21st Century Renewable Fuels, Energy, and Materials Initiative

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DOE Annual Review: MAY 14-18, 2012

Project ID # FC078

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Overview

**Timeline**
- **Start** - October 2010
- **Finish** - June 2012
- **95% Complete**

**Budget**
- **Total project funding**
  - DOE - $1,250,000
  - Cost share $312,500
- **Funding received in FY11**
  - $0
- **Planned funding for FY12**
  - $0

**Barriers**
- **Barriers**
  - A. Materials and manufacturing costs
  - B. Membrane performance and durability
  - C. Efficient multi-fuel reforming system
  - D. Alternative fuel source without impact on human food chain

**Targets**
- Improve membrane conductivity and durability
- Cost-effective multi-fuel reformer system
- High power density Lithium-Air battery for ease of use and at a reduced cost
- High energy yield agriculture bio-crop

**Partners**
- **Michigan Molecular Institute (MMI)** - Polymer membranes and lithium-air battery
- **Saginaw Valley State University** - High energy yield agriculture bio-crop (Miscanthus)
## Relevance

**Overall Objectives (2010 – 2012)**

- Development of an improved high-temperature PEM fuel cell membrane capable of low-temperature starts (<100°C) with enhanced performance.
- Development of a 5kWe novel catalytic flat plate steam reforming process for extracting hydrogen from multi-fuels and integration with high-temperature fuel cell systems.
- Development of an improved oxygen permeable membrane for high power density Lithium-Air batteries for ease of use and at a reduced cost.
- Development of novel high energy yield agriculture bio-crop (Miscanthus) for alternative fuels with minimum impact on human food chain.
- Extend math and science alternative energy education program to include bio-energy and power.
## Plan and Approach

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Progress</th>
</tr>
</thead>
</table>
| Task 1: High temperature fuel cell membrane | - Increased proton conductivity  
- Improved durability and thermal stability  
- Performance evaluation | 80% Complete |
| Task 2: 5kWe catalytic flat plate fuel reformer | - CFD study of catalytic flat plate reformer  
- Design and build the reformer prototype  
- Test and evaluate the performance | 95% Complete |
| Task 3: High power density Lithium-Air battery at a reduced cost | - Optimize the combination of electrolytes that are best suitable for Li-Air battery  
- Design and build the prototype  
- Test the prototype for durability and efficiency | 85% Complete |
| Task 4: Research on high energy yield agriculture bio-crop (Miscanthus) | - Literature survey  
- Develop energy and economic model  
- Identify methods to produce alternative fuels from bio-crop (Miscanthus) | 100% Complete |
| Task 5: Alternative energy education program to include bio-energy and power | - Develop an educational module to incorporate the project results for bio-energy and power education | 90% Complete |

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Approach

Overview for High Temperature PEM Membrane

- We used novel patented nano-additive synthesis technology to prepare higher conductivity and more robust high temperature PEM fuel cell membranes

- Patented Nano-additive Synthesis Technology

![Synthesis of Sulfonated-Polyhedral Oligomeric Silsesquioxane (S-POSS)](image)

- New Polymer Membrane

![Fabricated Membrane](image)

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Approach

Overview for Flat Plate Reformer Development

- Length of the channel 30 cm
- Width of the channel 2 mm
- Wall (flat plate) thickness 50 μm

Catalyst layer:
- Thickness: $20 \times 10^{-6} \text{m}$
- Pore radius: $10 \times 10^{-9} \text{m}$
- Porosity: 0.4
- Tortuosity: 4
- Thermal conductivity: 0.4 W/m.K
- Density: 2355 kg/m$^3$

Solid wall:
- Thickness: 0.0005m
- Thermal conductivity: 25 W/m.K

Catalyst containing 15.2% Ni supported on magnesium spinel

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**Approach**

**Overview for Lithium-Air Battery**

- **Schematic Representation of the Proposed Lithium-Air Battery**

```
- Air Cathode
- Electrolyte
- Lithium Anode
- Spacer
- Cell Casing
- Wave Spring
- Al Foil
- Cap
```

Fabricated Lithium-Air Batteries

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Approach

Overview for Biofuel from High Yield Energy Crop

- Approach for biofuel from high energy yield agriculture crop

Miscanthus Grass → Torrefied bio-mass → Ethanol (E-85) - Biofuel → Pyrolyzed bio-char
### Comparison of high temperature membrane conductivity

<table>
<thead>
<tr>
<th>Sample</th>
<th>Water at RT</th>
<th>90°C, 20% RH</th>
<th>90°C, 40% RH</th>
<th>90°C, 60% RH</th>
<th>90°C, 80% RH</th>
<th>120°C, 3% RH</th>
<th>150°C, 5% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literature² PBI (low RH)</td>
<td>--</td>
<td>80</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>160</td>
<td>220</td>
</tr>
<tr>
<td>PBI control (815-12) IV = 1.78</td>
<td>55.59</td>
<td>99.110</td>
<td>123.129</td>
<td>135.178</td>
<td>81.100</td>
<td>69.77</td>
<td>71.81</td>
</tr>
<tr>
<td>PBI control (829-8) IV = 2.02</td>
<td>55.26</td>
<td>66.96</td>
<td>103.209</td>
<td>152.243</td>
<td>166.176</td>
<td>71.103</td>
<td>79.120</td>
</tr>
<tr>
<td>10% S-POSS (815-16) Unwashed, no excess DAB IV = 1.46</td>
<td>74.82</td>
<td>81.109</td>
<td>120.116</td>
<td>128.144</td>
<td>192.204</td>
<td>111,115</td>
<td>117,139</td>
</tr>
<tr>
<td></td>
<td>+37%</td>
<td>-10%</td>
<td>-6%</td>
<td>-13%</td>
<td>+218%</td>
<td>+55%</td>
<td>+68%</td>
</tr>
<tr>
<td>10% S-POSS (829-24) Unwashed, no excess DAB IV = 2.45, near insoluble</td>
<td>15.16</td>
<td>103.66</td>
<td>108.105</td>
<td>109.184</td>
<td>94.164</td>
<td>42.63</td>
<td>54.69</td>
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<tr>
<td></td>
<td>-61%</td>
<td>+5%</td>
<td>-31%</td>
<td>-26%</td>
<td>-25%</td>
<td>-39%</td>
<td>-38%</td>
</tr>
<tr>
<td>10% S-POSS (829-14) Washed, no excess DAB IV = 1.49</td>
<td>24.43</td>
<td>75.96</td>
<td>134.114</td>
<td>173.128</td>
<td>150.108</td>
<td>84.112</td>
<td>102.153</td>
</tr>
<tr>
<td></td>
<td>-17%</td>
<td>+6%</td>
<td>-21%</td>
<td>-24%</td>
<td>-25%</td>
<td>+13%</td>
<td>+28%</td>
</tr>
<tr>
<td>10% S-POSS (815-20) Washed, excess DAB IV = 2.93</td>
<td>26.26</td>
<td>119.38*</td>
<td>181.128</td>
<td>273.254</td>
<td>201.233</td>
<td>125.42*</td>
<td>151.40*</td>
</tr>
<tr>
<td></td>
<td>-37%</td>
<td>+47%</td>
<td>-1%</td>
<td>+33%</td>
<td>+27%</td>
<td>+44%</td>
<td>+51%</td>
</tr>
<tr>
<td>10% S-POSS (815-24) Unwashed, excess DAB No IV, near insoluble</td>
<td>18.22</td>
<td>12.19</td>
<td>20.28</td>
<td>60.46</td>
<td>66.54</td>
<td>13.21</td>
<td>16.26</td>
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<tr>
<td></td>
<td>-51%</td>
<td>-80%</td>
<td>-85%</td>
<td>-73%</td>
<td>-65%</td>
<td>-80%</td>
<td>-79%</td>
</tr>
</tbody>
</table>

- The best conductivity across the range of experimental conditions was obtained with washed S-POSS and excess DAB (IV = 2.93, 815-20) with a 44% increase relative to a control at 120°C and a 51% increase relative to a control at 150°C.

- **Take away statement:** The presence of S-POSS in polybenzimidazole (PBI)-phosphoric acid fuel cell membranes results in increased conductivity, increased modulus and improved mechanical properties.
Accomplishments/Progress/Results

- Validation of catalytic flat plate fuel reformer performance

- Fuel to steam ratio vs H₂ production by catalytic flat plate fuel reformer.

- Transverse temperature difference in both reformer and combustion side.

**Take away statement:** In a conventional steam reformer $T_g$ is often greater than 250ºC whereas here it is less than 30ºC. Virtually no heat loss across the flat plate.

**Take away statement:** Increase of fuel to steam ratio leads to higher percentage of H₂ production.
Accomplishments/Progress/Results

• Experimental performance evaluation of fuel reformer (developed based on CFD model)

(a) Production of dry CO with water gas shift (WGS) reaction and optimized reformer geometry.

(b) Polarization curves of a PBI-membrane with 5-cell HTPEMFC stack at different temperatures with different % of CO and reformate. The CO concentrations are indicated in the figure.

Take away statement: Reduction of dry CO is more than 50% with WGS reaction. CO level has changed from 0.158 to 0.072 on a dry basis.

