Progress in SOFC Technology Development at FuelCell Energy

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Solid Oxide Fuel Cell Technology Overview

Anode-Supported Solid Oxide Fuel Cell

- Cell scale up to 1000 cm² active area

### Component Materials, Thickness, Porosity, Process

<table>
<thead>
<tr>
<th>Component</th>
<th>Materials</th>
<th>Thickness</th>
<th>Porosity</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Ni/YSZ</td>
<td>~0.3 mm</td>
<td>~ 40%</td>
<td>Tape casting</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>YSZ</td>
<td>5 - 10 μm</td>
<td>&lt; 5%</td>
<td>Screen printing</td>
</tr>
<tr>
<td>Cathode</td>
<td>Conducting ceramic</td>
<td>10 - 50 μm</td>
<td>~ 30%</td>
<td>Screen printing</td>
</tr>
</tbody>
</table>
Solid Oxide Manufacturing Highlights

Manufacturing processes scalable to high volume
at low cost

- 32,000 ft² facility engaged in R&D, cell/stack production and factory testing

- Tape Casting
- Automated Screen Printing
- Sintering
  “TSC 3 Process”

- Automated QC / Stacking
- Conditioning & Test Infrastructure
Long-term Performance

Overall Degradation:
31 mV over last 13,704 hrs
2.25 mV or 0.26% / 1000 hrs

3% cathode humidity throughout

1 Cell Stack - 81 cm² Active Area
Furnace Temperature: 750°C
Fuel: 55 H₂:45 N₂, uf = 50%
Oxidant: Air + 3% H₂O, Ua = 25%
Current: 40.1 A (0.5 A/cm²)

- Single cell configuration consisting of stack features: cross-flow pattern, stack flow fields, electrode contact layers and seals

Verified long-term cell endurance after >1.5 years of operation with 3% cathode air humidity resulting in 0.26%/1000h performance degradation
Recent Thin Cell Performance

Recent 300 μ anode development has further improved cell performance (2.34 W/cm² at 4.7 A/cm²)

- Performance of cell at high fuel utilization is strongly dependent on anode thickness and structure.

As Sintered Cell
200kW SOFC Power System Overview

- Includes (2) 100kW SOFC stack modules designed to operate independently
- Factory assembled & shipped to site

200 kW System Process Flow Diagram
100kW Module Design & Fabrication

Cell Size 25 x 25 cm²
Active Area 550 cm²
Number of Cells 120

• Excellent stack to stack performance reproducibility

100 kW modules include 4 towers each consisting of 2 legacy stacks (8 stacks per module)
200 kW System Operation Highlights

- Field Tests at Clearway Energy Center, Pittsburgh, PA
- Factory Tests at Danbury, CT

<table>
<thead>
<tr>
<th>Highlight of Factory Tests + Clearway Site 4/9/2019 – 10/14/2020</th>
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</thead>
<tbody>
<tr>
<td>Total Hours Net AC Generated</td>
</tr>
<tr>
<td>Total Net Energy Output from System</td>
</tr>
<tr>
<td>Gross DC Efficiency Achieved</td>
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</table>
Compact Solid Oxide Architecture (CSA) Stack

- Thinned components (cell + interconnect) to minimize stack material content (~0.5 kW/kg)
- Simplified unit cell with fewer components
- Designed for automated assembly
- Thermal and flow design to control temperature variations in module

Number of Cells | 350
Active Area     | 81 cm²
Power @ 0.25 W/cm² | 7 kW
Seal Technology | Crystallized glass

CSA offers low material content stack for commercialization
CSA Stack Overview

- Integrated compression
- Oxidant outlet manifold
- 350 cells - 17" tall
- 10 kW (pressurized)

Flexible structure offers compliance and robustness
## CSA Platform

<table>
<thead>
<tr>
<th>Property</th>
<th>CSA Stack Scale</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short</td>
<td>Mid</td>
</tr>
<tr>
<td>Cell count</td>
<td>45</td>
<td>150</td>
</tr>
<tr>
<td>Fuel cell voltage, V</td>
<td>38</td>
<td>128</td>
</tr>
<tr>
<td>Stack power, kW</td>
<td>0.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Stack power, kW</td>
<td>1.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Height, mm</td>
<td>91</td>
<td>211</td>
</tr>
</tbody>
</table>

Next generation CSA stacks utilizing advanced thin and lightweight cell structures
Automated Integrated Stacking & QC Station

Automated part handling, automated QC, and automated assembly are aided by the CSA small lightweight parts resulting in lower cost of stack manufacturing at higher quality than hand assembly.

