SECA SOFC Program at GE Global Research

Matt Alinger and Seth Taylor
GE Global Research
Niskayuna, NY

8th Annual SECA Workshop and Peer Review Meeting
San Antonio, TX
August 7-9, 2007
SECA SOFC Program at GE Global Research - Highlights

- Performed SOFC performance sensitivity analysis on baseline IGFC system. Results indicate 50% HHV efficiency achievable by improving SOFC performance. SOFC requirements that yield 50% efficiency are extremely challenging, but not inherently impossible.
- Identified component performance requirements that exceed today’s capability.
- Evaluated cell manufacturing techniques, sintering and air plasma spray, for impact on cell performance and manufacturing cost.
- Determined, through the manufacturing down-select study, that economic feasibility of SOFC is primarily dependent upon improving long-term stability of cell performance over choice of manufacturing process.
- Demonstrated effectiveness of Co,Mn spinel coated interconnect with LSM cathodes at reducing degradation rates from ~100 to ~25mΩ-cm²/1000h.
- Demonstrated Co,Mn spinel coated interconnect with LSCF cathodes is effective at reducing degradation rates.
- Validated effectiveness of Co,Mn spinel interconnect coating at impeding Cr bulk diffusion.
- Identified ‘free’ silicon in interconnect alloy as likely contributor to high performance degradation.
SECA Coal Based System Program - Overview

Team: GE Global Research
University of South Carolina
Pacific Northwest National Laboratory

Program Objective

- Identify significant barriers to feasibility and to develop solutions to enable high performing, cost-effective solid oxide fuel cells (SOFCs).
- Develop and optimize a design of a large-scale (>100 MW) integrated gasification fuel cell (IGFC) power plant incorporating a SOFC and a gas turbine (GT) in a hybrid system that will produce electrical power from coal. The system will be:
  - Highly efficient (>50% HHV),
  - Environmentally friendly (90% CO₂ separation), and
  - Cost-effective ($400/kW projected factory cost, exclusive of coal gasification and CO₂ separation subsystems).
Presentation Outline

• IGFC system analysis
• IGFC technology gap analysis
• Manufacturing down-select study
• Degradation testing
IGFC System Study
## IGFC System performance

### DOE Requirements

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End Date</strong></td>
<td>FY2008</td>
<td>Fy2010</td>
<td>FY2015</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Coal-Derived Hydrogen or Syngas</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cost (Power Blocks)</strong></td>
<td>$600/kW</td>
<td>$400/kW</td>
<td>$400/kW</td>
</tr>
<tr>
<td><strong>Efficiency (Coal HHV)</strong></td>
<td>40%</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td><strong>CO2 Isolated</strong></td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Validation Test (hours)</strong></td>
<td>1,500</td>
<td>1,500</td>
<td>&gt;25,000</td>
</tr>
<tr>
<td><strong>Degradation (/1000h)</strong></td>
<td>&lt;4.0%</td>
<td>&lt;2.0%</td>
<td>&lt;0.2%</td>
</tr>
</tbody>
</table>
IGFC System performance

<table>
<thead>
<tr>
<th></th>
<th>Power Summary, MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline System</td>
</tr>
<tr>
<td>Coal Feed, HHV</td>
<td>1047.1</td>
</tr>
<tr>
<td>Total Gross Generated Power</td>
<td>542.5</td>
</tr>
<tr>
<td>Total Parasitic Power</td>
<td>71.9</td>
</tr>
<tr>
<td>Net System Power</td>
<td>470.6</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>44.9%</td>
</tr>
</tbody>
</table>

*Note that all cases shown include 90+% CO2 isolation, as required.

- Baseline system (SOFC + HRSG/ST)
  - Efficiency of only 44.9% at these conditions.
  - Performance adequate for Phase I and Phase II
- “Super” SOFC (SOFC + HRSG/ST)
  - Target achieved by increasing the SOFC performance requirements
- Pressurized System (SOFC+ST+GT – 15atm)
  - Baseline stack - capable of achieving the 50% HHV efficiency target.
IGFC technology gap analysis

- **Coal**
  - DOE Minimum Requirement (high-rank bituminous coal - Pittsburgh No. 8)
    - Lower-rank coals result in a lower system efficiency
      - Factor to be considered

- **Gasifier**
  - Oxygen from ASU for gasification is significant efficiency driver
    - Assumption of ~10% improvement over current requires advancement in gasifier design / slurry mixing
      - High technology risk

