Analysis of SOFCs for Air Independent Applications

12th SECA Workshop, July 2011

A. Alan Burke, Louis G. Carreiro

Naval Undersea Warfare Center (NUWC), Division Newport, Newport, RI; USA
Conclusions

- Methane vs. Diesel-type Hydrocarbons
  - Comparable energy metrics
  - Requires less O\textsubscript{2} and CO\textsubscript{2} sorbent per BTU
  - Should facilitate reformer operation and waste heat utilization for reforming

- Methane/NG Can:
  - Be a first generation fuel for SOFC-powered demonstration UUVs
  - Open the door to other SOFC-powered platforms
  - Offer a cleaner, more sustainable, and more secure energy infrastructure for the Navy
Conceptual UUV (Unmanned Undersea Vehicle)

Propulsion Section: Trust Vectored Pumpjet, Control Surfaces, Recovery and Handling System, Future Integrated Motor Propulsor

Ballast and Trim Section: Pump, Valves, Aft Tank


Nose Section: FLS, Acoustic Communications System

Energy Section: -Lithium Battery, AgZn Battery, Future Fuel Cell

Mission Payload Section: ~5 Cubic Feet with Standard Interfaces

Forward Auxiliary Section: SATCOM & GPS Antennas, Antenna Mast, Anchor, Forward Ballast Tank

Distribution Statement A - Approved for public release; distribution is unlimited
Proposed System Design with Anode Recycle

- Fuel
- Water (for start-up only)
- CO2 Scrubber
- Heat to Reformer
- Scrubber Cooler
- Recycle Stream
- Condenser
- Cooled Exhaust
- Water Recovery
- Oxygen

SOFC

ANODE

CATHODE

Oxygen Utilization nearly 100% for this application!
Carbon Dioxide Scrubber

- CaO + CO\textsubscript{2} $\rightarrow$ CaCO\textsubscript{3} + HEAT (178 kJ/mol)
- CaCO\textsubscript{3} Decomposes $\sim 850^\circ$ C

- Sorbent showed over 70% conversion of CaO in gas mixture of 21% CO\textsubscript{2}/44% H\textsubscript{2}/35% steam
- Sorbent shows fast kinetics and stability for repeated cycles
- Production methods have been scaled up for this extruded CaO sorbent
- Sorbent provided by TDA Research, Inc.
- Sorbent tested at NUWC

Over 50% mass gain demonstrated

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2008 Laboratory System Demonstration

- 30-Cell Delphi Stack integrated with
  1) InnovaTek’s Steam Reformer
  2) TDA Research’s CO$_2$ Sorbent
  3) R&D Dynamics’ High Temperature Blower

- Benchmarks achieved in first Demo:
  - > 75% S-8 Utilization
  - > 90% Oxygen Utilization
  - > 50% Efficiency ($P_{SOFC}$ / S-8 LHV)*
  - > 1 kW

* Furnace power neglected

All achieved simultaneously in initial proof-of-concept study (several hours of operation).
2010 Laboratory System Demonstration

- **Goal:** Show that Waste Heat from SOFC stack can be used to drive steam reformer (from Delphi Corporation)
- **This task could not be accomplished without also using a burner to partially drive (heat) the reformer**

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Isolated Steam Reformer Operation
(Simulated Anode Exhaust)

Steam Generator

H\textsubscript{2}O steam

N\textsubscript{2} gas (optional)
(0-20 SLPM)

Air from Compressor

CH\textsubscript{4} gas
(0-4 SLPM)

Liquid Fuel

Delphi Reformer

Reformate

Condenser

Anode exhaust (to GC)

Combustor

Combustor exhaust

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Reformer Operation Notes

- JP-10 and S-8 fuels successfully steam reformed
- HC slippage when Ref outlet T < 500° C
  - Ethane, ethylene...
- Combustor T > 800° C used to verify proper reformer temperature / active catalyst
- Mass balances > 95%
- Efficiency of 100-120% achieved (based on “free” superheated steam)
System Energy Balance

