Integrated Coal Gasification Solid Oxide Fuel Cell Systems

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FuelCell Energy (FCE)

- Premier developer of stationary fuel cell technology
- Headquarters in Danbury, CT (USA), with 65,000 ft² manufacturing facility in Torrington, CT (USA)
- Delivering Direct FuelCell power plants to commercial and industrial customers
- Developing large scale coal-based power plants as well as natural gas distributed generation (DG) systems utilizing planar SOFC
- Established commercial relationships with major distributors in the Americas, Europe, and Asia
Program Objectives

Development of large scale (>100 MWe) coal-based SOFC systems with:

- At least 50% electrical efficiency from coal (higher heating value)
- Performance to meet DOE specified metrics for power output, degradation, availability, and reliability
- Factory cost <$400/kW in 2002 USD ($700/kW, 2007 $)
- Greater than 90% of carbon capture from coal syngas as CO₂, for sequestration
- Reduced water consumption as compared to the existing coal power plant technologies

Program Status

- FCE team successfully completed Phase I of the Coal Based SECA Program in December 2008.
- Phase II work is underway to further the development of an affordable, multi-MW size SOFC power plant system to operate on coal syngas fuel, with near zero emissions.
SECA Coal Based Plan for IGFC Development

- FCE is currently engaged in development of stack tower and SOFC power module configurations suitable for large scale coal based power plants.

10 kW Stack  >25 kW Stack Tower  ≥ 250 kW Module Demonstration Unit  5 MW Proof of Concept

- Phase I
- Phase II
- Phase III
Phase II SECA Coal-Based Team

The FCE team is comprised of diverse organizations with expertise in key functional areas:

FuelCell Energy Inc. (FCE), Danbury, CT
- Manufacturing and commercialization of fuel cell power plant systems in sizes ranging from 250kW to Multi-MW.

Versa Power Systems Inc. (VPS), Littleton, CO
- Solid Oxide Fuel Cell (SOFC) development and manufacturing technologies.

Pacific Northwest National Laboratory (PNNL), Richland, WA
- SOFC cell and stack computational modeling.

WorleyParsons Inc. (WP), Reading, PA
- Design of the power plant, including: integration with gasifier and syngas clean-up technologies, system level costing, and system performance analysis.
FCE utilizes cell and stack design of its technology team partner, Versa Power Systems Inc. (VPS), for coal based system development.

ANODE SUPPORTED PLANAR CELL DESIGN:
- Anode – nickel-zirconia cermet (~1mm thick)
- Electrolyte – yttria-stabilized zirconia (YSZ) (~10µm thick)
- Cathode – conducting ceramic (~50µm thick)

VPS Cell Technology
The “TSC” process for SOFC component fabrication has proven to be cost effective with high yields and excellent quality.
Cell Fabrication Status

• Cell Scale Up
  > Cell process development was conducted and process capability was established for cells up to 33 x 33 cm² (largest size that can be made with existing equipment)

• Cell Fabrication Process Development
  > Capital equipment for all major process units was added in order to accommodate increased cell size and volume

• Cell Manufacturing
  > 25 x 25 cm² cells with 550 cm² active area is the current baseline size for SOFC stack fabrication.
  > More than 5000 cells (25 x 25 cm²) have been fabricated - production yields greater than 90% and volumes of 500 kW (annual) have been demonstrated.
Single Cell Performance Achievements

Performance Curves

Voltage, V vs. Current Density, A/cm²

Power Density, W/cm² vs. Current Density, A/cm²
Cell Stability Achievements

OVERALL:
21 mV over 7392 hrs
2.84 mV or 0.28% / 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)
Stainless Steel Current Collectors, Cross-Flow Gas Delivery

- T = 750°C
- J = 0.74 A/cm²
- Fuel = Hydrogen + 3% H₂O
- ηf = 23%
- Fuel flow = 24.7 ml/min/cm² cell area
- ηo = 54%
- Air flow = 24.7 ml/min/cm² cell area

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 x 10 cm²</td>
<td>0.608</td>
</tr>
<tr>
<td>12.5 x 12.5 cm²</td>
<td>0.598</td>
</tr>
<tr>
<td>20 x 20 cm²</td>
<td>0.612</td>
</tr>
<tr>
<td>25 x 25 cm²</td>
<td>0.606</td>
</tr>
<tr>
<td>33 x 33 cm²</td>
<td>0.612</td>
</tr>
</tbody>
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Building Block Approach

Single Stack
Building block for stack towers
30-100 kW

Stack Tower
Building block for stack modules of
≥ 250 kW

Stack Module
Building Block for a ≥100MWe
Integrated Gasification Fuel Cell (IGFC) system
### Stack Scale-up Progression

#### Phase I

<table>
<thead>
<tr>
<th>Stack Design</th>
<th>Power (kW/stack)</th>
<th>Quantity</th>
<th>Total Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 cells</td>
<td>1</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>16 cells</td>
<td>2.5</td>
<td>18</td>
<td>45</td>
</tr>
<tr>
<td>64 cells</td>
<td>10</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>45</strong></td>
<td><strong>126</strong></td>
</tr>
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</table>

#### Phase II

<table>
<thead>
<tr>
<th>Stack Design</th>
<th>Power (kW/stack)</th>
<th>Quantity</th>
<th>Total Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 cells</td>
<td>2.5</td>
<td>38</td>
<td>95</td>
</tr>
<tr>
<td>32 cells</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>92 cells</td>
<td>18</td>
<td>6</td>
<td>108</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>45</strong></td>
<td><strong>208</strong></td>
</tr>
</tbody>
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*Notice: Only authorized persons to enter this area.*
16-Cell Stack with TSC3 Thin Cell

GT057235-0043 TC0 - Fuel Utilizations 213Amp 25% DIR Stand 23

Elapsed Time (hours)

Voltage (V)

Cell 01
Cell 02
Cell 03
Cell 04
Cell 05
Cell 06
Cell 07
Cell 08
Cell 09
Cell 10
Cell 11
Cell 12
Cell 13
Cell 14
Cell 15
Cell 16

50%
60%
70%
80%
61.5F13.5A 25%DIR 213Amps
Stack Operational Stability

All Cells TC0 +TC1

5.6mV (0.64%) / 1000hrs @4206 hrs

32-Cell Stack - 550 cm² Active Area TSC3
Cells
Furnace Temperature: 700°C
Fuel: 63.2% H₂ : 11.7% N₂ : 5.2% CH₄ : 19.9%
H₂O, Uf = 61.5%
Oxidant: Air, Ua = 13.5%
Current: 213 A (0.39 A/cm²)
Stack Modeling

- A modeling-driven design approach for thermo-mechanical challenges has been adopted
- Progressively increased from single cell, short stack, full size stack block to tower modeling
- Modeling has provided guidance to engineering design and component development using both CFD and FEA
New Generation of Stack Blocks (Phase II)

**Operating Conditions**

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<table>
<thead>
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<tbody>
<tr>
<td>Fuel Utilization</td>
<td>68%</td>
</tr>
<tr>
<td>Air Utilization</td>
<td>14%</td>
</tr>
<tr>
<td>In-Stack Reforming</td>
<td>25 – 70%</td>
</tr>
<tr>
<td>Stack Current</td>
<td>250 A (455 mA/cm²)</td>
</tr>
<tr>
<td>Gross DC Electrical Power</td>
<td>~18 kW</td>
</tr>
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<p>| | |</p>
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<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Cell Size</td>
<td>25 x 25 cm²</td>
</tr>
<tr>
<td>Active Area</td>
<td>550 cm²</td>
</tr>
<tr>
<td>Number of Cells</td>
<td>92</td>
</tr>
</tbody>
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Stack Tower (SO-30-3) Test

- Demonstration of a stack tower operation in a simulated power plant environment was performed using 2x92-cell fuel cell blocks.
- A Power Rating of 30 kW was established during the operation.
Coal-Based SOFC System with Catalytic Gasification

Combined with high methane producing gasification, coal based SOFC systems are capable of achieving ~ 55% efficiency and 98% carbon capture.

<table>
<thead>
<tr>
<th>POWER GENERATION SUMMARY</th>
<th>kW</th>
<th>% Q input</th>
<th>% MW gross</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Gas Expandors Gross Power @ 20 kV</td>
<td>52,307</td>
<td>5.15%</td>
<td>8.49%</td>
</tr>
<tr>
<td>Fuel Cell Inverter AC Gross Power @ 20 kV</td>
<td>515,126</td>
<td>50.76%</td>
<td>83.57%</td>
</tr>
<tr>
<td>WGCU Off Gas Expander Gross Power @ 20 kV</td>
<td>9,361</td>
<td>0.92%</td>
<td>1.54%</td>
</tr>
<tr>
<td>Steam Turbine Gross Power at Generator Terminals @ 20 kV</td>
<td>39,599</td>
<td>3.90%</td>
<td>6.42%</td>
</tr>
<tr>
<td><strong>Total Gross Power Generation @ 20 kV</strong></td>
<td><strong>616,393</strong></td>
<td><strong>60.74%</strong></td>
<td><strong>100.00%</strong></td>
</tr>
<tr>
<td><strong>Total Auxiliary Load</strong></td>
<td><strong>56,152</strong></td>
<td><strong>5.53%</strong></td>
<td><strong>9.11%</strong></td>
</tr>
</tbody>
</table>

