Thermally Integrated High Power Density SOFC Generator

By:
FuelCell Energy, Inc.
Versa Power Systems

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Presentation Overview

• FCE Profile
• Program Objectives
• FCE Team and Synergistic Strength
• Approach for Phase I
• Progress Made: Pre-award Period
• Near Term Plans and Summary
FuelCell Energy Profile

- Delivering commercial products now with advanced Direct FuelCell® technology
- #1 high temperature stationary fuel cell manufacturer and developer including carbonate and solid oxide applications
- Over 33 million kWh of electricity generated to date from the 30 units delivered to global commercial and industrial customer sites
- A leading fuel cell technology developer for over 30 years – over $400 million invested
- Headquarters in Danbury, CT
  Manufacturing Facilities in Torrington, CT
- Strong balance sheet with $193 million in cash (1/31/04)
- NasdaqNM:FCEL
Current Customers

- Institutional
  - Hospitals
  - Universities

- Commercial
  - Hotels
  - Data Centers
  - Office/Shopping

- Industrial
  - Waste Water
  - Telecom
  - Food & Beverage
  - Chemical
  - Manufacturing

- Utility
  - Grid-support
SOFC – Complementary Products

SOFC GENERATOR COMPLEMENTS EXISTING PRODUCT LINE

<table>
<thead>
<tr>
<th>Rated Output (KW)</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1,000</th>
<th>10,000</th>
<th>100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future SOFC Products</td>
<td>SOFC Generator</td>
<td>300 kW DFC®</td>
<td>1.5 MW DFC®</td>
<td>3.0 MW DFC®</td>
<td>Hybrid (10-50 MW)</td>
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</tbody>
</table>

FuelCell Energy

MO2554b
06/02/03
Program Objectives

- Develop 3-10 kW-class SOFC power plant per SECA goals
- Fuel options: Natural gas (Phase I)
  Propane and diesel in Phase II
- Thermal integration for higher efficiency
- Manufacturing cost reduction
  - High power density (300-500 mW/cm² at system conditions)
  - Implement DFC technology experience
  - Focused input from complementary programs
Versa Power Systems

The Technology
- Patented planar, reduced temperature SOFCs
- Proprietary thermally integrated power system (TIPS) design
  - pathway to low-cost, compact power gen systems with the highest efficiency and power density

Status
- SOFC technology demonstrated in both 40-cell, 2”square and 25-cell, 4”-square stacks (370 to 420 W/l)
- Over 10,000 h lab scale durability
- Prototyping & scale-up underway
The Ongoing Activities Provide Valuable Design Input
Global Thermoelectric Resources Available

• Global Thermoelectric’s SOFC technology strengthens the FCE’s team
• High temperature technologies are synergistic – technical solutions to MCFC can apply to SOFC and vice versa
• Provides access to the emerging fuel cell opportunities in Canada
• Complementary products make companies an ideal fit for the present and the future
• Discussion in progress for optimal integration of all resources
Approach: Phase I

- Cell technology based on thin-film anode-supported SOFC operating at 700-750°C
- Utilize FCE’s Direct Fuel Cell (DFC) technology experience
  - Internal reforming to maximize efficiency and simplicity
  - Thin sheetmetal interconnects
  - External vs. internal manifolds
  - Thermo-mechanically compliant composite seals
- System based on triple mode cooling for high power density
- Simplify manufacturing process
Progress Made in Cell Technology Development

- Trilayer performance increased to 2400 mW/cm² at UU (button cells, H₂, high flows)
- Cell performance with interconnects increased to 1400 mW/cm²
- Long term cell tests on hydrogen and methane show encouraging results
- Large area cell testing initiated (100-400 cm²)
- Lowered operating temperature from 800 to 750°C (BOP cost reduction)
- Trilayer manufacturing process simplified from multiple fire to a single fire
• **Anode** – nickel-zirconia cermet, ~ 1 mm thick
• **Electrolyte** – yttria-stabilized zirconia (YSZ), ~ 5 µm thick
• **Cathode** – conducting ceramic, ~ 50 µm thick
Single Cell Modeling

