high efficiency H₂ dryer
  - Develop higher efficiency power electronics

### System Design Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Rate</td>
<td>0.5 kg H₂/hr</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>300-400 psid; H₂ 300-400 psig; O₂ atm</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>50-90°C</td>
</tr>
<tr>
<td>Membrane</td>
<td>DSM with PFSA ionomer</td>
</tr>
<tr>
<td>Stack Size</td>
<td>290 cm²/cell, 27 Cells</td>
</tr>
<tr>
<td>Stack Current Density</td>
<td>1500-2000+ mA/cm²</td>
</tr>
</tbody>
</table>
Membrane Progress: DSM

- **Performance Milestone** (Mar-2009/Mar-2010)
  - Performance of Laser-Drilled (L-) DSM > Chemically-Etched (C-) DSM > Nafion® 1135
- **C-DSM (1100EW) selected for electrolyzer build**
  - Lower cost, ease of fabrication

Nafion is a registered trademark of E.I. du Pont Nemours and Company
Performance: Scaled-up DSM & Stack Hardware

- **Milestone (Dec-2010): 5-cell Scaled-up Short-Stack**
  - Performance comparable to 160-cm² HW w/DSM > Nafion 1135®
  - Electrolyzer Stack utilizes scaled-up 290-cm² cell components (DSM, carbon/titanium, cell-separators)

![Performance Scan Diagram]

- **Test Conditions:**
  - 80°C
  - 320-330 psig Cathode (H₂)
  - 20 psig Anode (H₂O/O₂)

- **MEA/Hardware:**
  - DSM thickness (3 mil)
  - C(poco)/Ti separator used in scaled-up 290-cm² HW

<table>
<thead>
<tr>
<th>HW</th>
<th>#Cells</th>
<th>MEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>160-cm²</td>
<td>1</td>
<td>C-DSM</td>
</tr>
<tr>
<td>290-cm²</td>
<td>1</td>
<td>C-DSM</td>
</tr>
<tr>
<td>290-cm²</td>
<td>5</td>
<td>C-DSM</td>
</tr>
<tr>
<td>160-cm²</td>
<td>1</td>
<td>Nafion 1135</td>
</tr>
</tbody>
</table>

Nafion is a registered trademark of E.I. du Pont Nemours and Company
Membrane Progress: Life Testing

Performance
- Completed 1000 Hour Life Test Milestones
  - 1-cell (160-cm²) & 5-cell (290-cm²)
  - 5-cell includes scaled-up components
  - 1.73-1.75V (~88% HHV)
- DSM MEA from 5-cell short stack re-assembled into a single-cell stack, total operating time = 2800+ hours

Membrane Degradation (Estimated Lifetime)
- F ion Release Rate: 3.7 µg/hr (<10 ppb)
- DSM -1100EW (Stabilized Ionomer): ~55,000 hours
Membrane/Catalyst Evaluations

3M Catalyst Performance
- 3M NSTF cathode catalyst performance equivalent to GES (Jan 2010)
- Successful testing of 3M NSTF PtIr anode catalyst, performance equivalent to GES (Feb 2011)
- Pt loadings of 3M anode & cathode catalyst are one-order magnitude lower than currently in use (~0.10 to 0.15mg Pt/cm²)!
- 3M catalyst: Life testing required

Membrane Performance
- BPSH-35 ≅ 3M ≅ DSM ≅ Nafion® 112 > Nafion® 1135
- 3M 850EW is stabilized ionomer
- Initiated Tokuyama membrane evaluation
  - Low-Cost hydrocarbon membrane
  - Life testing > 5000 hours in DMFC (Tokuyama)
Cell-Separator Progress

Carbon/Titanium

- Carbon/Titanium Cell-Separators Scaled-up to 290-cm² (Milestone Oct-2010)
  - Evaluated in 5-cell short stack for 1000-hours
  - Single cell-separator testing ongoing (2700+ hours)
  - Cell-Separators fabricated with low porosity carbon
    - POCO Pyrolitic Graphite (Surface Sealed)
    - Low hydrogen uptake (embrittlement)
    - Life-time estimate > 60,000 hours

- Analysis
  - C/Ti: No carbon delaminating or loss in thickness
  - Zr/Ti & ZrN/Ti (PVD coatings)
    - Delamination, contaminated DI water
  - New low-cost carbon materials identified

<table>
<thead>
<tr>
<th>Cell-Separator</th>
<th>Time (Hours)</th>
<th>H₂ uptake (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/Ti (290-cm²)</td>
<td>1000</td>
<td>105</td>
</tr>
<tr>
<td>C/Ti (160-cm²)</td>
<td>500</td>
<td>64</td>
</tr>
<tr>
<td>Zr/Ti (160-cm²)</td>
<td>500</td>
<td>140</td>
</tr>
<tr>
<td>ZrN/Ti (160-cm²)</td>
<td>500</td>
<td>31</td>
</tr>
<tr>
<td>Dual Layer Ti (160-cm²)</td>
<td>500</td>
<td>1105</td>
</tr>
<tr>
<td>Ti (baseline)</td>
<td>0</td>
<td>~60</td>
</tr>
</tbody>
</table>

Ti Failure/Embrittlement: ~8000 ppm

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>DOE Target FC Bipolar Plates 2015</th>
<th>GES C/Ti Cell-Separator 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$/kW</td>
<td>3</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Weight</td>
<td>kg/kW</td>
<td>&lt;0.4</td>
<td>0.08</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>S/cm</td>
<td>&gt; 100</td>
<td>&gt; 300 (680 Poco)</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>MPa</td>
<td>&gt;25</td>
<td>86.1 (Poco)</td>
</tr>
<tr>
<td>Contact Resistance to GDL (MEA interface)</td>
<td>mΩ. cm²</td>
<td>&lt; 20 @ 150 N/cm²</td>
<td>17 @ 350 N/cm²</td>
</tr>
</tbody>
</table>
Stack Progress: Cost Reduction

The graph shows the trend of stack capital cost ($/kW_e) from 2001 to 2011. The cost has decreased significantly over the years, indicating progress in cost reduction. The graph includes different categories such as Misc Non-Repeating Parts, End Plates, Misc Repeating Parts, Compression, Separator, Frames, Cathode MSS, Anode MSS, Catalyst, and Membrane.
**Stack Progress: Advancements & Cost Reductions**

- Increased active area (290cm²)
- Reduced catalyst loadings
- Reduced Part Count 41 to 16
- Pressure Pad: Sub-assembly eliminated
- Molded Thermoplastic Cell Frame
- Cell-Separators: Replaced Nb/Ti with Carbon/Ti

**2007-2010**

- Frame Thickness reduced (by 30%)
  - Reduces Cathode & Anode Support Mat'l
- Reduced Part Count from 16 to 10 Parts/Cell-50% labor reduction
- Nb and Zr mat'l in Anode & Cathode supports eliminated- up to 98% material cost reduction
- DSM MEAs fabricated w/chem-etch supports- 90% cost reduction
- Carbon Steel End Plate (previously S.S.) - 66% material cost reduction

**2010-2011**

- Frame thickness reduced by 90%
- Carbon Steel Fluid End Plate
- Poco in carbon/Ti cell-separators replaced w/low-cost carbon (Entegris).
- Further catalyst reductions (3M)
- Increase Cell-Size
- Low-Cost Ionomers (Tokuyama)

---

The repeating cell unit comprises 90% of electrolyzer stack cost
Anode Support Material & MEAs (membrane & catalyst) dominate cost of the electrolyzer stack.
System Progress

- Assembly: >80% Complete
- System design complete: P&ID, PFD
- Safety:
  - Manuals covering Hydrogen Safety & Response Plan
  - Reviewed National & International Codes & Standards (Prof. Zalosh – H₂ safety expert)
  - GES contributed comments to ISO/DIS 22734-2 draft

- Failure Modes and Effects Analysis (FMEA) - Analysis indicates highest degree of safety with use of Dome over stack
  - Eliminates highest severity cases related to hydrogen ignition & electrocution
  - Satisfies Codes Pertinent to Hydrogen Refueling Systems
  - Dome design modified for lower cost
  - Pressurized dome: reinforces stack during high pressure operation (future study)

System Specs
Dimensions: 7.20’ tall x 6.6′ long x 7.84’ wide.
Water Consumption: 5.75 liters/hr
Stack Power Requirement: 24 kW
Cooling Requirement: 3.3 kW
Production Rate
0.5 kg H₂/hr (-3% dryer)
2.0 kg-H₂/hr (w/larger Stack & Power Supply)
Operating Pressure
H₂ 350 psig; O₂ atm
Operating Temperature
80°C
Membrane
DSM-PFSA,
Stack Size
290 cm²/cell, 27 Cells
Stack Current Density
~1750 mA/cm²
System Progress: Assembly