| Net Power Output at 230 kV | 560,241 | 55.21% | 90.89% |

Net Efficiency Excluding CO2 Compression & Thermal Input

| As Fed Coal feed, lb/h | 291,667 |
| HHV (AF), Btu/lb | 11,872 |
| Thermal Input, kWh | 1,014,809 | 100.00% | 164.64% |
| Net Plant Efficiency (HHV) | 55.21% |
Baseline SOFC Power Plant Efficiency vs. Competing Technologies

Baseline coal based SOFC system is >18 percentage points more efficient than IGCCs and Pulverized Coal (PC) Steam Turbine power plants.

References for Competing Technologies:
* Cost and Performance Baseline for Fossil Energy Plants, Volume 1 - Bituminous Coal and Natural Gas to Electricity, DOE/NETL-2007/1281, Revision 1, August 2007
** Pulverized Coal Oxycombustion Power Plants, Volume 1 - Bituminous Coal to Electricity, DOE/NETL-2007/1291, Final Report, August 2007
Baseline SOFC Power Plant Water Consumption vs. Competing Technologies

Baseline coal based SOFC system requires significantly less water than IGCCs and Pulverized Coal (PC) Steam Turbine Power Plants.

References for Competing Technologies:
* Cost and Performance Baseline for Fossil Energy Plants, Volume 1 - Bituminous Coal and Natural Gas to Electricity, DOE/NELT-2007/1281, Revision 1, August 2007
** Pulverized Coal Oxycombustion Power Plants, Volume 1 - Bituminous Coal to Electricity, DOE/NELT-2007/1291, Final Report, August 2007
Stack Costing (Q3, 2009)

- **92-cell stack block**
  - 18 kW nominal, 19.87 peak
  - 0.393 W/cm²
- **Cell dimensions**
  - 550 cm² active area
  - 645 cm² cell substrate
  - 1.0 mm thick
- **1036 MW/yr production volume**
  - 57,600 stack blocks
  - 5,299,200 cell repeat units
  - 341,900 m²
  - 1,711,000 kg, cells

Stack Block Cost by Category (Phase II Interim)

- Materials, $2,597
- Labor, $145
- Other, $296
Stack Cost Reduction Path

- Higher Power Density
- Stack Block Scale Up
- Thin Cell Development
- Stack Materials Reduction

Stack GT057382-0004
64-Cell Stack Block
Furnace Temperature = 705°C

14.8 kW @ 300 A
Average Cell Performance:
771 mV @ 545 mA/cm²

420 mW/cm²

$120/kWac
$100/kWac
$197/kWac

Q1 2009 Q4 2009 Q3 2009 Q2 2009 Q1 2010 Q4 2010 Q3 2010 Q2 2010
Cost estimation is based on two nominal 560 MW power plants manufactured per year (2002 USD).

Estimate includes Factory Equipment costs for the Power Island, exclusive of gasification, syngas cleanup, and CO₂ separation/compression systems.
Baseline System Power Island Layout

SOFC power island includes:

- 8 Sections of 42 fuel cell stack modules
- Steam turbine
- Two syngas expanders
• A similarly sized (MW) IGCC and IGFC will be comparable in real estate requirement.
IGFC Site Layout
Summary of Recent Achievements

Cell Technology:
- Fuel cell manufacturing processes were developed to achieve the new scaled-up cell (33 cm x 33 cm).
- Cell materials development continued to improve performance and endurance.

Scale-up of stack size:
- Manufacturing of the scaled-up stack blocks was accomplished to establish the building blocks for multi-MW power plants.
- Improved stack design and component advancements resulted in high power densities suitable for large scale coal plants.

Baseline IGFC System:
- A Baseline System with Catalytic Gasifier was developed which could achieve efficiency (HHV) of >55% and be able to remove greater than 98% carbon from syngas.
- Baseline 560MW IGFC power plant layout and factory cost estimates were developed resulting in a cost estimate of ~$400/kW (in 2002 dollars) for the SOFC power island.
- The developed IGFC system showed significantly lower water consumption as compared to IGCC and other coal fueled power plants.
Acknowledgement

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Thank You!