COAL-BASED IGFC PROJECT
PHASE I
FC26-08NT0003894

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SECA OBJECTIVES

• Reduce SOFC-based electrical power generation system cost to ≤ $700/kWe (2007 dollars) for a >100MW Integrated Gasification Fuel Cell (IGFC) power plant, exclusive of coal gasification and CO₂ separation subsystem costs

• Achieve an overall IGFC power plant efficiency of ≥50%, from coal (HHV) to AC power (inclusive of coal gasification and carbon separation processes)

• Reduce the release of CO₂ to the environment in an IGFC power plant to ≤ 10% of the carbon in the coal feedstock

• Increase SOFC stack reliability to achieve a design life of >40,000 hours
SOFC TEAM

UTC Power
A United Technologies Company

DELPHI
United Technologies Research Center

TASK 2.1
Cell Development
- Scaling
- Cell fabrication
- Cathode, anode, and electrolyte development

TASK 2.2
Stack Development
- Analysis and Design Interconnect & seal development
- Performance & durability
- Stack fabrication & delivery

TASK 3
Stack Materials & Process Development
- Alloy evaluation
- Seal development
- Cathode interconnect coatings

TASK 7
System Concepts & Stack Design Integration
- 250-1000 kW power module concepts
- 5 MW POC concepts
- Baseline IGFC concepts
- System cost analysis

TASK 6
Verification Testing
- 50 kW test stand
- Test of ≥ 25 kW stack
OUTLINE

Stack

• Summary Highlights
• Cells
  – Scale up
  – Cost Reduction
• Gen 4 Stack performance
  – Electrochemical performance of Gen 4
  – Comparison of Gen 4 performance data to Gen 3 data
  – Gen 4 max power performance on SECA coal gas blend
• Durability
  – Constant current
  – Stack tested with actual hydrocarbon fuel reformate
  – Thermal cycling of Gen 4 stack
• Modeling
  – Scale up to larger power systems

Systems

• 50kW Test Stand
• 1500hr Stack Module Endurance Testing
• Power Module
• IGFC Systems
SUMMARY HIGHLIGHTS - STACK

• Scaled up cells from 105 cm\(^2\) (active area) cells to 403 cm\(^2\) for Gen 4 stacks

• Expanded cell and stack fabrication and testing capability for large footprint Gen 4 stacks

• Developed low cost, high volume manufacturable processes for Gen 4 stack components. Fabricated and tested more than 40 Gen 4 stacks.

• Demonstrated maximum power of 6.4 kW on a 40-cell Gen 4 stack with SECA simulated coal gas blend
  – Power density of 398 mW/cm\(^2\)
  – Average cell voltage of 0.7V

• Demonstrated up to 9,700 hours continuous durability on Gen 3.2 stack. Demonstrated 3,000 hours on Gen 4 stack.

• Completed 60 full thermal cycles on Gen 4 stack, with less than 5% voltage degradation
CELL SCALE-UP

- Scaled up to a larger cell without increasing cell thickness
- Gen 4 stacks being fabricated with the large footprint cell
STACK MANUFACTURING

- Delphi manufacturing system design processes reduce stack build variation

Gen 3.2 is baseline platform for evaluation of technology and components to scale up into Gen 4
Cells fabricated with a low cost supply of cathode powder have statistically the same electrochemical performance as cells made from current cathode powder.
• Cathode and anode materials development have demonstrated improved power density in button cell tests
• Further testing ongoing at a stack level
DURABILITY OF LSCF CATHODE

- Data from button cell durability test of current cells with LSCF cathode - demonstrating stable performance
- Greater than 5000 hours of test

Cell tested under constant 0.7V with 0.65 A/cm²
- data taken every 10 hrs
- 0.52%/1000 hrs under constant 0.65A/cm²
- 3.91%/1000 hrs under constant 0.7 V.
Recent 30-cell Gen 4 stack performance

Produced 5.76 kW (476 mW per cm²) @ 0.80 Volts per cell with 48.5% H₂, 3% H₂O, rest N₂
• Recent Gen 4 stack fuel utilization

• Current density of 600 mA per cm²
  – Minimal lowering of power density up to 85% utilization (Fuel 48.5% H₂, 3% H₂O, rest N₂)
  – Power density of 460 mW per cm² at 70% fuel utilization
GENERATION 4 VERSUS GEN 3 STACK PERFORMANCE

Gen 4 30-cell stack vs Gen 3 30-cell stack comparison

- Gen 4 Mean Voltage (V)
- Gen 3 voltage
- Gen 4 Power Density (mW/cm²)
- Gen 3 power density

Current Density (mA per cm²)

Voltage (Volts)

Power Density (mW per cm²)
GEN 4 STACK TESTED WITH SIMULATED COAL GAS REFORMATE - SECA MAX POWER TEST

- Generation 4 40-cell stack evaluated with simulated coal gas reformate – one hour steady state at maximum power
  - Produced a power density of 398 mW per cm² (6.4 kW per 40-cell stack) at an average voltage of 0.7 Volts per cell
GEN 4 STACK MAX POWER ON SECA COAL GAS BLEND

Fuel: 23.79%H2-46.9%CO2-11.95%CH4-17.36%H2O  Flows: 201.9(A) 800(C)

Stack Gross and Net Power for Constant Current Test

Net Power (W)
GEN 4 STACK TESTED WITH SIMULATED COAL GAS REFORMATE-SECA MAX POWER TEST

- Generation 4 40-cell stack evaluated with simulated coal gas reformate – one hour steady state at maximum power output
- Minimal Cell to cell voltage variation (0.08 V) under max power conditions
GENERATION 3 30-CELL STACK DURABILITY

- 9700 hours of durability test on Generation 3 30-cell stack
  - Fuel = 48.5% H₂, 3% H₂O, rest N₂; current = 333 mA/cm²
  - Total degradation is 1.12% per 500 hours
  - Degradation mechanism during initial 1000 hours and after 5000 hours is understood and technology solutions are being implemented
  - Test stopped due to facility failure
Ongoing durability test with improved technology solutions show minimal initial degradation in the first 1000 hours

- Fuel = 48.5% H₂, 3% H₂O, rest N₂; current = 570 mA/cm²
- 5000+ hours completed, test continuing
- Total degradation is 0.88% per 500 hours
• Ongoing durability test with Gen 4 30-cell stack
  – Fuel = 48.5% H₂, 3% H₂O, rest N₂; current = 153 mA/cm²
  – After the first 300 hours (4% degradation), minimal degradation rate observed (less than 0.5%)
  – 2500+ hours completed, test continuing
STACK TESTED WITH REFORMATE

- Gen 3.2 5-cell stack evaluated with hydrocarbon fuel reformate
- 1000 + hours of stable performance (voltage and pressure)
- Initial degradation due to sulfur in hydrocarbon fuel
MG735G026 Thermal Cycle Test
Mean RU Voltage at each Thermal Cycle

Stand exhaust upgrade performed. Cathode back pressure reduced 2 kPa
Detailed CFD modeling of Gen 4 stack completed to optimize for 100 repeating units
- Detailed geometry of Gen 4 repeating unit captured in computational mesh
- 30-RU to 100-RU stack model developed
- Pressure drop analyzed for Gen 4 with varied fuel and air flow rates
- Pressure drop prediction validated with actual Gen 4 stack flow data
- Robust engineering project completed to optimize stack design for robustness to mass flow distribution between cassettes in 30 to 100 RU stacks
  - ± 0.5 slpm for fuel, ± 1.0 slpm for air

Cathode Flow Optimization

Anode Flow Optimization
STACK MASS FLOW DIST. OPTIMIZED FOR FUEL FLOW

Baseline Design (12 slpm/RU)

32 RU - 100% within limits
64 RU - 100% within limits
100 RU - 38% within limits

Optimized Design (12 slpm/RU)

32 RU - 100% within limits
64 RU - 100% within limits
100 RU - 100% within limits
STACK ASSEMBLY FOR STATIONARY POWER PLANTS

- Modular array design
- Simplified fuel manifolding
- Plenum Air Supply and Return
- Volume ~ 111ft³ (500kW)
PHASE I ACHIEVEMENTS - SYSTEMS

- Commissioned the 50 kW capable test stand at UTC Power.
- Started 1500 hr endurance testing of stack module.
- Developed multiple Power Module concepts for 400 kW net AC and $\eta \geq 60\%$ (LHV).
- Developed multiple IGFC designs for > 100 MW net AC power, $\eta \geq 50\%$ (HHV), and $\geq 90\%$ carbon capture.
TASK 6
50kW Test Stand

• Automated operation

• Provide anode/cathode gases
  – Forming gas, 50%/50% H₂/N₂, Coal syngas
  – 750°C-775°C process gas temperature

• Provide loads up to 50kW
  – 400 amperes/600 volts

• Tested/commissioned in Q2, 2011 using extensive testing on debug stack

• Currently testing Delphi stack module for 1500 hr endurance
50KW TEST STAND

Test Facility

Piping, heat exchanger and heater insulation not shown

1. Fluid Management Skid
2. Test Room
3. Load Bank
4. Afterburner
5. Cathode Exhaust
6. Emergency air, 4%H2 bottles
7. Methane Bottles
50KW TEST STAND

Test Room

1. Test Article (in Hot Box)
2. Cathode Heater
3. Cathode Recuperative Heat Exchanger
4. Anode Constituent Heaters
5. Anode Supply
6. Anode Exhaust
7. Cathode Exhaust
8. Test Article Room

Test Room

Test Room with Test Article
1500 HR ENDURANCE HOLD

- Started 1500 hr endurance hold with 2-stack module
  - Coal gas: (23.79%H₂-46.9%CO₂-11.95%CH₄-7.36%H₂O)
  - NOC point: 0.8V/cell at 165A & 5.2kW
  - Stack performance stable
TASK 7

Power Module Design

• 12 systems designed and analyzed
  – Categorized into 4 groups

• All systems designed for 400 kW net AC and $\eta \geq 60\%$ (LHV)