- **Syngas Coolers**
  - Conventional RSC produce saturated steam: $T_{exit} = \sim 650^\circ F$
    - System in analysis - RSC generates superheated steam: $T_{exit} = 850^\circ F$
      - Modification not major gap but, Higher $T_{op}$ = materials change / cost challenge
        - Moderate technology risk

- **High Temperature CO Shift**
  - Current shift reactors operate with excess steam (avoid C-containing byproducts)
    - Analysis assume no byproducts produced despite steam/carbon near equilibrium
      - Capability requires major advances in catalyst or change to new shift methods
        - High technology risk
IGFC technology gap analysis

- **SOFC**
  - Majority of gap between current technology and 50% efficient IGFC systems
  - >0.5 W/cm² required for economically viable IGFC systems
    - Cell voltage and fuel utilization requirements extremely challenging
    - Methods of controlling degradation at T >800°C must be developed
    - Achieving high UF in large stack of 100+ cells is a major engineering challenge
    - **Risk of achieving SOFC performance targets extremely high**

- **SOFC Recycle**
  - IGFC design ~50% recycle of the SOFC air
    - Recycle fraction huge driver on efficiency (reduce fresh air flow requirement)
    - Blowers for 800+°C do not exist at present and will need development
    - Largely reliability and cost challenge as opposed to a technology challenge
    - **Reliability and cost risks significant**
Manufacturing down-select
Manufacturing down-select Process

- Detailed Data Gathered by Entire SOFC Team
  - SOFC Team Risk Sensing Sessions Input
- Independent Team Review
  - Scorecard
  - Greatest Concern
  - 4 Categories on Sinter vs. Deposition
  - Risks of Technology Elements
  - Independent Assessment
Technical Team Review Conclusions

• No meaningful difference in perceived success between cell manufacturing technologies

• Material cost and degradation solution are keys to success

• Viability of technology elements are greater challenge than manufacturing process
SOFC degradation
SOFC degradation - materials focus

Using a ‘fixed’ materials set: Focus on cathode side, high-impact degradation mechanisms

- **Air Interconnect – GE-13L**
  - Chromia scale resistance (Cr$_2$O$_3$) Ohmic resistance
  - Insulating scale growth (SiO$_2$) Ohmic resistance

- **Protective Coating – MnCo spinel**
  - Coating resistance (MnCo spinel) Ohmic resistance

- **Cathode bondpaste - LSC / coating interface**
  - SrCrO$_4$ layer resistance Ohmic resistance
  - ‘other’ reaction phases Ohmic resistance
  - Mechanical delamination Active area reduction

- **Cathode - LSCF**
  - Chromia poisoning Electrochem. activity red.
  - Coarsening Electrochem. activity red.

- **Cathode / electrolyte interface**
  - Zirconate resistive layer Ohmic resistance
  - Cathode poisoning Electrochem. activity red.
  - Mechanical delamination Active area reduction

- **Leakage driven degradation**
  - Cathode reduction Active area reduction
  - Anode oxidation Active area reduction
  - Combustion thermal Active area reduction

---

**Mechanism**

**Type**

- Air Interconnect – GE-13L
- Protective Coating – MnCo spinel
- Cathode bondpaste - LSC / coating interface
- Cathode - LSCF
- Cathode / electrolyte interface
- Leakage driven degradation

**Type**

- Ohmic resistance
- Active area reduction
- Electrochem. activity red.
Ceramic Test Vehicle – The Browaller*

Idealized test fixture (2”x2” active area)

- Simulate real SOFC operating conditions
  - Known ‘boundary conditions’
- High performance (<300 mΩ-cm²)
- High utilization (80% UF)
  - Monitor fuel and air gases
- Interchangeable interconnect
  - Gold
  - Ferritic stainless steel

Provide confidence and accuracy in degradation measurement

*after Ken Browall, ret 6/1/07
Browaller Test I, II

Sintered Supercell
LSCF cathode
LSC Bond paste
Au mesh CC

ASR Data
Cell I 173 mΩ-cm² @ 0.7V
Cell II 142 mΩ-cm² @ 0.7V

Excellent cell performance – equal to buttons
Fully sealed – no leakage, cracking

800°C, Low Utilization, 64% H₂

Current density, A/cm²

Voltage, V

Power density, W/cm²

Extrapolated points: Lost cathode current lead
Electrochemical testing - Button Cells

