COAL-BASED IGFC PROJECT
PHASE I
FC26-08NT0003894

Praveen Narasimhamurthy – UTC Power
Rick Kerr – Delphi
• Summary of stack performance highlights from past year
• Cell and stack fabrication
• Gen 4 stack seal development
• Gen 4 stack voltage variation improvement
• Interconnect and contact material development
  • Constant current
  • Thermal cycling
SUMMARY OF SECA COAL BASED SYSTEM STACK DEVELOPMENT

• Completed scale up of cells from 105 cm$^2$ (active area) cells to 403 cm$^2$ for Gen 4 stacks
• Added additional Gen 4 stack fabrication and testing capabilities
• Fabricated and tested 24 Gen 4 stacks and 55 Gen 3 stacks in past year
• Completed Red X® investigations to improve stack sintering process and decrease stack voltage variation
• Demonstrated 7,000+ hours continuous durability on Gen 3.2 stack; demonstrated 5,000+ hours on Gen 4 stack.
• Completed 70 full thermal cycles on Gen 4 stack, with less than 5% voltage degradation
Fabricated in past year

- About 2,200 Gen 4-sized cells
- 24 Gen 4 stacks of varied configurations (most 30-cells or greater)
- 55 Gen 3 stacks of varied configurations (many 30-cells or greater)
CONCENTRATION DIAGRAMS OF POROUS SEAL MICROSTRUCTURES

Stack G041
40-Cell Gen 4

Stack G035
40-Cell Gen 4
STACK SINTERING OPTIMIZATION PROJECT

- Confirmed overheating of the stack seals
  - PNNL XRD analyses
  - Microstructural analysis
  - Coupon confirmation testing at increased sintering temperatures
- Teardown analyses of previous stacks
- Thermal mapped build stands and stacks during standard build process
- Developed strategy for investigating build control factors for improved thermal control during sintering
- Completed stack mapping thermal profiles with varied build controls
- Confirmation run with new build control parameters
TEMPERATURE PROFILES PRIOR TO OPTIMIZATION OF SINTERING CYCLE
TEMPERATURE PROFILES AFTER OPTIMIZATION OF SINTERING CYCLE
SEAL STRUCTURAL IMPROVEMENT FROM SINTERING OPTIMIZATION

Stack Perimeter Seal Prior to Optimization of Sintering Cycle

Stack Perimeter Seal After Optimization of Sintering Cycle
Date: 8/19/2011
Fuel: 48.5%H2-48.5%N2-3%H20

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>5747</th>
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<tbody>
<tr>
<td>Power Density (mW/cm²)</td>
<td>472.99</td>
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<tr>
<td>Current (A)</td>
<td>240.05</td>
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<tr>
<td>Mean RU Voltage (V)</td>
<td>0.7981</td>
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<tr>
<td>Voltage Spread (V)</td>
<td>0.0524</td>
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RED X® STUDY ON MINIMIZING STACK REPEATING UNIT VOLTAGE VARIATION

- Analyzed numerous Gen 4 stacks
  - Cross sections
  - Repeating unit teardowns
  - X-ray and metallographic analyses of repeating units
  - Measurement studies of numerous repeating unit components
  - Optical and SEM inspection of components
- Conducted sintering studies
  - Component level
  - Full stack level
MOST RECENT 38-CELL GEN 4 STACK INITIAL POLARIZATION PERFORMANCE AFTER RED X® PROJECT

Date: 06/27/2012
Fuel: 48.5%H2-48.5%N2-3%H2O

Stack Voltage (V)
Power Density (mW/cm²)
Current (A)
MOST RECENT 38-CELL GEN 4 STACK INITIAL POLARIZATION VOLTAGE SPREAD

Date: 06/27/2012
Fuel: 48.5%H2-48.5%N2-3%H20

<table>
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<tr>
<th>Pressure (kPa)</th>
<th>Anode External (sccm)</th>
<th>Cathode External (sccm)</th>
<th>Cross (sccm)</th>
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<tr>
<td>7.00</td>
<td>0.00</td>
<td>16.00</td>
<td>0.00</td>
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</tbody>
</table>
Date: 06/27/2012
Fuel: 48.5%H2-48.5%N2-3%H2O
GEN 3.2 STACK DURABILITY TESTING (0.57 A/cm²)

Fuel: 48.5%H₂-48.5%N₂-3%H₂O

Stack Voltage (V)
Power Density (mW/cm²)

Time (Hrs)
GENERATION 3 30-CELL STACK DURABILITY

Fuel: 48.5%H2-48.5%N2-3%H2O

Stack Voltage (V)

Power Density (mW/cm²)

Time (Hours)

800 mV 750C Impedance
30-CELL GEN 4 STACK THERMAL CYCLING

Fuel: 48.5%H2-48.5%N2-3%H2O
30-CELL GEN 4 STACK CONSTANT CURRENT DURABILITY (0.27 A/cm²)

Gen 4 30-Cell Stack

Fuel: 48.5%H₂-48.5%N₂-3%H₂O
INTERCONNECT MATERIAL PERFORMANCE

![Graph showing cell voltage over time for Interconnect Materials 1, 2, and 3.](image)

- **Mean Cell Voltage**
- **Interconnect Materials 1**
- **Interconnect Materials 2**
- **Interconnect Materials 3**

**Axes:**
- **Y-axis:** Cell Voltage, Volts
- **X-axis:** Time, Hours

**Legend:**
- Red: Mean Cell Voltage
- Green: Interconnect Materials 1
- Purple: Interconnect Materials 2
- Blue: Interconnect Materials 3
UTC OBJECTIVES FOR PHASE II

• Design and build 15-25kW SOFC breadboard

• Make modifications to SOFC test stand from Phase I to test breadboard

• Perform extensive verification of test stand and breadboard on beater stack prior to start of endurance testing

• Demonstrate 1500 hours endurance on 4-stack module in a system construct (breadboard)

• Demonstrate thermally self-sustaining operation

• Demonstrate peak power operation
SUMMARY HIGHLIGHTS - SYSTEM

- Demonstrated ~1,250 hours durability on Gen 4 stack module.
- Improved test stand reliability by ~3x to complete Phase I
- Completed conceptual and preliminary design for the 25kW breadboard
- Detailed design and breadboard build is ~80% complete
- Test stand modifications for Phase II are ~80% complete
- Software design and bench verification is 90% complete
- Ex-situ verification of breadboard fuel recycle assembly is underway
  - Completed ~100 hours of continuous durability at operating temperatures on an ex-situ test rig
TASK 6.3 - STACK MODULE ENDURANCE TESTING

Stack Module

Delphi Stack Module in the 50 kW capable test stand at UTC Power
TASK 6.3 - STACK MODULE ENDURANCE TESTING

Phase I Stack Performance

Stack A (G013) Endurance Voltage

- Endurance Hold
- Dates: 8/16/2011 to 3/8/2012
- Fuel: Simulated Coal Gas

Mean Stack Voltage (V/cell)

Endurance Hrs

Endurance Stack Voltage
TASK 6.3 - STACK MODULE ENDURANCE TESTING

Endurance Test – System Level Learning

- Completed fuel contaminant tests
- Completed cathode side chromium sampling
- Obtained data on stack manifold temperature distribution
  - Temperature data used to estimate stack heat loss for Phase II
- Obtained data on stack manifold pressure drop
  - Currently anode over cathode at stack exit; working with Delphi
- Improved test stand reliability
NPD Gated Process for System Design and Development

**Conceptual Design**
- ✓ Requirements Generation
- ✓ Trade Studies
- ✓ Conceptual Models
- ✓ System Matches
- ✓ Preliminary Physical Layout

**Preliminary Design**
- ✓ Component Requirements Generation
- ✓ Component Design
- ✓ Controls Design
- ✓ FMEA/FA/HA
- ✓ Detailed Physical Layout

**Detailed Design/Test**
- • Component Tests
- • Hardware Build/Integration
- • Test Plan Review
- • Breadboard Checkouts
- • Endurance Test

**Design Review**

**Design Review**

**Test Report**
TASK 4.1 - BREADBOARD/SYSTEM DESIGN

Breadboard Schematic

- Fuel recycle for maximizing efficiency
- HEXs for exhaust heat recovery
- Catalytic burner for exhaust management and heat up of cathode inlet air
Breadboard Projected Efficiency

Breadboard Projections vs. Ideal
- Several BOP (recycle blower) over-sized
- Heaters included for contingency on breadboard; not required for a product
- Air blower for cathode supply not optimized
Task 4.1 - Breadboard/System Design

Control Strategy

Test stand controller
- Controls breadboard startup sequence, transition to load, on-load operation and breadboard shutdown for product protection

Host PC & Data Acquisition
- GUI-based user interface for controlling test process, monitoring and data collection

Other Controllers
1. Safety Controller
   - Hard-wired controls for safety and personnel protection
2. Facility Controller
   - Provides safety shutoff for all reactant supply system
3. After Burner Controller
   - Controls test stand afterburner
4. Heater controllers
   - Maintain test stand controller requested heater set point
TASK 4.1 - BREADBOARD/SYSTEM DESIGN

Breadboard Layout

UTCP
Balance of Plant (BOP)

Delphi Stacks
TASK 4.1 - BREADBOARD/SYSTEM DESIGN

Breadboard Design

Fuel System Components

Air System Components
TASK 4.1 - BREADBOARD/SYSTEM DESIGN

Risk Mitigation: Ex-situ Blower Tests

Test Rig for Blower Performance and Endurance Test
FUTURE WORK

Beyond Phase II

• Continue cost reduction of stack and power plant components

• Improve stack durability to meet SECA goals

• Demonstrate breadboard endurance

• Risk reduce for critical components: blowers, fuel processing components, catalytic burners

• Collect system level data for scaled-up power plant/prototype design in future phases
Thanks to Joe Stoffa, Briggs White, and Dan Driscoll of the DOE for their support and technical guidance.