Reactions:

\[ \text{CH}_4(g) + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}(g) + 800 \text{ kJ/mol}_{\text{CH}_4} \]

\[ \text{CO}_2(g) + \text{CaO}_s \rightarrow \text{CaCO}_3(s) + 178 \text{ kJ/mol CO}_2 \]
<table>
<thead>
<tr>
<th>Process</th>
<th>Energy</th>
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</table>
| Total HEAT of RXNS for 7.5 kg CH\(_4\), 30 kg LOX, & 40 kg sorbent | 104 kW-hr from CH\(_4\)  
23 kW-hr from sorbent  
(127 kW-hr Total)                                              |
| SOFC (output)                                    | -82 kW-hr electricity +  
-42 kW-hr heat                                                        |
| Scrubber (output)                                | -23 kW-hr heat                                                         |
| Methane Steam Reformer (input)                   | 30 kW-hr heat                                                          |
| LOX heat-up                                      | 3 kW-hr heat                                                           |
| Total Waste Heat (output)                        | -32 kW-hr or 25% of energy generated                                  |
| Expected System efficiency based on LHV of methane | >60% after parasitic losses                                             |
### Reactant-Based Energy Metrics

<table>
<thead>
<tr>
<th>System Reactants &amp; Fuel Cell Type</th>
<th>Specific Energy, W-hr/kg</th>
<th>Energy Density, W-hr/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC, S-8/LOX/CO₂ sorbent</td>
<td>1130</td>
<td>1050</td>
</tr>
<tr>
<td>SOFC, LNG/LOX/CO₂ sorbent</td>
<td>1420</td>
<td>1060</td>
</tr>
<tr>
<td>SOFC, JP-10/LOX/CO₂ sorbent</td>
<td>1180</td>
<td>960</td>
</tr>
<tr>
<td>PEM, 4wt.% H₂ / LOX</td>
<td>1010</td>
<td>720</td>
</tr>
<tr>
<td>PEM, Liquid H₂ / LOX</td>
<td>1150</td>
<td>710</td>
</tr>
</tbody>
</table>
Reformer Testing with Real Anode Exhaust

Steam Generator
- H₂O steam

CO₂ gas (0-5 SLPM)

H₂ gas (0-20 SLPM, switchover)

N₂ gas (0-20 SLPM)

Delphi SOFC Stack

Cathode exhaust

Delphi Steam Reformer

Liquid Fuel OR CH₄ gas (0-5 SLPM)

Anode Exhaust

Compressor Air Supply

O₂ gas (0-10 SLPM, 2 channels)

CH₄ gas for burner (0-5 SLPM)

Reformate (to condenser and GC for analysis)

Combustor

Combustor Exhaust

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During Methane UUV Test

- SOFC Inlet:
  - 20 sL/min H₂ (65mol%), 4 sL/min CO₂ (13%), and 4.8 g/min steam (21%). (30.4 sL/min total)
- 45 Amps, 30-cell stack
- SOFC Exhaust Blended with 3 sL/min CH₄
- Reformer Outlet: 36.4 sL/min
  - 39% H₂, 3% CO, 4.8% CH₄, 41.7% H₂O, 11.2% CO₂,
- Reasonable reformate composition considering no CO₂ scrubbing and unreformed CH₄, but some water collection will be needed to avoid excessive steam accumulation in anode recycle loop
2011 Test Plans

System Level Demonstrations with only methane gas and pure oxygen reactant feeds

O₂ gas (0-10 SLPM, 2 channels)
CH₄ or H₂ gas (0-20 SLPM)
N₂ gas (0-20 SLPM)

O₂ gas (0-10 SLPM, 2 channels)
CH₄ or H₂ gas (0-20 SLPM)
N₂ gas (0-20 SLPM)