Take away Statement: For the case of reformate, the stack performance is much better (i.e., voltage drop is much lower) compared to 2% CO and 5% CO especially at high current density (0.3~0.4 A/cm²) at 160°C. This implies that the reformate can be more preferable than 2% CO ~ 5% CO at 160°C.
• Take away statement: The SEM images provide insight to the fate of cathode materials.
• Take away statement: SEM images clearly show that some particles were formed on the surface of the carbon materials, however, further investigation is needed in order to determine the chemical composition of these particles.

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Performance Evaluation of Lithium-Air Battery

- The battery cell shows improved performance when tested in oxygen (a) rather than in dry air (b) with 0.1 mA/cm² current at room temperature.

- Charge-discharge cycles testing. The cell shows promising cycle-ability when tested in pure oxygen at room temperature with 0.1 mA/cm² current.

- Take away statement: The Li-air battery shows one of the highest cell capacity reported to date along with good cycle-ability.
Accomplishments/Progress/Results

• Optimization of bio-fuel production using Miscanthus

• Effects of land rental versus land ownership on simulated production costs of miscanthus and switchgrass.

• Comparison of experimentally measured and theoretically predicted yields of methane from the following silages [Pokoj et al. (2010)]: corn maize (Z. mays L.), sugar sorghum (S. saccharatum), and two types of miscanthus.

• **Take away statement:** Based on the developed model in a northern Midwestern US setting, cost- and energy-balances as well as the sensitivity analysis revealed that miscanthus is more cost- and energy-efficient in terms of costs of land use, harvest operations, and raw-materials transportation.
## Collaboration

**PI:** Kettering University

- **Task 2:** 5kWe catalytic flat plate fuel reformer
  - CFD study of catalytic flat plate reformer
  - Design and build the reformer prototype
  - Test and evaluate the performance

**Co-PI:** Michigan Molecular Institute (MMI)

- **Task 1:** High temperature fuel cell membrane
  - Increased proton conductivity
  - Improved durability and thermal stability
  - Performance evaluation

- **Task 5:** Alternative energy education program to include bio-energy and power
  - Prepare an educational module to incorporate the project results for bio-energy and power education

**Co-PI:** Saginaw Valley State University (SVSU)

- **Task 3:** High power density Lithium-Air battery at a reduced cost
  - Optimize the combination of electrolytes that are best suited for Lithium-Air battery
  - Design and build the prototype
  - Test the prototype for durability and efficiency

- **Task 4:** Research on high energy yield agriculture bio-crop (Miscanthus)
  - Develop energy and economic model
  - Identify methods to produce alternative fuels from bio-crop (Miscanthus)
Future Work

• Future Work (FY2012)

• Performance improvement of high temperature PEM membrane
  - Optimize a membrane electrode assembly (MEA) using a PBI-phosphoric acid-POSS nano-additive proton exchange membrane
  - Test thermal stability and life-cycle sensitivity
  - Document performance evaluation

• Design and build 5kWe catalytic flat plate fuel reformer
  - Test prototype performance and benchmark the results
  - Optimization of reformer system
  - Develop cost analysis for an optimized reformer system
Future Work

• Future Work (FY2012)

  • Explore other avenues for performance enhancement of Lithium-Air battery
    - Optimization of processing steps to improve the battery’s performance.
    - Once a reproducible procedure has been identified, batteries with and without the oxygen permeable membrane will be prepared and evaluated under various atmospheric conditions (i.e., different relative humidity values).
    - Final performance evaluation of developed Lithium-Air batteries.

  • Cost effective procedure for bio-fuel production from high energy yield agriculture crop
    - Economic and technical feasibility of procedures to convert the energy crop, Miscanthus x giganteus (MXG), into either hydrogen or hydrogen carriers suitable for fuel cell use.
    - Calculation of optimal combination of bio-fuel production procedures for Miscanthus bio-crop.

  • Develop a bio-energy education module
    - Math and science alternative energy education program for bio-energy and power.
Relevance: Helped to develop high temperature PEM fuel cell membrane, Lithium-Air battery and bio-fuel from bio-crop for fuel cell applications.

Approach: Patented nano-additive synthesis technology for high performance membrane, multi-fuel capable reformer based on CFD study, Lithium-Air battery with high-efficiency membrane for oxygen and moisture management.

Technical Accomplishments and Progress: Higher conductivity and more robust HTPEM fuel cell membranes have been developed. Performance evaluation of a multi-fuel reformer has been completed. Preliminary testing of Lithium-Air battery performance evaluation has been completed.

Technology Transfer/Collaborations: Active partnership with MMI and SVSU, including presentations, publications and patents.

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