Adaptive SOFC for Ultra High Efficiency Power Systems

Project Vision
Development of flexible Solid Oxide Fuel Cell (SOFC) technology suitable for integration with other power producing equipment achieving > 70% electrical efficiency based on natural gas lower heating value

7 kW Compact SOFC Architecture (CSA) Stack, Atmospheric Pressure
100 kW SOFC Module, Pressurized
Project Overview

Context/history of project

- FCE and its wholly-owned subsidiary, VPS, have been involved in development of fuel cell systems, including a recent 200kW SOFC unit fueled by natural gas. Both organizations have been collaborating in two ARPA-E projects under REFUEL and REBELS programs.
- UCI is a leader in the field of hybrid fuel cell systems and dynamics, including partnerships with Siemens Westinghouse to develop and test the world's first hybrid SOFC-GT system.
- FCE and UCI have a long established working relationship, in excess of a decade, including “Advanced Control Modules for Hybrid Fuel Cell/Gas Turbine Power Plants” (DE-FG02-02ER86140), and “Validation of an Integrated Hydrogen Energy Station” (DE-FC36-01GO11087).

<table>
<thead>
<tr>
<th>Team member</th>
<th>Location</th>
<th>Role in project</th>
</tr>
</thead>
<tbody>
<tr>
<td>FuelCell Energy (FCE)</td>
<td>Danbury, CT</td>
<td>Stack Module Design, System Design</td>
</tr>
<tr>
<td>Versa Power Systems (VPS)</td>
<td>Calgary, AB</td>
<td>Cell and Stack Design, Fabrication and Testing</td>
</tr>
<tr>
<td>University of California, Irvine (UCI)</td>
<td>Irvine, CA</td>
<td>System and Components Dynamics &amp; Control</td>
</tr>
</tbody>
</table>

Fed. funding: $3.1M
Length 24 mo.
Innovation and Objectives

**Innovation**
Develop low-cost Compact SOFC Architecture (CSA) stack technology for pressurized operation, tolerance to cathode Cr species, and adaptability for integrated hybrid system configurations.

**Task outline, technical objectives**
- Develop cell materials and fabrication processes suitable for pressurized operation.
- Develop stack technology suitable for operation of up to 4 bar pressure with low degradation in voltage, yielding a stack module cost of $400/kW.
- Develop steady-state and dynamic simulation models for design of integrated hybrid system.

**Tech-to-Market objectives**
- Utilize FCE’s established sales, marketing, and field service infrastructure for fuel cell power plants.
- Anticipated first markets are on-site power and microgrids.
- Use existing pilot manufacturing facility (500 kW/yr → 5 MW/yr) for market entry.

---

<table>
<thead>
<tr>
<th>Component</th>
<th>Material/Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Ni/YSZ 0.3 - 0.6 mm</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>YSZ 5 - 10 μm</td>
</tr>
<tr>
<td>Cathode</td>
<td>Conducting ceramic 10 - 50 μm</td>
</tr>
</tbody>
</table>
Compact Solid Oxide Architecture (CSA) Stack

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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Cells</strong></td>
<td><strong>350</strong></td>
</tr>
<tr>
<td><strong>Active Area</strong></td>
<td><strong>81 cm²</strong></td>
</tr>
<tr>
<td><strong>Power @ 0.25 W/cm²</strong></td>
<td><strong>7 kW</strong></td>
</tr>
<tr>
<td><strong>Seal Technology</strong></td>
<td><strong>Crystallized glass</strong></td>
</tr>
</tbody>
</table>

CSA offers low material content stack for commercialization

- **130 kW LAS module**
- **140 kW CSA module**

![Table showing performance metrics for different configurations of the stack](image)

- **Gross Power (W)**
  - Baseline PCI: 390 mA/cm², 1100 W
  - 96 cell Wärtsilä: 360 mA/cm², 14900 W
  - 120 cell coal based: 290 mA/cm², 16200 W

- **Stack voltage (V/dc)**
  - Baseline PCI: 24 V
  - 96 cell Wärtsilä: 75 V
  - 120 cell coal based: 101 V

- **Weight (kg)**
  - Baseline PCI: 17.3 kg
  - 96 cell Wärtsilä: 185 kg
  - 120 cell coal based: 213 kg

- **Power to Weight Ratio (W/kg)**
  - Baseline PCI: 64 W/kg
  - 96 cell Wärtsilä: 80 W/kg
  - 120 cell coal based: 76 W/kg

- **Approx. envelope (L)**
  - Baseline PCI: 5.3 L
  - 96 cell Wärtsilä: 69 L
  - 120 cell coal based: 88 L

- **Power to Volume Ratio (W/L)**
  - Baseline PCI: 207 W/L
  - 96 cell Wärtsilä: 215 W/L
  - 120 cell coal based: 185 W/L
## CSA Stack Family

<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>1.24</td>
<td>4.13</td>
</tr>
<tr>
<td>Height, mm</td>
<td>91</td>
<td>211</td>
</tr>
</tbody>
</table>

38% stack power up-rate at pressure targeted
145-cell CSA Stack Operational Data

1.9 kW, Degradation: -5.9 mV (-0.73%) / kh
50% uf (36% internal reforming), 30% ua,

+150 hours hot
+3 thermal cycles
+ many load cycles
Pressurized Cell Testing

Met Project Milestone:
Achieved >850 mV at 350 mA/cm² and 4 bar in 16 cm² cell and characterize voltage degradation at these conditions over ≥200 hours and 80% internal reformation (conversion) of a system relevant anode inlet fuel composition containing >8% CH4 (dry basis); representing a system configuration with an anode recycle and a pre-reformer upstream of SOFC.
Market Applications

Stationary Power Generation

Low cost and ultra high efficiency systems using adaptive SOFC combined with other power cycles provide a superior alternative for distributed electricity generation in near term markets:

- On-site / Micro-grid
- Grid-support

Transportation / Mobile Application

High efficiency, near-zero emissions, fuel storage volume reduction and rapid load following features make hybrid systems candidates for transportation applications.

The largest marine fuel cell installation to date is the 330kW MCFC, installed on board Viking Lady (2009-2012)

50 kW SOFC System  200 kW SOFC Power Plant
Risks

Anticipated challenges

- Accelerated performance degradation mainly due to Cr poisoning of cathode due to higher water vapor partial pressure
- Materials degradation and reduced stability at high pressure
- In-stack reforming of natural gas at high pressure
- Pressurized operation driving stricter leak requirements (cell and seals)
- Imparting robustness to tolerate anode-to-cathode differential pressures
- Impact of system dynamics and severe transients/upsets during operation
- Meeting installed cost target of $1800/kW for pressurized systems