• Heat-up and power ramp studies were performed

• Conceptual design decisions based on
  – Customer value drivers: Cost, Efficiency, Reliability, Operability
  – Technology Readiness Level (TRL) for critical components: Blowers, HEX, Desulfurizer

• Design decisions driven by
  – System design simplification
  – Component interface conditions: Lower recycle blower inlet temperature, Improve desulfurization step, Meet stack interface conditions
COAL-GAS POWER MODULE

Design Features:
- Simplified FPS
- Fuel recycle for efficiency and fuel pre-heat
- Anode HEX for lower blower temp, pre-heat coal gas
- Cat burner for emissions management and air pre-heat

Key Power Module Requirements

<table>
<thead>
<tr>
<th>Net AC power</th>
<th>System electrical efficiency (LHV of CG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 [kW]</td>
<td>60.3 [%]</td>
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</table>

<table>
<thead>
<tr>
<th>Cell voltage</th>
<th>Stack inlet temperature</th>
<th>Stack outlet temperature</th>
<th>Single pass fuel utilization</th>
<th>Overall fuel utilization</th>
<th>Steam/Carbon at anode inlet</th>
<th>Anode exhaust recycle ratio</th>
<th>Recycle blower inlet temperature</th>
<th>Stack oxygen utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 [mV]</td>
<td>700 [°C]</td>
<td>825 [°C]</td>
<td>80.0 [%]</td>
<td>90.0 [%]</td>
<td>2.0 [-]</td>
<td>55.8 [%]</td>
<td>193 [°C]</td>
<td>27.1 [%]</td>
</tr>
</tbody>
</table>

Simulation results of CG system start-up
## POWER MODULE CONCEPTS

Preliminary Concept Down-select

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (η ≥ 60% (LHV))</td>
<td>Integrated FPS-CB with Anode Recycle</td>
<td>Integrated APS-CB with Anode Recycle</td>
<td>Integrated APS-CB with Anode and FPS Recycle</td>
<td>Integrated APS-CB-Boiler with Anode and FPS Recycle</td>
</tr>
<tr>
<td>Reliability (Relative Scale)</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>Operability (Relative Scale)</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>Cost (&lt;700 $/kWe)</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
<td>Yellow</td>
</tr>
<tr>
<td>TRL (&gt; TRL6)</td>
<td>Red</td>
<td>Red</td>
<td>Red</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

FPS – Fuel Processing System; APS – Air Processing System; CB – Catalytic Burner
IGFC SYSTEM DESIGN

• 3 system concepts designed and analyzed
  – Atmospheric SOFC/ST system with air blower
  – Atmospheric SOFC/ST system with gas turbine
  – Pressurized SOFC/ST system with gas turbine

• All concepts designed for 100 MW net AC power, $\eta \geq 50\%$ (HHV), and $\geq 90\%$ carbon capture
Atm. SOFC/ST/GT - Performance Comparison

<table>
<thead>
<tr>
<th>Atmospheric</th>
<th>SOFC/ST U_{f,p} = 80%</th>
<th>SOFC/ST/GT U_{f,p} = 80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Efficiency* [%, HHV]</td>
<td>51.0</td>
<td>57.0</td>
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<tr>
<td>Net AC Power [MW]</td>
<td>108.0</td>
<td>122.0</td>
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<tr>
<td>SOFC AC [% gross]</td>
<td>87.7</td>
<td>80.0</td>
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<tr>
<td>Steam Cycle [% gross]</td>
<td>9.0</td>
<td>5.7</td>
</tr>
<tr>
<td>Coal-gas Expander [% gross]</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td>Gas Turbine [% gross]</td>
<td>—</td>
<td>11.1</td>
</tr>
</tbody>
</table>

**Model Assumptions**
- Cell voltage = 0.8V/cell
- Per pass fuel utilization = 80%
- Overall fuel utilization = 90%
- Inverter efficiency = 97%
IGFC POWER BLOCK DESIGN

IGFC Performance – Sensitivity Analysis

- 1-D sensitivity analyses performed with key system parameters
- 3 IGFC designs meet DOE requirements over broad range of parameters
- Studied operating variables to be modified to maintain performance
FUTURE WORK

Phase II

• Continue cost reduction of stack and power plant components

• Design high power stack module utilizing results of stack array testing

• Focus on system development leveraging existing stationary platforms

• Develop breadboard to test power plant components at 25 kW scale

• Demonstrate scalable 100+kW power plant
Thanks to Shailesh Vora, Joe Stoffa, Briggs White, and Heather Quedenfeld of the DOE for their support and technical guidance.
BACKUP SLIDES
PHASE I OBJECTIVES

Task 6
- Design, build and commission a test stand capable of testing SOFC stacks up to 50 kW
- Complete 1500 hours of stack module operation

Task 7
- 250-1000kW power module design
- 5MW proof of concept design
- IGFC system development
GEN 4 STACK MAXIMUM POWER CELL PERFORMANCE

Fuel: 23.79%H2-46.9%CO2-11.95%CH4-17.36%H2O    Flows: 201.9(A) 800(C)
Stack RU Voltages for Constant Current Test