Predicted Thermal Profile

Actual Thermal Profile
Cell Manufacturing Process Flow

Tape Casting

Screen Printing

Co-sintering

Anode Tape

Unfired Cell

Single Fired

Raw Materials

Raw Materials

These processes are scalable to high volume and low cost production
Cell Size Scale-up In Progress

- 64 cm²
- 100 cm²
- 400 cm²

[Image showing cell sizes]
Cell performance for a 10 x 10 cm² cell using stainless steel current collectors, cross-flow gas delivery
Single Cell Endurance at 750°C

Trend Data
Glob 10545; (Long Term Test: TSC1, 10 cm x 10 cm cell)
Oven #6, January 9, 2002 - February 22, 2004

Test Conditions:
750°C, 3000 mlpm air, 25% air utilization
630 mlpm H₂, 630 mlpm N₂, 50% fuel utilization

Degradation rate is approximately 1% per 1000 h (10 mV per 1000 h)
Internal Reforming of Methane – Excellent Stability

![Graph showing the conversion of CH4 over time with different current densities.](image-url)
Gen 4.x Stack Assembly

**Characteristics:**

- Internally manifolded
- 700-750°C operation
- Stainless steel interconnects, current collectors, end plates
- Compressive seals
- Internal compression system
- Cross flow
Glass Seal Development

Trend Data, Glob 10920
(Glass Seal: 50% Fuel Utilization, 25% Air Utilization, 0.5 A/cm², 10 x 10 cell)
Oven #3, (October 2, 2002 - January 3, 2004) 750°C

Degradation rate is approximately 1% per 1000 h (11 mV per 1000 h)
Gen 4 → Gen 4.1

- Cell active area: 81 cm² → 121 cm²
- Number of cells: 16 → 20
  - Increase in stack active area = 87%
This tower is used in the Aurora System
Gen 4.2 Stack Performance

Gen 4.2 Stack Steady State Performance
20-cell, 121 cm² Cell Active Area
Stands 10, 11 & 15: 16-Jul-03 to 12-Feb-04

Degradation rate is approximately 1.5-2.5% per 1000 h
(16-20 mV per 1000 h)

Test Conditions:
700°C Air Out Temp, 388 mA/cm²
48.1 slpm Air, 35% Air Utilization
11.3 slpm H₂, 11.3 slpm 4.2%H₂/bal N₂,
60% Fuel Utilization

52831-0009: 6 Thermal Cycles
52831-0012: 5 Thermal Cycles
52831-0016: 5 Thermal Cycles
Sub-scale Stack Development

- **MSRI**
  - Fabricated, QC’d and delivered 50 single cells and hardware for baseline Team testing.

- **GTI- short stack gear-up**
  - Refurbished existing DOE single-cell, FC test stand
  - Ready for endurance tests of short stacks--100-200 W
  - NG, all simulated gases
CEC program is developing modules that radiate stack-generated heat to air pre-heating panels

- Reduces airflow in large systems
- Provides “active” insulation in small systems
- Smoothes out in-plane temperature distribution by selectively removing stack heat
- Facilitates compactness, modularization, and scale up

ΔT_{STACK} = 47 C
System Development: Model Verification

- MSRI has tested multiple 5, 10, 20, 25, and 40-cell stacks. Results suggest that ~0.5 W/cm² will be obtainable on a kW level with realistic conditions and fuels at 700-800°C.

- Out-of-stack tests have verified the desired temperature rise in the air preheater panels.

- Completed preliminary facility “shakedown” test on a 20-cell stack without panels.

