Siemens Energy

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July 27, 2010

Joseph Pierre
Siemens Energy
Fossil Power Generation
Stationary Fuel Cells
The world is changing – Siemens has answers to these burning questions

**Population growth**
- We solve the challenges of a booming population

**Increasing life expectancy**
- We supply better and affordable healthcare

**CO₂ emissions**
- We lower CO₂ emissions with our energy solutions

**GDP increase in developing countries**
- Source: Siemens
### Answers provided by 15 Divisions in three Sectors

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Divisions</th>
<th>Former Groups</th>
</tr>
</thead>
</table>
| Industry | ■ Industry Automation  
           ■ Drive Technologies  
           ■ Building Technologies | ■ Automation and Drives (A&D)  
                        ■ Industrial Solutions and Services (I&S)  
                        ■ Siemens Building Technologies (SBT)  
                        ■ Osram  
                        ■ Transportation Systems (TS) |
| Energy   | ■ Oil & Gas  
           ■ Fossil Power Generation  
           ■ Renewable Energy        | ■ Power Generation (PG)  
                        ■ Power Transmission and Distribution (PTD)  
                        ■ Industrial Solutions and Services (I&S OGM) |
| Healthcare| ■ Imaging & IT  
            ■ Workflow & Solutions  
            ■ Diagnostics            | ■ Medical Solutions (Med) |
### Energy products and solutions – in 6 Divisions

|-----------|--------------------------|------------------|----------------|-------------------|-------------------|

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# Fossil Power Generation Division – Organizational structure

## Fossil Power Generation
CEO Dr. Michael Suess

### Products (E F PR)
- Steam Turbines
- Generators
- Gas Turbines
- Sales
- System Integration
- Feeder Plants

### Energy Solutions (E F ES)
- Power Plant Solutions, Europe, CIS
- Power Plant Solutions, Near Middle East, Africa, Asia-Pacific
- Power Plant Solutions Americas
- Steam Power Plant Solutions
- Project Site Execution
- Module & Project Engineering

### Instrumentation & Electrical (E F IE)
- Northern Europe, CIS, Germany
- Southern Europe, Africa, Middle East, West Asia
- Region Americas, Asia-Pacific, Australia, Spain, Portugal
- Intergroup Business and Operational I&C NPPs
- Product Management

### Business Segment

### New Technologies (E F NT)
- Fuel Gasification
- Stationary Fuel Cells
- Carbon Capture and Storage

### Nuclear Power, Conventional Island (E F NP)

### Market position
- Nr. 2
- Nr. 2
- Nr. 1
New Technologies Business Segment (E F NT)

<table>
<thead>
<tr>
<th>Portfolio</th>
<th>Strategy</th>
</tr>
</thead>
</table>
| ■ Fuel gasification  
  – Gasifier  
  – Technology licenses  
  – Gasifier island solutions for IGCC, production of chemical products from coal („Coal-to-Chemicals“)  
  ■ Stationary fuel cells  
  ■ New technologies for carbon capture | ■ Expansion of the gasifier component business  
  ■ Development and marketing of other CCS components (Carbon Capture and Storage)  
  ■ Development of IGCC-integrated concept solutions |
SFC Technology has demonstrated Best-in-Class performance

Nuon, Westervort, Netherlands - 100 kW CHP

RWE, Essen, Germany – 100 kW CHP

Ontario Power - 250 kW CHP

GTT Torino, Italy - 100 kW CHP

SCE, Irvine, CA - 220 kW Pressurized Hybrid

SECA HPD 5 kW

Phase I Stack Test

Stadtwerke Hannover, Germany SFC 200 CHP

Developed over 25 fully integrated SOFC power generating systems, including the world’s first pressurized hybrid demonstration unit
Acknowledgement

This material is based upon work supported by the Department of Energy under Award Numbers DE-FC26-05NT42613
# DOE SECA Coal-based System Program

## Program Objectives

### Phase I
- Conceptual design and feasibility analysis of baseline design and Proof-of-Concept (POC) system
- Verify Delta-8 performance via cell and stack tests
- Initiate and complete 5,000 hrs Delta8 R0 stack test

### Phase II
- Detailed design, performance, and cost analysis of baseline design
- Initiate and complete 1,500 hrs of operation Delta8 R1 Stack Test

### Phase III
- Initiate and complete 5,000 hrs operation of Delta8 “MWe-class” module
- Initiate and complete 25,000 hrs operation of MWe-scale POC System
- Corroborate performance and cost of 100 MWe baseline design

### A Multi-Year, Multi-Phase DOE Program
- Phase I – 3 years: $26M
- Phase II – 2 years: $17M
- Phase III – 5 years: $33M

The ultimate goal of DOE program beyond Phase III: Coal syngas fueled, >100 MWe class fuel cell central station efficiency >50%, with 90% CO₂ isolation at $400/kWe (excluding CO₂ sequestration and gasification systems)
DOE SECA Coal-based System Program
Phase II Key Activities

- Baseline Systems Analysis
- Cell and Module Development
- POCD8R1 Stack Test
Significant Results

• Identified an alternate high(er) efficiency cycle concept
• Increased power density between 800-1000°C on cylindrical cells through material and process improvements
• Showed voltage stability of the power-enhanced cells at 900° and 1000°C
• Demonstrated stability of the power-enhanced cells through 10 thermal cycles
• Transfer power enhancement technology to Delta8 cells
• Initiated testing of a power-enhanced Delta8 cell
• Continued HPD test with an excellent voltage stability
• Completed construction and initiated validation of Pressurized Test Facility
• Initiated POCD8R1 Stack Test
Baseline System Analysis

Goals
Must Operate on Coal Synthesis Gas
Must Use a Fuel Cell
CO₂ Capture ≥ 90%
Efficiency ≥50% (Net AC/Coal HHV)
Power System Capacity >100 MWe
Cost ≤ $600/Max kWe (End Phase 1 Concept Design)

Objectives
Baseline System Performance and Cost Estimate Updates
Baseline System Performance Analysis
Confirm the Proffered Baseline System Concept
Baseline System(s) Definition and Analysis
Baseline System Cost Analysis
Factory Cost Report

Technical Challenges
Cell performance confirmation
Efficiency targets
Handling inerts in the alternate high efficiency cycle concept
Water management

Accomplishments
Continued evaluation of alternate higher efficiency concept
Validated performance and cost of the Baseline System
Pressurized Cell Testing

**Goals:**
Validate the existing test facility against existing pressurized cell test data.
Obtain performance data on the Delta8 cell configuration under pressurized conditions

**Technical Challenges:**
Fuel distribution within the test article
High temperature leak rate
Fuel bypass

**Objectives:**
Design improved Delta8 pressurized test articles
Procure and assemble tubular test articles to validate test rig
Upgrade existing test facility
Conduct testing and obtain performance data at elevated pressures
Conduct post test analysis

**Activities:**
Assembly of tubular cell test article completed
Installation of tubular test article into test facility completed
Facility modifications and shakedown underway
Pressurized Cell & Stack Test
Tubular Cell Test 1213 – Heater Assembly

Test article

1 \(\frac{1}{2}\) clam shell heaters installed

All (4) clam shell heaters installed
Pressurized Cell & Stack Test
Tubular Cell Test 1213 – Insulation Wrap

Before final insulation

Insulation complete

Covered with Aluminum sheeting
Pressurized Cell & Stack Test
Tubular Cell Test 1213 – Installation in Test Rig

Article installed in pressure vessel with final insulation wraps

Article lowered into the pressure vessel
Cell Development

Goals

- Achieve cost and performance requirements utilizing HPD Delta8 seal-less planar cell design
- Manufacture Cells and Bundles for Proof-of Concept tests

Objectives

- Develop process conditions for the manufacturing of the air electrodes for the Delta8 one meter active length cells which improve quality and lower cost
- Develop process conditions for the application of electrolyte, fuel electrode, and interconnection utilizing PS which improve quality and lower cost
- Develop high quality, low cost process for the bundling of Delta8 cells
- Development lower operating temperature cell

Technical Challenges

- Dimensional control (side bow and taper) of Delta8 cell
- Elimination of air electrode flaws
- Elimination of closed end cracks
- Ability to achieve high yield with Delta8 cell
- Ability to spray electrolyte at high feed rates in carousel design
- Demonstrate ability to implement additive into a manufacturing friendly process

Activities/Accomplishments

- Dimensional control of air electrode
- Reduction of Air Electrode Flaws
- Elimination of closed end cracks
- Application of electrolyte at commercially viable conditions
- Cell and Bundle Development and Manufacturing
- Demonstrate stable high performance of power-enhanced cells
- Evaluation and definition of manufacturing process for power enhanced cells

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Performance of Power Enhanced Cylindrical Cell

Enhanced power at all temperatures
Voltage Stability of Power Enhanced Cylindrical Cell

Excellent Voltage Stability … Test continues…
Cell went through 10 thermal cycles without losing voltage and was very stable at 1000°C. Test continues…
Delta8 Cell Assembly
Delta8 Cell Performance Curve - Voltage vs. Current Density

Cell assembly process needs to be improved to lower fuel bypass
Delta8 Cell Life Time Plot

- **Closed End Voltage**
- **Current (amps)**
- **Average Temperature**

- **Cell Voltage (V)**
- **Elapsed Time on Test (hours)**
- **Temperature (°C)**
- **J = 250 mA/cm² (485 Amperes)**

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HPD Voltage Stability

- Average Temperature: 900°C
- Fuel Utilization: 80%
- Fuel: Humidified Hydrogen

Test Duration (Hours)

Cell Voltage (V)

Current Density (A/cm²)
## POCD8R1 Stack Test

### Goals
- Deliver a $\geq 25 \text{kWe SOFC stack}$ incorporating Delta8 cells
- Initiate End-of-Phase II Stack Test
- Achieve 1,500 hrs operating time prior to End-of-Phase II
- Satisfy performance requirements as specified in the Minimum Requirements Document