800°C
Galvanostatic
LSCF Cathode
LSC Bond paste
Interconnect – Ferritic SS
Button cells - Coated Vs Bare

GE-13L ferritic stainless steel interconnect
(Co,Mn)$_3$O$_4$ spinel coating

*(Mn,Co)$_3$O$_4$ spinel coated samples exhibit lower degradation rate with respect to bare.*

*Data from I-V curves at 0.7V and 800°C*
Button cells - Coated Vs Bare

GE-13L ferritic stainless steel interconnect (Co,Mn)$_3$O$_4$ spinel coating

*Data from I-V curves at 0.7V and 800°C

(Mn,Co)$_3$O$_4$ spinel coated samples exhibit lower degradation rate with respect to bare.
No measurable Cr found in the LSC Bond Paste after 886h at 800°C
Button cells - Coated E-Brite Vs GE-13L

(Mn,Co)₃O₄ spinel coating

GE-13L exhibits higher performance over E-Brite
Mn,Co Spinel Coated E-Brite

Cathode BP, Spinel Coating on E-Brite shown after 900°C 24h

Button Cell Test after 886h at 800°C - 1 A/cm²
Mn,Co Spinel Coated E-Brite

Increased Si at E-Brite interface after 3000 h test.
E-Brite – \( \text{Cr}_2\text{O}_3 / \text{SiO}_2 \)

Significant \( \text{SiO}_2 \) concentrations are observed at \( \text{Cr}_2\text{O}_3 \) interface on E-Brite.

Si content:
- E-Brite \(~0.2\text{wt}\%\)
- GE-13L \(<0.1\text{wt}\%\)
Ohmic losses
-Contact resistance testing

Electrochemical cell configuration:
- Air Interconnect (GE-13L)
- Coating (Ca$_{1.5}$Mn$_{1.5}$O$_4$)
- Cathode Pre-bond (LSC)
- Cathode Bond Paste (LSC)
- Cathode (LSCF)
- Barrier Layer (GDC)
- Electrolyte (8YSZ)
- Anode (Ni,YSZ)
- Anode bond paste (NiO)
- Fuel interconnect (GE-13L)

Equivalent circuit:
- Interconnect/Coating interface
- Coating/Bond paste interface
- Cathode
- Total ohmic due to bulk material resistivity

Direct measurement of interface contribution for ASR breakdown
Ohmic losses
- Contact resistance testing

Direct measurement of interface contribution for ASR breakdown
Bond Paste Conductivity

Stable bond paste (no increase in resistance over time)
Bond Paste Conductivity

Activation Energies

![Graph showing activation energies](graph.png)

**Bond paste resistivity negligible**

Literature values for LSC at 800 °C and pO$_2$=1 atm:

- Bulk electrical conductivity ~ 1585 S/cm
- Activation energy ~ 0.015 eV in pure O$_2$ – (Excellent agreement)
Co,Mn coated Vs Bare

(Mn,Co)$_3$O$_4$ – spinel coating

Coating effective for LSC samples
Commercial 441SS very promising
(Mn,Co)$_3$O$_4$ Stability Study – As-Received

Sample shows spinel and tetragonal phases present initially.
(Mn,Co)$_3$O$_4$ Stability Study – 500h, 800°C

Sample shows both spinel and tetragonal present in near 50-50 wt% mixture.
Summary

• Performed SOFC performance sensitivity analysis on baseline IGFC system
  – 50% HHV efficiency achievable by improving SOFC performance
  – SOFC requirements for 50% efficiency are challenging, but not impossible
• Identified component performance requirements exceeding current capability
• Evaluated cell manufacturing techniques, sintering and air plasma spray, for impact on cell performance and manufacturing cost
  – Determined economic feasibility of SOFC primarily dependent on improving long-term stability of cell performance over choice of manufacturing process
• Demonstrated Co,Mn spinel coated interconnect with LSCF cathodes is effective at reducing degradation rates
• Validated effectiveness of Co,Mn spinel interconnect coating at impeding Cr bulk diffusion
• (Mn,Co)$_3$O$_4$ coating effective at reducing degradation rate in LSCF SOFCs
• Free silicon in interconnect alloy results in detrimental SiO$_2$ at IC/Cr$_2$O$_3$ interface
Acknowledgements

• Travis Shultz, Wayne Surdoval, Lane Wilson of DOE/NETL
• GE SOFC Team
• The material presented was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-05NT42614. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE.