Advances in SOFC Development at FuelCell Energy

14th Annual SECA Workshop
Pittsburgh, PA
July 23-24, 2013

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Presentation Outline

- Introduction
  - FCE SECA Program Team Members
  - SECA Coal-Based SOFC Program Overview
- Progress in SOFC Technology
  - Cell Development and Manufacturing
- Stack Development
  - Scale-up and Tower Tests
- Proof-of-Concept Module (PCM) Development
  - Stack Module
  - 60 kW PCM System
- SOFC Technology Applications
- Summary
Integrated Fuel Cell Company

Design & Manufacture
Megawatt-class power generation solutions

Services
Over 80 DFC® plants operating at more than 50 sites – 1.6 billion kWh ultra-clean power produced

Direct Sales & via Partners
Installations/orders in 9 countries

Engineering / Construction
Over 300 megawatts installed and in backlog
Global Foundation for Growth

• **Global footprint solidified**
  – Asian market expansion / POSCO agreement ($181M)
  – FuelCell Energy Solutions (FCES), GmbH
    – JV partnership with Fraunhofer IKTS

• **Trend towards larger installations**
  – 14.9 MW Bridgeport fuel cell park
  – 59 MW fuel cell park in S. Korea

• **Increasing annual run-rate in USA by 25%**
  – Ramping in 2013 to 70 MW annually from 56 MW

• **Entered data center market - Microsoft project**

• **Versa Power Systems (SOFC) acquisition**

• **World’s largest renewable biogas fuel cell plant now operating**
  – 2.8 MW plant operating at a wastewater treatment facility
Bridgeport Fuel Cell Park

- Five DFC3000 Powerplants produce 14 MW
- Waste heat from powerplants drives Organic Rankine Cycle (ORC) system which produces an additional 930 kW
- Total system nominal capacity 14.93 MW
- Nominal system LHV efficiency ~50%
- Construction in process, startup late 2013
- Project owner is Dominion
- Power purchased by CL&P under 15 year agreement
World’s largest fuel cell installation

- Located in Hwasung City, S. Korea
- Comprised of 42 modules
- Expected to be fully operational in early 2014

Project being developed by POSCO, Korea Hydro Nuclear Power Co. (KHNP) and Samchully Gas Co in Hwaseong, South Korea
• Planar anode supported cells (up to 1000 cm²)
• Capable of operating from 650°C to 800°C
• Ferritic stainless steel sheet metal interconnect
• Cross-flow gas delivery, with integrated manifolding
• Standardized stack blocks configurable into stack towers for various power applications
### Coal-Based SECA Program Status

#### Phase I
- Cell & stack scale-up
- Validation testing of 64-cell stack block (10 kW)
- Pilot manufacturing process development and yield increase

![10 kW Stack](10 kW Stack.png)

#### Phase II
- Increased cell performance and endurance combined with cost reduction
- Standardization of 96-cell stack block
- Demonstration of 2-stack tower (30 kW) operation
- Configuration of an IGFC system achieving DOE’s performance and cost targets

![30 kW Stack Tower](30 kW Stack Tower.png)

#### Phase III
- Increased cell and stack robustness and reliability
- Design, fabrication and tests of a 60kW (peak) stack module
- Design of a natural gas fueled 50 kW Proof-of-Concept (POC) power plant underway

![60 kW Stack Module](60 kW Stack Module.png)
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- SOFC Technology Applications

- Summary
• **Cell Scale Up**
  - Tape casting/Screen Printing/Co-firing (TSC) process has proven flexible enough to allow for cells up to 33 x 33 cm²
  - 25 x 25 cm² cells (550 cm² active area) are the focus for large area stack development

• **Cell Process Development**
  - Capital equipment for all major process units was added in order to accommodate increased cell size and volume
  - Thin (from 1 mm to 0.6 mm) TSC3 cell manufacturing process development was completed

• **Cell Fabrication**
  - More than 6000 cells (25 x 25 cm²) have been fabricated
  - Production yield greater than 95% was obtained
  - Production volumes of 500 kW (annual) have been demonstrated
**Third Generation of Cell Technology (TSC-3)**

- **Temperature (°C)**: 650°C, 700°C, 750°C, 800°C
- **Voltage (mV)**: 500, 550, 600, 650, 700, 750, 800, 850, 900, 950
- **Improvement (°C)**: 0%, 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, 20%

**Significant ASR reduction below 700°C**

- **TSC 2**
- **TSC 3**

Cell Performance at 740 mA/cm²: TSC2 vs. TSC3

- **Temperature (°C)**: 650°C, 700°C, 750°C, 800°C
Overall:
51 mV over 18000 hrs
2.8 mV or 0.32% / 1000 hrs

1 Cell Stack - 81 cm² Active Area
Furnace Temperature: 750°C
Fuel: 55 H₂:45 N₂ + 3% H₂O, Uf = 50%
Oxidant: Air, Ua = 25%
Current: 40.5 A (0.5 A/cm²)
Interconnect Coating Studies
Using a 32-Cell Stack

Investigated the effect of chromium vapor species on cell degradation by testing a 32 cell stack consisting of both coated and uncoated Interconnects.
Post Test Analysis of the 32-Cell Stack

Non-coated Layers

Cr rich dense Layer

Coated Layers

Cr rich dense Layer

Cell1

Cell 8

Cell19

Cell27

Cell2

Cell10

Cell18

Cell28
Cr resistant cell technology has shown promising stability in presence of high humidity.
Cr resistant cell technology was implemented in short stacks with excellent performance stability and low degradation rates.
Chromia Volatility Tests

Chromia Volatility Evaluation Test Setup

- **TC TUBE**
- **SAMPLE HOLDER (SEE DETAIL)**
- **WOOL INSULATION**
- **INSULATE FROM FURNACE TO CONDENSE**
- **HEATER CONTROLLER**
- **CONDENSER**
- **100 PSIG HOUSE AIR**
- **FLEX TUBING**
- **PUMP**
- **1500 W MINITROL**
- **HEAT TRACE**
- **HEATEX MOTOR**
- **FAN**
- **HEATHER WRAP**
- **TYPE K MINI TC**
- **AIR FLOWCUBE**
- **900 mL ERFENMEYER**

Test Setup

Atomic Emission Spectrometer
Introduction
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- Scale-up and Tower Tests

Proof-of-Concept Module (PCM) Development
- Stack Module
- 60 kW PCM System

SOFC Technology Applications

Summary
Power Module Scale-Up Using Building Block Approach

- **Lab-Scale Planar Cell**
- **Scaled-up Cell**
- **15 kW 96-Cell Stack**
- **Stack Building Block for Large SOFC Plants**
- **30 kW Stack Tower (2 Stacks)**
- **1 MW Stack Module**
  - 16 Horizontal Towers (4 Stacks Each)
- **250 kW Stack Module**
  - 8 Vertical Towers (2 Stacks Each)
### Stack Fabrication

<table>
<thead>
<tr>
<th>Stack Size</th>
<th>2006-2008</th>
<th>2008-2010</th>
<th>2011-2013</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Stacks 6 - 32 Cells</td>
<td>39</td>
<td>43</td>
<td>29</td>
<td>111</td>
</tr>
<tr>
<td>Full Size Stacks &gt; 64 cells</td>
<td>6</td>
<td>9</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Total Quantity</td>
<td>45</td>
<td>52</td>
<td>46</td>
<td>143</td>
</tr>
<tr>
<td>Total kW</td>
<td>126</td>
<td>255</td>
<td>349</td>
<td>730</td>
</tr>
</tbody>
</table>

- **6-cell short stack**
- **16-cell short stack**
- **64-cell stack block**
- **92-cell stack block**
- **96-cell stack block**
Self-Sustained 3-5kW Module
Tests

• Rapid prototype tests subject to system conditions
• Identify preferred system operating conditions and controls
• Evaluate performance and thermal profiles as function of fuel composition, extent of internal reforming, and fuel/air utilizations
• Evaluate system level heat-up/shut down procedures during normal operation and forced power trip events
• Assess technology developments in a quick turn-around sub-scale testing platform
Lower per pass utilization resulted in:

- Significant on-cell dT increase due to increase in on-cell reforming
- Lower overall cell temperatures
- Significantly higher cell voltage (performance)
Phase III Stack Manufacturing

- 15 stack blocks (225 kW) were produced in Phase III
- Implemented additional QC steps in stack component preparation and stack build
- Implemented refined stack conditioning procedures
- Key design modifications
  - Decreased stack part counts
  - Eliminated instrumentation plate
Stack Quality Testing

- **Step 1: Fuel Utilization Curve (before thermal cycle)**
  - Load stack to 200 A (0.364 mA/cm²) at 25% in-stack reforming (DIR)
  - Test at 50% to 75% $U_f$ in 5% increments
  - All cells greater than 0.7 V at 75% $U_f$

- **Step 2: Thermal Cycle**
  - Cool to $< 150^\circ C$
  - Reheat to $750^\circ C$

- **Step 3: Utilizations are Repeated (after thermal cycle)**
  - Reload stack to 200 A (0.364 mA/cm²) at 25% DIR
  - Test at 50% to 75% $U_f$ in 5% increments
  - $< 10$ mV decrease in cell voltage, compared to before thermal cycle

- **Step 4: Steady State Hold**
  - Stack is held at constant conditions for $\geq 50$ hours to verify stable performance of all cells
• Objectives:
  – Thermally self-sustaining test environment
  – Provisions for simulated anode gas representative of both coal-derived syngas and natural gas fueled systems

• Highlights:
  – 3,300 hours on load
  – 3,500 hours hot (>500°C)
  – Max Power: 30.0kW
  – Electricity Generated: 75.2 MWh
  – Multi-stack tower configuration validated under system conditions
2nd Generation Stack Design

- Next generation stack design utilized anode in cell manifold to increase the reliability and robustness:
  - Contact improvement
  - Sealing improvement
  - Cost reduction
- Conceptual stack design including CFD modeling is underway
Cost Reduction Focus Areas

1. **Stack Performance Increase**
   - Peak power increase
   - Improved thermal management

2. **Material Reduction:**
   - Thinner cells and stack components
   - Interconnect material reduction
   - Eliminated intermediate plates

3. **Manufacturing Process Changes & Optimization**
   - Interconnect manufacturing development
   - Improved material utilization
   - Automation
   - Elimination of process steps

The fuel cell stack cost has decreased substantially mainly due to the R&D activities in the SECA project.
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  - Stack Module
  - 60 kW PCM System
- SOFC Technology Applications
- Summary
1. Base
2. Towers on a single base forming a “Quad”
3. Compression plates
4. Anode nozzles
   A. Anode in
   B. Anode out
5. Insulation
6. Cathode-out collector
7. Fuel distributor
8. Conductive gaskets
9. Bus bars
60 kW module tested in the existing 400 kW Power Plant Facility

• Major Equipment:
  – Anode & Cathode High Temperature Blowers (700°C)
  – High Temperature Recuperators (750°C)
  – Catalytic Oxidizer, Desulfurizers, and Reformer
  – DC-AC Inverter and Switch Gear for Utility Tie-in
• Designed and implemented new control system for 60kW SOFC operation
• Module screen shows all fuel cell module controls and measurements along with cathode and anode heaters and anode recycle blower
• More than 400 total instrument tags measured and recorded each minute
60 kW SOFC Module

- 60 kW SOFC module using four ~15 kW TSC3 stacks was installed in the grid-connected Power Plant Facility at Danbury, CT.
- 1,130 hours on load
- 1,645 hours hot (above 500°C/932°F)
- Max Power: 60.6 kW
- Electricity Generated: 51.2 MWh

<table>
<thead>
<tr>
<th>BOL Performance (100-hour average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Current</td>
</tr>
<tr>
<td>Cell Voltage</td>
</tr>
<tr>
<td>Stack Voltage</td>
</tr>
<tr>
<td>Gross Module Power</td>
</tr>
<tr>
<td>Fuel Utilization - System</td>
</tr>
<tr>
<td>Module Efficiency (LHV)</td>
</tr>
</tbody>
</table>
Uniform Voltage Distribution Confirmed the Outstanding 60 kW SOFC Module Design and Stack Blocks Performance.
**Inter and Intra-Stack Thermal Uniformity within 60 kW Module**

*In Cell Temperatures vs. Height*

- **1.2% Max Temp. Variation**
  - Stack-to-Stack Inlet Gasses

- **1.7% Max Temp. Variation**
  - Top to Bottom Inlet Gasses

- ~**6% Average Temp. Variation**
  - from Middle of Stack to Ends of Stack
VPS fabricated and delivered a 10 kW SOFC module to VTT

Integrated with VTT balance of system at Technical Research Centre of Finland in 2010 using one 10 kW TSC2 stack

Restacked in 2012 using one 10 kW TSC3 stack

<table>
<thead>
<tr>
<th></th>
<th>Design - TSC2 cells -</th>
<th>100 h Average - TSC2 cells -</th>
<th>100 h Average - TSC3 cells -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Current</td>
<td>200 A</td>
<td>200 A</td>
<td>200 A</td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>780 mV</td>
<td>772 mV</td>
<td>843 mV</td>
</tr>
<tr>
<td>Stack Voltage</td>
<td>49.92 V</td>
<td>49.43 V</td>
<td>53.92 V</td>
</tr>
<tr>
<td>Module Power</td>
<td>9.984 kW</td>
<td>9.885 kW</td>
<td>10.785 kW</td>
</tr>
<tr>
<td>Fuel Utilization - System</td>
<td>80%</td>
<td>81%</td>
<td>80%</td>
</tr>
<tr>
<td>Module Efficiency (LHV)</td>
<td>60%</td>
<td>60%</td>
<td>65%</td>
</tr>
</tbody>
</table>
Integrated with Wärtsilä balance of system in Finland in 2012 using four ~15 kW TSC2 stacks

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>100 h Average - TSC2 cells -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Current</td>
<td>200 A</td>
<td>200 A</td>
</tr>
<tr>
<td>Cell Voltage</td>
<td>780 mV</td>
<td>784 mV</td>
</tr>
<tr>
<td>Stack Voltage</td>
<td>74.88 V</td>
<td>75.27 V</td>
</tr>
<tr>
<td>Module Power</td>
<td>59.90 kW</td>
<td>60.22 kW</td>
</tr>
<tr>
<td>Fuel Utilization - System</td>
<td>80%</td>
<td>76%</td>
</tr>
<tr>
<td>Module Efficiency (LHV)</td>
<td>59%</td>
<td>59%</td>
</tr>
</tbody>
</table>
PCM system is designed to lay the foundation for market entry 60 kW (peak) SOFC product operating on natural gas and biogas.

### PCM System Block Flow Diagram & Performance

**SOFC Gross Power**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Power</td>
<td>70.1 kW</td>
</tr>
</tbody>
</table>

**Energy & Water Input**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Fuel Flow</td>
<td>6.3 scfm</td>
</tr>
<tr>
<td>Fuel Energy (LHV)</td>
<td>103.4 kW</td>
</tr>
<tr>
<td>Water Consumption @ Full Power</td>
<td>0 gpm</td>
</tr>
</tbody>
</table>

**Consumed Power**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Power Consumption</td>
<td>3.3 kW</td>
</tr>
<tr>
<td>Inverter Loss</td>
<td>3.2 kW</td>
</tr>
<tr>
<td>Total Parasitic Power Consumption</td>
<td>6.5 kW</td>
</tr>
</tbody>
</table>

**Net Generation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC Plant Net AC Output</td>
<td>63.6 kW</td>
</tr>
<tr>
<td>Available Heat for CHP (to 120°F)</td>
<td>22.6 kW</td>
</tr>
</tbody>
</table>

**Efficiency**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Efficiency (LHV)</td>
<td>61.6 %</td>
</tr>
<tr>
<td>Total CHP Efficiency (LHV) to 120°F</td>
<td>83.4 %</td>
</tr>
</tbody>
</table>
60kW PCM System BOP Layout

- 18’ L x 8’ W x 10’ H
- Stack Module, MBoP, & EBoP factory assembled: shipped as a single skid
- Field-removable enclosure
  - Protects equipment from the elements
  - Enables field maintenance access without returning the entire unit to the factory
• Utilizes proven designs which have been validated in testing
  – Quad base stack support
  – Fuel and oxidant distribution/collection system

• 2nd generation design improvements for PCM
  – Integrated balance-of-plant components
  – Significant reduction in heat loss
  – Reduced plant cost
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SOFC Technology Applications

Summary
3kW SOFC Power Generator

Net AC Output (Peak) 3,138 W
Efficiency (LHV) 58.4%

Project supported by US Department of Energy (DOE):
- Demonstration of 3 kW SOFC on a Dairy farm to operate with biogas from animal waste.
- Unattended operation
- Dual fuel (Natural gas & Biogas)
- Water self-sufficient
- Plug and Play with Remote monitoring

Small Footprint: 3.5’ x 3’ x 5’
Office of Naval Research (ONR):

- Develop a compact hybrid SOFC-battery system with high-energy density/high-peak power capabilities, specifically designed for Large Displacement Unmanned Underwater Vehicle (LDUUV) service
  > SOFC provides base load power
  > No discharge: CO₂ and water stored on board

DARPA/Boeing:

- DARPA Vulture II Project
  > Develop a light-weight high-efficiency energy storage subsystem for uninterrupted intelligence and surveillance over an area of interest.
High Power Density Stack

Evolution of the planar SOFC stack technology:
From largest “power rating” in the world to super high “power density”

<table>
<thead>
<tr>
<th>Distributed Generation (DG) Stacks (DOE SECA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 28-cell Stack (2006)</td>
</tr>
<tr>
<td>64-cell large scale (2008)</td>
</tr>
<tr>
<td>92 cell large scale (2010)</td>
</tr>
<tr>
<td>Gross Power (W)</td>
</tr>
<tr>
<td>Power to Weight Ratio (W/kg)</td>
</tr>
<tr>
<td>Power to Volume Ratio (W/L)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High Power density Stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>225 cell HPD</td>
</tr>
<tr>
<td>1760</td>
</tr>
<tr>
<td>733</td>
</tr>
<tr>
<td>1546</td>
</tr>
</tbody>
</table>

- Achieved 10x improvement in specific power (W/kg)
- Demonstrated operational endurance of over 7000 hours in a 60 cell stack
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Summary
Significant advances made in SOFC technology as the result of SECA Coal Based Program will increase the prospects for future natural gas system products.

- **Cell Technology**
  - Performance enhancement (18% increase at 650°C)
  - Degradation reduction (1.4%/1000 hrs. → 0.3%/1000 hrs.)
  - Scale up (121 cm² → 1000 cm²)
  - Low cost (1 mm → 0.57 mm)
  - Cr resistant technologies developed

- **Stack Technology**
  - Scale Up (1 kW → 15 kW)
  - Performance enhancement (7-8% increase)
  - Degradation reduction (2%/1000 hrs → 0.4%/1000 hrs)
  - Reduced Cost

- **System Development**
  - Largest anode supported SOFC module to date (60 kW) was designed, fabricated and tested in a self-sustaining grid-connected mode
  - Detailed design of a 60kW (peak) system is underway
The “SECA Coal-Based Systems” development at FuelCell Energy is supported by DOE/NTEL Cooperative Agreement No. DE-FC26-04NT41837

Guidance from NETL Management team: Travis Shultz, Shailesh Vora, and Heather Quedenfeld