Controller & Power Supply
- Power Supply Efficiency: 94%
- 30kW, 600A, 50V
- Stack Requirement: 23.8kW

Electrolyzer Stack & Dome (O\textsubscript{2} Compartment)
- Stack Efficiency: 88%
- Output: 0.5 kg-H\textsubscript{2}/hr
- Stack Voltage: 47 V (27 Cells @1.75 V/cell, 1741mA/cm\textsuperscript{2})
- Dome can accommodate >90-cell stack
- Use of Dome satisfies Codes Pertinent to Hydrogen Refueling Systems

H\textsubscript{2} – Dryer (H\textsubscript{2} Compartment)
- Dryer Efficiency: 96-97%
- Dual desiccant bed
- H\textsubscript{2} cooling prior to dryer

- Use of Dome satisfies Codes Pertinent to Hydrogen Refueling Systems
Projected H₂ Cost

Specific Item Cost Calculation
Hydrogen Production Cost Contribution

<table>
<thead>
<tr>
<th>H2A Model Version (Yr)</th>
<th>Rev. 2.1.1 (FY2010)</th>
<th>Rev. 2.1.1 (FY2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs</td>
<td>&lt;$0.79</td>
<td>$0.60</td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>&lt;$0.49</td>
<td>&lt;$0.39</td>
</tr>
<tr>
<td>Feedstock Costs</td>
<td>$1.86 (DSM)</td>
<td>$1.86 (DSM)</td>
</tr>
<tr>
<td>Byproduct Credits</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Other Variable Costs</td>
<td>$0.01</td>
<td>$0.01</td>
</tr>
</tbody>
</table>

Total Hydrogen Production Cost ($/kg)
(Delivery not included)

|                | 3.15    | 2.86    |

Delivery (H2A default)

|                | 1.80    | 1.80    |

Total Hydrogen Production Cost ($/kg)

|                | 4.95    | 4.66    |

H2A Model Analysis

Forecourt Model

- Design capacity: 1500 kg H₂/day
- Assume large scale production costs for 500th unit
- Assume multiple stacks/unit
  - Low-cost materials and component manufacturing
- 333 psig operation. H₂ compressed to 6250 psig
- Operating Capacity Factor: 70%
- Industrial electricity at $0.039/kWhr

Feedstock Costs
$1.54 min. @ 39.4 kWhₑ/kg-H₂
$1.86 (DSM)
$1.86 (DSM)

Byproduct Credits
$0.00

Other Variable Costs (including utilities)
$0.01

Industrial electricity at $0.039/kWhr

Total Hydrogen Production Cost ($/kg)
4.95
4.66
Future Plans for FY2010-11

- **Parker**
  - Fabricate deliverable system
  - Operate/Evaluate system
  - Complete critical design review

- **GES**
  - Deliver Stack to Parker
  - Assist in system start-up at Parker facilities
  - Receive and install operating system at GES
  - Verify stack/system performance
  - Prepare for shipment to NREL
  - Continue investigation on low-cost components
    - Frame Thickness/Material cost reduction
    - Low-cost carbon for cell-separators
    - Membrane/catalysts
    - Further reduction in components/cell
Summary

- **Demonstrated membrane reproducibility and durability**
  - Demonstrated DSM membrane performance better than that of Nafion 1135 at 80°C
  - Demonstrate DSM membrane lifetime at 80°C for 1000 hours
    - Single-cell (160cm²), 5-Cell (290cm²)
    - Single-cell (290cm²) life test ongoing – 2800+ hours

- **Cell Separator Development:**
  - Demonstrated performance comparable to dual-layer Ti separator in 160-cm² & 290-cm² electrolyzer
  - Demonstrated significantly reduced hydrogen embrittlement with carbon/Ti separators
    - Expected cell-separator lifetime in the range > 60,000 hours

- **Scaled-Up Stack Design**
  - Completed preliminary stack design review
    - Stack Assembly Complete
    - Significant progress made in stack cost-reduction (cell-components, membrane, & catalyst)

- **System Development:**
  - Completed preliminary system design review
    - P&ID, PFD, Layout, FMEA, Safety Reviews
    - System near completion