Development of a 50kW Fuel Processor for Stationary Fuel Cell Applications Using Revolutionary Materials for Absorption-Enhanced Natural Gas Reforming

Program Manager: Jim Stevens
Contractor: ChevronTexaco Technology Ventures, LLC
Subcontractor: Cabot Superior MicroPowders
Project Duration: October 2003 - September 2006
DOE 2004 Yearly Review Meeting
May 26, 2004

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Project Overview/Objectives

Assist DOE in Developing Distributed Hydrogen Production Technology with Significant Cost Advantages in:

• Reduced reformer + PEMFC system operating costs through improved fuel efficiency
• Reduced capital costs through reduced system complexity
• Reduced reformer + fuel cell system costs

First Six Months Objectives

• Samples of low temperature reforming and high temp shift catalysts, CO₂ fixing materials, integrated function materials
• Process Simulation
• Efficiency Analysis
• Capital Cost Estimates
• Reactor Tests
## Budget

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>DOE</th>
<th>Contractor</th>
</tr>
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<tbody>
<tr>
<td><strong>Project Total</strong></td>
<td>$8,954,793</td>
<td>$5,551,972</td>
<td>$3,402,821</td>
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<tr>
<td><strong>Year 1</strong></td>
<td>$2,258,066</td>
<td>$1,400,001</td>
<td>$858,065</td>
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<tr>
<td><strong>Year 2</strong></td>
<td>$3,214,568</td>
<td>$1,993,032</td>
<td>$1,221,536</td>
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<tr>
<td><strong>Year 3</strong></td>
<td>$3,482,160</td>
<td>$2,158,939</td>
<td>$1,323,221</td>
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</table>
DOE Technical Barriers

- **Hydrogen Production**
  - A. Fuel Processor CAPEX
  - B. Operation and Maintenance

- **Crosscutting Barriers**
  - Catalysts
  - Hydrogen Separation and Purification

- **Fuel Flexible Processors**
  - I. Start-up time
  - J. Durability
  - K. Emissions
  - L. Hydrogen Purification
  - M. Efficiency
  - N. Cost
## DOE Technical Targets

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Calendar Year</th>
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<tbody>
<tr>
<td></td>
<td>2005</td>
<td>2010</td>
</tr>
<tr>
<td>Reforming Cost</td>
<td>$/Kg H2</td>
<td>1.98</td>
</tr>
<tr>
<td>Reforming Efficiency % (LHV)</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Purification Cost</td>
<td>$/Kg H2</td>
<td>0.11</td>
</tr>
<tr>
<td>Purification Efficiency % (LHV)</td>
<td>82</td>
<td>90</td>
</tr>
</tbody>
</table>
Approach – Absorption Enhanced Reforming

Conversion of natural gas to hydrogen using a reformer that combines steam reforming, water gas shift, and purification processes into one reactor.

- Developing calcium based materials that are capable of fixing and releasing carbon oxides over thousands of cycles
- Building reactors and control systems that take advantage of process simplification
- Conducting process modeling and testing to demonstrate significant savings in OPEX and CAPEX of these systems
Project Safety

Qualitative Hazard Analysis (HAZOP) conducted for all new test systems according to AIChE guidelines.

• P&ID analysis
• Material Safety Data Sheets
• Equipment Specifications and Operating Procedures

Formal Management of Change Process

• Codes and Standards, EH&S, Process Engineering, Electrical, etc. reviews
• Management authorization/sign-off

Pre-Startup Reviews

Extensive Safety Training tied to annual bonus

Inspection by peers, EH&S, and management
## Program Timeline

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1.1 Reforming Catalysts</td>
<td>2.1 Screening of Materials</td>
<td>3.1 Equipment Installation</td>
</tr>
<tr>
<td>1.2 Sorption Materials</td>
<td>2.2 Short Term Cycle Test</td>
<td>3.2 Reactor Catalyst</td>
</tr>
<tr>
<td>1.3 Pelletization</td>
<td>2.3 Long Term Cycle Test</td>
<td>3.3 Scale up Phase 1</td>
</tr>
<tr>
<td>1.4 Integrated Materials</td>
<td></td>
<td>3.4 Reformer Catalyst</td>
</tr>
<tr>
<td>1.5 Improved Kinetics</td>
<td></td>
<td>3.5 Scale up Phase 2</td>
</tr>
<tr>
<td>1.6 WGS Integration</td>
<td></td>
<td></td>
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</tbody>
</table>

### Timeline:

- **2004**: Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3
- **2005**: Q1 Q1 Q3 Q3 Q2 Q2
- **2006**: Q1 Q1 Q3 Q3 Q2 Q2

- **Q4 2004**: 1
- **Q1 2005**: 1, 2
- **Q2 2005**: 1.2
- **Q3 2005**: 6
- **Q4 2005**: 7

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4. Reformer Concept Testing
   4.1 Process Simulation
   4.2 Efficiency Analysis
   4.3 Reformer Design Guide
   4.4 Design and Cost Estimates

5. Reactor Design and Construction
   5.1 First 1 kW Reactor Design
   5.2 First 1 kW Reactor Fabrication
   5.3 First 1 kW Installation
   5.4 Second 1 kW Reactor Design
   5.5 Second 1 kW Reactor Fab
   5.6 Second 1 kW Reactor Inst
   5.7 5 kW Reactor Design
   5.8 5 kW Reactor Fabrication
   5.9 5 kW Reactor Installation
Program Timeline

6. Reactor Testing
   6.1 First Test Stand
   6.2 First Reactor Tests
   6.3 Second Test Stand
   6.4 Second Reactor Tests
   6.5 Third Test Stand
   6.6 5 kW Reactor Tests

7. 50 kW Reformer Construction
   7.1 Control Design/Coding
   7.2 Hardware Purchase
   7.3 Fabrication

8. 50kw Reformer Test
   8.1 Site Safety Review
   8.2 Reformer Installation
   8.3 Start-up/Shut Down
   8.4 Transient Testing
   8.5 Durability Tests
# Milestone Schedule

<table>
<thead>
<tr>
<th>Number</th>
<th>Milestone/Decision point</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90% of the thermodynamic equilibrium conversion of methane</td>
<td>09/30/04</td>
</tr>
<tr>
<td>2</td>
<td>&gt;50 % CO₂ theoretical. adsorption capacity after 50 cycles, &gt;90 % equilibrium conversion of CO at 800 h⁻¹</td>
<td>09/30/04</td>
</tr>
<tr>
<td>3</td>
<td>&gt;98 % H₂, CO/CO₂ &lt; 1% on dry basis after 50 cycles</td>
<td>11/15/04</td>
</tr>
<tr>
<td>4</td>
<td>&gt;98 % H₂, CO/CO₂ &lt; 1% on dry basis after 500 cycles</td>
<td>08/15/05</td>
</tr>
<tr>
<td>5</td>
<td>Predicted efficiency of system must be greater than 78% and low capital cost</td>
<td>07/06/04</td>
</tr>
<tr>
<td>6</td>
<td>Deliver enough integrated material for one full scale reactor,</td>
<td>11/15/04</td>
</tr>
<tr>
<td>7</td>
<td>Deliver enough integrated material for one full scale fuel processor, estimated 350 kg</td>
<td>08/15/05</td>
</tr>
<tr>
<td>8</td>
<td>Reactor ready for testing</td>
<td>11/12/04</td>
</tr>
<tr>
<td>9</td>
<td>Reactor meets design criteria</td>
<td>08/03/05</td>
</tr>
<tr>
<td>10</td>
<td>Stand alone reformer installed in Houston Test area</td>
<td>09/15/05</td>
</tr>
<tr>
<td>11</td>
<td>Reformer start-up/shut-down cycle testing, transient testing, durability testing.</td>
<td>09/30/06</td>
</tr>
</tbody>
</table>
Reactor Systems

Single Cycle Example

- 3 (2 CTTV & 1 CSMP) tube reactors and 2 kg H₂/day operational
- Additional 2 kg/day in construction
- 10 kg/day reactor design started
Simultaneous Reforming, WGS & CO₂ Fixing

97% methane conversion, >99% CO removed, >98% CO₂ removed
CSMP Materials Synthesis Approach---Synthetic Sorbents by Spray Conversion

- Over 100 sorbents synthesized and screened with multiple cycle TGA testing
- Over 30 sorbents extruded and tested in microreactor
- Over 20 integrated function materials synthesized
- Over 20 steam reforming catalysts synthesized
- 3 sorbent powders manufactured in >10 kg scale
High Activity Steam Reforming Catalyst from CSMP ---- Exceeds Milestone #1

Reaction conditions: S/C=3:1 and 600°C
Highly Durable CO₂ Fixing Materials from CSMP ---- Exceeds Milestone #2

C2873-29-34: carbonation 600 C; decarbonation 800 C

CaO reaction fraction (mol%)

>1500 hours and still meeting specs
# Cost and Efficiency Studies---- Exceeds Milestone #5

## Efficiency Comparison

<table>
<thead>
<tr>
<th></th>
<th>SMR/PSA</th>
<th>AER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>1.23</td>
<td>0.88</td>
</tr>
<tr>
<td>Fuel</td>
<td>0.25</td>
<td>0.34</td>
</tr>
<tr>
<td>Total</td>
<td>1.48</td>
<td>1.22</td>
</tr>
<tr>
<td>Efficiency</td>
<td>67.6%</td>
<td>82.0%</td>
</tr>
</tbody>
</table>

Notes: (kcal/kcal-H2 – LHV Basis)

- SMR Case adjusted for no steam export, includes NG Compression to 440 psia, PSA H₂ recovery = 88%
- AER Case includes parasitic power for BFW & CW pumps, ID fans

## CAPEX Comparison

<table>
<thead>
<tr>
<th></th>
<th>SMR/PSA</th>
<th>AER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Equipment</td>
<td>15.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Other direct Field Costs(*)</td>
<td>5.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Indirect Field Costs</td>
<td>4.6</td>
<td>3.5</td>
</tr>
<tr>
<td>Engineering &amp; HO</td>
<td>4.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Total MM$ (**)</td>
<td>29.4</td>
<td>17.0</td>
</tr>
</tbody>
</table>

* = Piping, Civil, Steel, Instruments, Insulation, Paint
** Exclusive of catalyst, contingency, taxes, permits, escalation, other Administrative Overheads

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Interactions and Collaborations

- Cabot Superior Micropowders - Joint Development Agreement in place
- Reactor design discussions with two potential manufacturers
- Confidential discussions with two automakers
- Confidential discussions with three hydrogen technology companies
- Confidential discussions with commercial catalyst company
- Confidential discussions with university and commercial forming technology leaders
Future Work

Remainder of 2004 FY

• Continue material synthesis and testing
• Dynamic modeling using experimental kinetic data
• Complete cost study
• Operate four installed reactors
• Design and fabricate 5 kW reactor

Remaining Two Years of Project

• Install & operate 5 kW reactor
• Design and fabricate stand alone 50 kW fuel processor
• Operate processor for 10 months continuous operation