### Technical Challenges (D&B)
- Cell Production / Bundle Assembly
  - Cell production yield
  - Cell/bundle dimensional tolerances
  - Bundle assembly and sintering
- Back-up for critical contractor
- Delta8 cell and bundle integrity

### Objectives (D&B) (FY)
- Complete R1 module design 3Q09
- Complete R1 module assembly 2Q10
- Cells and bundle manufacturing 4Q09
- Complete R1 BOP design 3Q09
- Complete R1 BOP assembly 4Q09
- Complete R1 test article assembly and installation 2Q10
- Initiate stack test 2Q10

### Activities/Accomplishments
- Integrating BOP with test article
- Validating control system software
- Assembling external recirculation loop
- Identify and qualify backup machining contractor

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## POCD8R1 Stack Test

### Goals
- Initiate End-of-Phase II SECA Stack Test
- Achieve 1,500 hrs operating time prior to End-of-Phase II
- Satisfy performance requirements as specified in the Minimum Requirements Document

### Technical Challenges
- Fuel side heating
- Anode stream recirculator
- New stack architecture (IBA)
- One meter Delta8 cells

### Objectives

<table>
<thead>
<tr>
<th>Activity/Goal</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>System startup</td>
<td>03/01</td>
</tr>
<tr>
<td>Begin Load to NOC</td>
<td>03/07</td>
</tr>
<tr>
<td>Initiate cell conditioning</td>
<td>03/21</td>
</tr>
<tr>
<td>Peak power test</td>
<td>04/06</td>
</tr>
<tr>
<td>VJ curves at NOC</td>
<td>04/25</td>
</tr>
<tr>
<td>Initiate Stability Test</td>
<td>04/25</td>
</tr>
<tr>
<td>Initiate system shutdown</td>
<td>06/25</td>
</tr>
<tr>
<td>Stack test completed</td>
<td>06/27</td>
</tr>
<tr>
<td>Complete Root Cause Investigation</td>
<td>06/15</td>
</tr>
</tbody>
</table>

### Activities/Accomplishments

<table>
<thead>
<tr>
<th>Activity/Goal</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiated stack test</td>
<td></td>
</tr>
<tr>
<td>Heatup completed</td>
<td></td>
</tr>
<tr>
<td>Introduction of NHmix and Hydrogen</td>
<td></td>
</tr>
<tr>
<td>Achieved current loading &gt;300 amps</td>
<td></td>
</tr>
<tr>
<td>Disassembly/Root Cause Investigation completed</td>
<td></td>
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POCD8R1 Stack Test Summary

• Second generator to test Delta 8 cells
  – First, POCD8R0, operated for 5300 hours with max DC power of 9.8 kW
  – Stack was damaged due to failure of the control system hard drive
• Began operation in March 2010
  – Operated for 400 hours
  – Loaded to 11.1 kW stack DC power
• Design successfully demonstrated many advanced features:
  – Integral Bundle Assembly (IBA)
  – Cast ceramic components
  – Fuel side heating
  – Fuel recirculator
• Several cells failed during an air transient at 400 hours
  – Stack failed during loading (311 amps at failure vs 818 amps at NOC)
  – Stack was damaged early in heatup by intermittent electrical shorts caused by carbon formation
  – Stack contained more organic binders than previous generators
Delta 8 Cell

**Delta 8 Cell Materials**

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode (Air Electrode)</td>
<td>Doped lanthanum manganite</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Scandia stabilized zirconium oxide</td>
</tr>
<tr>
<td>Interconnection</td>
<td>Doped lanthanum chromite</td>
</tr>
<tr>
<td>Anode (Fuel Electrode)</td>
<td>Nickel – zirconium oxide cermet</td>
</tr>
<tr>
<td>Plating</td>
<td>Nickel</td>
</tr>
</tbody>
</table>
POCD8R1 Stack Test – Delta8 Bundle (8 cell)
Bundle rows installed in the stack assembly fixture
POCD8R1 Generator and Recirculation Loop

Advanced features:
- Integral Bundle Assembly (IBA)
- Cast ceramic components
- Fuel side heating
- Fuel circulator

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POCD8R1 Test Facility
Root Cause Analysis Process

- Review stack voltage data
- Review stack temperature data
- Review fuel cell manufacturing history
- Review operating procedure
- Review thermal stress models
- Carefully examine disassembly of test article
- Perform fractography analysis on broken fuel cell
- 58 observations
- 12 failure mechanisms
- 31 recommendations
- Path forward defined
In-stack Carbon

Damaged Bundle Row

Carbon on Saffil Felt
POCD8R1 Stack Test Root Cause Investigation

Bundle 5 Shorting During Heat Up

Bundle 5 voltage experienced two shorts during heat up

Bundle 5 shorting at low temperature may have led to tight closed end fuel cell cracks

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Acknowledgements

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- Travis Shultz
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