Compressor
Air Supply

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Mass Spectrometer

Steam levels of 25-75% were measured with the MS.
Issues Affecting Waste Heat Usage

- Two Primary sources of waste heat:
  - SOFC Stack & CO\(_2\) scrubber bed
- Variable active locations in CO\(_2\) scrubber bed
- Directing heat towards fuel vaporization
- Range of volatility in most liquid fuels, preventing carburization
- Variable SOFC power level
Methane Pros/Cons for UUV Application

- **Pros**
  - Easily vaporized, avoids carburization
  - Internal Reforming
  - “De-localized” Reforming
  - Help prevent coking in SOFC (C2+ HC’s)
  - Max H/C ratio, thus lowers O₂ consumption

- **Cons**
  - Decreased heat from CO₂ scrubber
  - Dewar for storage
  - Water separation from anode loop
Other Fuel Options?

- Liquid propane or butane
  - **PRO:** Facilitates distribution & storage
  - **CON:** Decrease H/C ratio

- Methanol
  - **PRO:** Can backfill reactant space with product water
  - **CON:** Toxic, corrosive, & generally accepted as more hazardous than NG

- Ethanol
  - **PRO:** Can backfill reactant space with product water
  - **CON:** Lower H/C ratio
Navy Goals for Fleet

- Reduce Foreign Oil Dependence (Energy Security)
  - NG from ocean floor or bio-feedstocks
- Energy Efficiency
- Environmental Cleanliness
  - Reduce Carbon Footprint
- Economics
  - Long-term availability & multiplatform uses
Conclusions

- **Methane**
  - Comparable energy metrics vs. liquid fuels
  - Requires less $O_2$ and $CO_2$ sorbent per BTU
  - Should facilitate reformer operation and waste heat utilization for reforming

- **Methane/NG Can:**
  - Be a first generation fuel for SOFC-powered demonstration UUVs
  - Open the door to other SOFC-powered platforms
  - Offer a cleaner, more sustainable, and more secure energy infrastructure for the Navy
Acknowledgements

• Sponsor
  • U.S. Department of Energy (DOE)
    • Interagency Agreement with National Energy and Technology Laboratory (NETL)

• Collaborator
  • National Aeronautics and Space Administration (NASA)
    • Lyndon B. Johnson Space Center/EP3; Houston, TX
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Ken Poast, John Scott, Koorosh Araghi
National Aeronautics and Space Administration (NASA)
Lyndon B. Johnson Space Center/EP3; Houston, TX

A. Alan Burke, Louis G. Carreiro
Naval Undersea Warfare Center (NUWC),
Division Newport, Newport, RI

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Conclusions

- Efficiency ~45% with fuel and oxidant utilizations near 85% is possible. 45% efficiency with 90% $U_f$ results in a theoretical reactant specific energy of 4900 kJ/kg.

- Uncertainties remain regarding optimized CPOX design and operation using pure oxygen (pre-combustion, sooting, start-up).

- Optimized pure-$O_2$ CPOX design is of interest to the NASA and could be valuable for potential missions.
Motivation

- LO$_2$/LCH$_4$ Offers a Significant reduction in the Size and Dry mass of a Spacecraft over LO$_2$/LH$_2$
- There are benefits to being able to have a power system that can share common fluids with the propulsion system
Project Morpheus

- Morpheus is a vertical test bed vehicle demonstrating new green propellant propulsion systems and autonomous landing and hazard detection technology. Designed, developed, manufactured and operated in-house by engineers at NASA’s Johnson Space Center, the Morpheus Project represents not only a vehicle to advance technologies, but also an opportunity to try out “lean development” engineering practices.