Robotic work cell for:
(a) Cell QC - measure / leak test
   (>3 MW/shift/year throughput)
(b) Interconnect sub-assembly / QC
   (> 3 MW/shift/year throughput)
(c) Stack build
   (> 10 MW/shift/year throughput)
• Initial operation showed no degradation with a narrow band of voltage distribution (~40 mV for 350 cells)
• Stable operation for 674 hours when test stand failed and damaged stack due to no flows to the stack while the load kept on drawing current
Repeat of Full Height Stack Test

- Completed over 1800 hours of fuel cell operation on reformate with good voltage stability and tight voltage spread (except cells group of 251-260)
CSA Stack Cost Update @1 GWe/yr Production

- CSA Stack Factory Cost was updated from its last estimate in 2019 (DE-FE0026093) including the following major modifications:
  - Cost sensitivity analysis of different parts containing nickel (part thickness and porosity) for high volume costing
  - Updating cost of re-designed non-repeat parts (NRP) including top and bottom end plates and air manifolds
  - Advances in manufacturing automation
  - Cost trade-off analysis for Manganese-Cobalt Oxide (MCO) coating processes (in-situ versus ex-situ)
  - Update of cost parameters subject to Inflation

Cost Contributions Included:
- Procured Parts
- Commodity Materials
- Direct Fabrication Labor
- Direct Assembly Labor
- Indirect Labor
- Utilities
- Capital Recovery
- Equipment Maintenance
- Consumables
- Equipment Commission and Test
- Overhead & Building

Excluded:
- R&D, sales and marketing, G&A, warranty expenses and taxes
GWe/y Production Costing for Manganese-Cobalt Oxide Spinel (MCO) Coating

- Protective MCO interconnect coating is needed to prevent Cr-poisoning
- Costing approach is to bring both in-situ and ex-situ coating processes into GW factory to assist feasibility against current cost basis
  - compare costs of labor, materials & capital
- Compare thin sub-micron in-situ against 5 micron ex-situ coating
 CSA Stack Cost Distribution

Yr2011 CSA-SOFC Stack Factory Cost Estimate for 1 GW Stacks per Year

- $940 / stack
  - at 160,000 stacks/year

- SOFC @ 300 mW/cm² = $111 $/kWe out (gross stack DC)
- = $116 $/kWe out (gross stack AC)*
  - < $225 / kWe AC DOE cost target

* Assuming 96% DC to AC power conversion efficiency

62% of the estimated cost is due to material
Factory Cost Estimate – Waterfall Chart

**Top 3 cost contributors by **Functional Area** are:**
1) Cell Materials
2) Cell Fabrications
3) Repeat Components
CSA-SOFC Stack Factory Cost Estimate

Yr2011 Costing for 1 GW stacks per Year – by Cost Category

Top 3 cost contributors by Cost Category are:
1) Commodity Materials, 2) Procured Parts & 3) Overhead & Building
First-of-a-kind 40 kWdc multi-stack module is being developed to test an array of 6 CSA stacks.
CFD Analysis for Module Air Distribution

Stacks’ flow variation from average (a, b denote two sides of each stack)

- stack-in-air-1a: 0.1%
- stack-in-air-1b: -0.2%
- stack-in-air-2a: -0.1%
- stack-in-air-2b: 0.2%
- stack-in-air-3a: 0.1%
- stack-in-air-3b: 0.0%
- stack-in-air-4a: -0.2%
- stack-in-air-4b: 0.1%
- stack-in-air-5a: 0.2%
- stack-in-air-5b: -0.1%
- stack-in-air-6a: -0.3%
- stack-in-air-6b: 0.1%

Min = -0.3%
Max – min = 0.5 %

CFD modeling shows uniform flow distribution to stacks within the module enclosure
Configurable & Scalable Stack Arrays:

- Accommodate module structural designs for both present and future systems
- Forkliftable and serviceable stack module for integration in packaged systems

<table>
<thead>
<tr>
<th># of Stacks</th>
<th>Module Gross Output</th>
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<tbody>
<tr>
<td>16</td>
<td>6.7 x 16 = 107 kW</td>
</tr>
<tr>
<td>48</td>
<td>6.7 x 48 = 322 kW</td>
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Next Generation SubMW SOFC System

- Designed to operate with natural gas, biogas, and hydrogen fuels
- Provides waste heat for combined heat and power applications

300kW System
- 62% eff (LHV NG)
- 57% (LHV H2)

Next generation SubMW system utilizes CSA stack technology
Layout of the 1200 kW system including 4 stack modules and the associated distributed BOP

MW-Class SOFC System

SureSource™ 1500 Product
47% eff (LHV NG)

25% reduction in plot area

4x 48-Stack Modules

Process Control

DC/AC Inverter

Natural Gas Desulfurizers

MW-Class SOFC
62% eff (LHV NG)
Thank You

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Enable the world to live a life empowered by clean energy