- Scheduled first stack/air preheater panel test:
  - May 24
  - 40-cell, 100-cm² stack
  - Blended gases will simulate various fuels.
Counter Flow Yields Lowest $\Delta T$

- ~0°C Gas $\Delta T$
- 50° to 100°C Stack Hardware $\Delta T$ Possible

Cross-Flow: 99°C Hardware $\Delta T$

Co-Flow: 86°C Hardware $\Delta T$

Counter-Flow: 67°C Hardware $\Delta T$

- Ideal Case- No Limit RAP
- 100 cm$^2$, 0.6V @400mA/cm$^2$, 80%UtF/54%UtO
- Stack Cooling: 65% Radiation/35% IR/0%Air Cooling
Stack/RAP Parametric Model Runs

Cell $L/W$, $RAP/IR$ Variable

- Stack Hardware $\Delta T$ can be $<50^\circ C$
  - Cross-flow; 81% $U_{FU}$, 54% $U_{OX}$
  - Stack Avg T: 800$^\circ C$
  - Cooling: 34% RAP; 40% IR; 26% Air
  - Cell Perf: 610 mV @ 400 mA/cm$^2$
  - Including Bench RAP Data
Prototype Systems: kW-class

Natural Gas Fuel
Grid Parallel

2000
2001
2001
2002
2003

RP-2
Aurora

FuelCell Energy
## RP-2 Prototype Highlights

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Systems Operated</td>
<td>5</td>
</tr>
<tr>
<td>Original Commission Date</td>
<td>May 2002</td>
</tr>
<tr>
<td>Final Decommission Date</td>
<td>December 2003</td>
</tr>
<tr>
<td>Total Hours Operated</td>
<td>24,387 hours</td>
</tr>
<tr>
<td>Total kWh Produced</td>
<td>7,856 kWh</td>
</tr>
<tr>
<td>Peak Net Power Output (AC)</td>
<td>2.1 kW</td>
</tr>
<tr>
<td>Peak Net Electrical Efficiency</td>
<td>31%</td>
</tr>
<tr>
<td>Total Thermal Cycles</td>
<td>39</td>
</tr>
<tr>
<td>Fleet Availability</td>
<td>50.7%</td>
</tr>
</tbody>
</table>
RP-2 Experience: Forced Outages

Opportunity: Improve BOP Reliability Also

- Inverter 61%
- Stacks 13%
- Fluid Delivery 8%
- Controls 4%
- Electrical 2%
- Facility 4%
- Operator Error 6%
- Hot Components 2%

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Aurora System

- Smaller volume ~ 1.3 m³
- New approach to thermal integration to maximize performance, efficiency and controllability at 2 kW net AC
- Single 80 cell stack tower with external compression in compact Hot Zone
- Designed towards applicable codes and standards compliance
Aurora System Performance Summary

<table>
<thead>
<tr>
<th>Metric</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Heat-up Time (h)</td>
<td>13</td>
</tr>
<tr>
<td>Peak Net AC Power Output (kW)</td>
<td>2.275</td>
</tr>
<tr>
<td>Peak Net Electrical Efficiency (%)</td>
<td>35.4%</td>
</tr>
<tr>
<td>Average Net Electrical Efficiency (%)</td>
<td>24.7%</td>
</tr>
</tbody>
</table>
System Development Plan

• Baseline System
  - Incorporate lessons learned from the CEC program and other on-going FCE activities
  - Upgrade the current kW-class system to expand operability on methanol and improve performance.
  - Target Capability: Handle 80% of US natural gas quality variations
  - Well-packaged 3 kW system suitable for delivery to the DOE NETL in 2006.

• Advanced System
  - Develop and incorporate advance options to improve efficiency and reduce cost (10 kW).
Summary

- Cell and Stack technology development
  - Key mechanisms identified for performance and decay
  - 20,000 h cell operation at 450 mA/cm² at 750°C
  - 7,000 h cell with stable internal reforming
  - High volume manufacturing developed
  - Three 20-cell stacks accumulated over 12,000 h, 16 thermal cycles at 400 mA/cm² and 700°C
Summary (continued)

- System Experience

  - Models developed for thermal management at high power density, verification in progress
  - kW-class systems accumulated greater than 24,000 h, peak net AC efficiency >30%
  - Opportunities for further improvement in mBOP and eBOP identified