- Solid Oxide Fuel Cells could provide power by using scavenged LOX/CH₄ left as residuals in the propulsion tanks or by tapping into propellant made by In-Situ Resource Utilization(ISRU) processes.
System Layout for 2010 NASA Testing

CH₄ gas (0-10 SLPM, switchover)

O₂ gas (0-5 SLPM)

N₂ gas (0-20 SLPM)

Delphi CPOX Reformer

H₂ (0-5 SLPM), for Start-Up

Reformate

Delphi SOFC

Vented CPOX Exhaust During Start-Up

O₂ gas (0-10 SLPM, 2 channels)

Anode exhaust (to condenser and GC)

Cathode exhaust

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Feeds to the CPOX reformer were 3.3 L/min O\textsubscript{2} and 4.9 L/min CH\textsubscript{4}. Cathode Inlet Feed was 5.5 L/min O\textsubscript{2}.

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Transient Analysis

Response of internal SOFC thermocouples during peak power excursion and transient power stepping analysis.

First order response

\[ T' = (I')^2 K_p (1 - e^{-t/\tau_p}) \]
Stack Voltage, Current, & Utilizations over second day of testing
## Summary of Performance

<table>
<thead>
<tr>
<th>Steady State Feeds into CPOX Reactor</th>
<th><strong>Peak Performance</strong></th>
<th><strong>Notes</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt; Flow: 5.1 SLPM</td>
<td>Fuel flow slightly increased from steady state to meet original O/C target</td>
<td></td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt; Flow: 0 SLPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt; Flow: 3.3 SLPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O/C = 1.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SOFC Stack with cathode feed of 5.5 SLPM pure O&lt;sub&gt;2&lt;/sub&gt;</th>
<th>46 Amps</th>
<th>Stack was pushed to 50 amps to achieve ~90% fuel utilization &amp; 45% efficiency, but cells 1,3,5, and 13 suffered from fuel starvation</th>
</tr>
</thead>
<tbody>
<tr>
<td>85% CH&lt;sub&gt;4&lt;/sub&gt; Utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60% O&lt;sub&gt;2&lt;/sub&gt; Utilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ 0.88 V/cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1210 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~ 43% CH&lt;sub&gt;4&lt;/sub&gt;, LHV</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>SOFC Exhaust</th>
<th>2.4 SLPM H&lt;sub&gt;2&lt;/sub&gt; (16%)</th>
<th>Mass balance &gt; 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4 SLPM H&lt;sub&gt;2&lt;/sub&gt;O (50.5%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 SLPM CO&lt;sub&gt;2&lt;/sub&gt; (27%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 SLPM CO (6.5%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Planned Targets</th>
<th>Actual Steady Performance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start-up Combustor Flow</strong></td>
<td>CH&lt;sub&gt;4&lt;/sub&gt; Flow: 2.15 SLPM N&lt;sub&gt;2&lt;/sub&gt; Flow: 20 SLPM O&lt;sub&gt;2&lt;/sub&gt; Flow: 5 SLPM</td>
<td>We had to lower N&lt;sub&gt;2&lt;/sub&gt; gas to get combustor to ignite at these flows, which are lower than typical start-up flows</td>
</tr>
<tr>
<td><strong>Steady State Reformate Product</strong></td>
<td>5.3 SLPM H&lt;sub&gt;2&lt;/sub&gt; (44%) 1.8 SLPM H&lt;sub&gt;2&lt;/sub&gt;O (15%) 0.9 SLPM CO&lt;sub&gt;2&lt;/sub&gt; (8%) 3.0 SLPM CO (25%) 1.0 SLPM CH&lt;sub&gt;4&lt;/sub&gt; (8%)</td>
<td>With reformer outlet temperature ~600 C, equilibrium favors 5-10% methane</td>
</tr>
</tbody>
</table>
Future Plans

- Forward Plan at NASA-Johnson Space Center (JSC)
  - Continue breadboard CPOX reformer and stack testing at JSC to establish baseline performance on pure oxygen and methane reactants.
  - Investigate SOFC capabilities for potential integration into future spacecraft missions
Acknowledgements

- DOE/NETL for SOFC stack & Support
- NUWCDIVNPT for Preliminary Testing