Advances in Development of SOFC Technology at FuelCell Energy

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21st Annual Solid Oxide Fuel Cell (SOFC) Project Review
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• Cell fabrication process evolved from laboratory to pilot-production in 2001
• Techniques utilized are tape casting, screen printing and electric tunnel kiln for continuous firing

• These processes are flexible & scalable to high volume and low cost production

<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>Cathode</td>
<td>Perovskites</td>
<td>~ 50 µm</td>
</tr>
<tr>
<td>Barrier</td>
<td>CGO</td>
<td>~ 4 µm</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>YSZ</td>
<td>~ 5 µm</td>
</tr>
<tr>
<td>AFL</td>
<td>Ni/YSZ</td>
<td>~ 8 µm</td>
</tr>
<tr>
<td>Anode Substrate</td>
<td>Ni/YSZ</td>
<td>~ 350 µm</td>
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Atomic Layer Deposition (ALD)
LSCF Cathode

- LSCF cathode is known to have severe degradation
- EIS spectra reveals increases over time in both the Low frequency arc as well as a High frequency arc
- Has been shown to be deactivation of the cathode surface by Sr segregation that can also deposit at the electrolyte surface
• HfO₂ surface modification improves long term degradation
• Impedance spectroscopy suggests improved ORR
Post-test Physical Analysis by TEM

- HfO$_2$ surface modification suppresses Sr segregation
- SrZrO$_3$ appears reduced at GDC/YSZ interface
HfO₂ Coated FCE Cathode Powder Button Cell Testing

500 mA/cm² @ 750 °C

Potential, V

Time, Hr
• Methods were developed at Northwestern University to tape cast extremely thin (~ 2 micron) dense YSZ electrolyte layers
• The GDC layer was also 1 – 2 microns thick, either co-fired (dense) or separately fired (porous)
  – The images below show the basic cell architecture, for the case of a porous GDC layer
• Either method can yield high power density cells
Cells With Ultra-Thin Electrolyte

- Dense bi-layer electrolyte: ~1.7 μm YSZ, 1.0 μm GDC
- Note that reduced firing temperature (1250 °C) is essential to avoid complete inter-diffusion of YSZ and GDC
• Results shown for cell with dense bi-layer electrolyte
• Excellent performance achieved down to 700 °C
• Performance at 600 °C lacking
  – Electrolyte resistance is acceptable
  – Polarization resistance is too large
• Low temperature performance could be improved with better electrodes, e.g. via infiltration
Cathode Infiltrated Cell: Diagnostics

- LSCF infiltrated into LSCF-GDC
- Variation of H$_2$ concentration shows that low frequency response is related to the anode
  - Since this is the main contribution to the polarization resistance, improved anodes are needed to make further improvements in cell performance
• infiltration of Gd-doped Ceria $\text{Gd}_{0.2}\text{Ce}_{0.8}\text{O}_2$ (GDC) into Ni-YSZ
  – GDC chosen due to its excellent catalytic and mixed ionic/electronic conducting properties

• Initial study done with Ni-YSZ / YSZ / Ni-YSZ symmetric cells
  – Reduced prior to infiltration

• Single-step infiltration of different concentrations (0.1 – 2.0 mol L$^{-1}$)
  – $\text{Gd(NO}_3\text{)}_3\cdot6\text{H}_2\text{O}$ and $\text{Ce(NO}_3\text{)}_3\cdot6\text{H}_2\text{O}$ dissolved in distilled water

• SEM images show increasing density of GDC nanoparticles with increasing molarity
  – Surface appears to be fully covered for 1.5M
EIS carried out at 600 C in humidified H₂
Main response centered at ~ 1000 Hz decreases with increasing GDC amount to 1M, then increases
Smaller response centered at 10 – 100 Hz also minimized using 1M GDC
Similar improvements seen at 700 and 800 C
GDC Infiltrated Ni-YSZ: Polarization Resistance

- Impedance spectroscopy carried out in humidified H$_2$
- Resistance and apparent activation energy decreases with increasing GDC molarity up to 1.0 M
- Most pronounced effect at lower temperature
  - At 600 °C, decrease from > 0.5 to < 0.2 Ωcm$^2$
  - Viable for low-temperature SOFC!
- Preliminary life tests show good stability at 650 °C
  - Challenging because Ni-YSZ must be reduced prior to infiltration
200 kW System Update
200kW SOFC Power System Overview

- Includes (2) 100kW SOFC stack modules designed to operate independently
- Factory assembled & shipped as a standard ISO 20’ x 8’ container
• Excellent stack to stack performance reproducibility
• Stacks for 200 kW system meet cell voltage criteria
• Stacks shipped to FCE Danbury, CT and integrated into 100 kW modules
100 kW Stack Module Architecture:

- Fully integrates all hot BoP equipment within the module
- Eliminates high-temperature plant piping & valves
- Reduces Cr evaporation protective coatings within plant/module
- Integrated anode blower & module-specific instruments greatly decreases plant footprint
200 kW SOFC System Factory Testing

200 kW system installed at FCE’s Danbury, CT Test Facility.
Factory Acceptance Test Results at 100% Load

Module A Voltages

Module B Voltages
Installation at Demonstration Site

Energy Center Pittsburgh - Clearway Energy (Formerly NRG Yield)
Operation at Clearway Site

Total Gross DC Power

- SCR Failure/Replacement, Electrical Enclosures Cooling Solution
- Desulfurizer Media Changed Out
- ModB Anode Blower replaced
- × = Grid Disturbance

Elapsed Time (hours)

Gross DC Power [kW]
The system accumulated ~3500 hours of hot operation (includes FAT in Danbury and commissioning/demonstration test at Clearway).

Anode Recycle Blower (ARB) on Module B failed after ~2000 hours of demonstration testing and was replaced with a spare unit.

Sulfur breakthrough starting after ~2000 hours of demonstration testing:
- Desulfurizer Media was replaced
- Cause of sulfur breakthrough is NG supply far off specification, extreme high sulfur content and challenging mix of sulfur species.
- Rapid breakthrough of replaced desulfurizer beds

The system was shutdown and returned to FCE HQ (Danbury, CT) for further testing.

Module A was disassembled for post-test autopsy and diagnostic testing.

System has initiated operation using module B only, with >500 hours of operation as of 6/2/2020.
Next Generation SOFC Stack Technology Development
Compact SOFC Architecture (CSA) Platform

Integrated compression

Oxidant outlet manifold

350 cells - 17” tall
~7 kW

Flow Geometry

Oxidant Outlet
Fuel Inlet
Fuel Outlet
Oxidant Inlet
Fuel Inlet
Fuel Outlet
Oxidant Outlet

Underlying Structure (expanded)

Bellows structure separates fuel and air and offers compliance and robustness
### CSA Stack Family

<table>
<thead>
<tr>
<th>Property</th>
<th>Scale</th>
<th>Comments</th>
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<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Mid</td>
</tr>
<tr>
<td>Cell count</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Operating Voltage, V</td>
<td>43</td>
<td>128</td>
</tr>
<tr>
<td>Power, kW</td>
<td>0.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Height, mm (in)</td>
<td>91</td>
<td>211</td>
</tr>
<tr>
<td></td>
<td>(3.6)</td>
<td>(8.3)</td>
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Test results suggested an air flow sensitivity. A re-examination of the air inlet distribution tubes showed a potential cause. Flow momentum at the higher flow rates was favoring air flow to the top. A revised air inlet was designed and built.
Impact of Design Improvements

GT060248-0014
GT060248-0015
GT060248-0017

Base plate modification is yielding higher performance
Contact modification is yielding better uniformity

Design Freeze this configuration for project deliverables
Stack GT060248-0017 into fuel cell reformate hold for characterization
Prior to this: Test stand and load bank failures led to shorting of the stack as well as many loading cycles.
The first full height CSA stack ran over 3000 hours after a very harsh initial startup (load bank failure fully shorted stack on initial startup).

Stack started test at an average cell voltage of 0.861 V, and ended with an average cell voltage of 0.855 V, albeit at a lower air utilization (20% vs 35%).

With cleaner testing (avoid shorting stack at the start), improved air flow distribution, and the latest design improvements currently running in 45-cell stacks, we’d expect even better results.
Automated production

The CSA stack achieves a 6x reduction in material content per stack compared to prior generation stacks, using smaller and lighter components.

Automated part handling, automated QC, and automated assembly are aided by these small lightweight parts, and deliver lower cost at higher quality than hand assembly.

Automated cell printing (in development)  Automated QC and stack build (fully deployed)

50 minutes to assemble a 350-cell stack
~60 kW/shift production rate
Robotic work cell for:

(a) Cell QC - measure / leak test (Demonstrated >3 MW/shift/year throughput)
(b) Interconnect sub-assembly / QC (Demonstrated > 3 MW/shift/year throughput)
(c) Stack build (Demonstrated > 10 MW/shift/year throughput)
Acknowledgements

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