SECA Objectives

• Reduce SOFC-based electrical power generation system cost to ≤ $400/kWe (2002 dollars) for a >100MW Integrated Gasification Fuel Cell (IGFC) power plant, exclusive of coal gasification and CO$_2$ 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 CO$_2$ 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
UTC Power
Markets: Buildings & Transportation

A world leader in developing and producing fuel cells that generate energy for buildings and transportation.
Stationary Fuel Cell Solutions

Successful track record around the world

56,573 hrs
10,793 MWHRS
Chevron
San Ramon, CA

56,359 hrs
6,321 MWHRS
District Heating works
Halle, Germany

61,040 hrs & 57,640 hrs
11,897 MWHRS 11,033 MWHRS
Casino
Uncasville, CT

61,950 hrs
11,457 MWHRS
Hospital
Bocholt, Germany

51,277 hrs
9,141 MWHRS
Seiko Epson Ina Works
Ina, Japan

54,694 hrs
3,752 MWHRS
Huis Ten Bosch
Sasebo, Japan

51,931 hrs
9,521 MWHRS
Yokohama Sewage Plant
Yokohama, Japan

Fleet Leader
65,615 hrs
6,405 MWHRS
Toshiba
Houston, TX

56,321 MWHRS
Central Park Police Station
New York City, NY

200 kW systems
Stationary Fuel Cell Solutions

400 kW PureCell® system advantages

- 400 kW electric output
- Natural gas
- 42% electrical efficiency*
- 1.7 MMBtu/hr heat output†
- Up to 90% system efficiency
- Designed to meet CARB 2007 standard‡
- 20-year powerplant life**
- “Dual Mode” capability
- Modular approach for MW-size applications

* At beginning of life
** With overhaul at end of year 10
† ~ 500 kW
‡ California Air Resources Board 2007 emissions standard
Driving Global Innovation-
In Close Collaboration with Our Customers

Key Global Technical Centers

- Detroit, USA
- Bascharage, Lux.
- Krakow, Poland
- Juarez, Mexico
- Shanghai, China
- Bangalore, India
- São Paulo, Brazil

24 Technical Centers ■ 21 Countries ■ 16,000 Scientists & Engineers
Core Innovations = Future Possibilities

Core Automotive Markets
- Electrical/Electronic Architecture
- Electronics & Safety
- Powertrain Systems
- Thermal Systems
- Aftermarket

Adjacent Markets
- Residential/Commercial Heating and Cooling
- Commercial Vehicles
- Military/Aerospace
Delphi: Committed to Innovation and Excellence

- Superior Engineering and Systems Integration
- Leading-Edge Technology
- Quality Products and Services
- World-Class Customer Support
- Global, Precision Manufacturing Capabilities
- Collaborative Innovation
- Award Winning Performance

Safe.

Green.

Connected.
Technical Capabilities

Physical Sciences...
- Chemical engineering
- High temperature materials
- Materials analysis
- Applied mechanics

Thermal & Fluid Sciences...
- Acoustics
- Combustion
- Applied fluid dynamics
- Thermal management

Systems...
- Cyber physical systems
- Control modeling
- Embedded intelligence
- Decision support
- Power electronics
• Phase I Accomplishments Summary

• System concepts & stack design integration
  – 250-1000kW Power Module
  – IGFC concepts
    • Atmospheric SOFC/ST
    • Atmospheric SOFC/GT/ST

• Verification testing
  – 50kW Test Stand
  – Test of Delphi ≥ 25kW stack
Phase I Accomplishments Summary

- Completed the detailed design, including an FMEA and Hazard Analysis, of a Test Stand capable of testing stacks up to 50 kW
- Procured all major components, including the fully completed fluid skid, and initiated the final assembly of the 50kW Test Stand
- Completed an initial downselect of the 250-1000 kW SOFC Power Module operating on pre-reformed natural gas
- Developed a conceptual design for atmospheric IGFC systems with an SOFC/GT/ST cycle achieving 57 percent (HHV) efficiency
250-1000kW Power Module

- Developing systems based on
  - Cost
  - Efficiency
  - Reliability
  - Operability

Value proposition for customers
• Efficiencies > 60% (LHV)
  – Largely invariant when operated at reduced load
- Catalytic gasification: High cold gas efficiency & methane content
- Oxygen generation via cryogenic distillation (ASU)
- Sulphur removal via Selexol or warm-gas clean-up
- CO₂ separation via oxy-combustion
• Systems of increasing sophistication and efficiency have been developed
  – Atmospheric SOFC with Steam Turbine Cycle
  – Atmospheric SOFC with Gas and Steam Turbine Cycle
  – Pressurized SOFC with Gas and Steam Turbine Cycle
• Steam cycle with reheat: [1800 psig, 1050°F]
• Gas turbine: Modified P&W FT-8 at 5 atm
• Heat recovery unit maximizes re-use of waste heat from cathode exhaust and oxyburner
  – Steam generator, re-heater
  – Cathode pre-heat
  – Indirectly heated gas turbine
IGFC Power Block Design

Atmospheric SOFC/ST

<table>
<thead>
<tr>
<th></th>
<th>$U_{f,p} = 70%$</th>
<th>$U_{f,p} = 80%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC AC power [MW]</td>
<td>106.6</td>
<td>106.6</td>
</tr>
<tr>
<td>Steam cycle net power [MW]</td>
<td>16.3</td>
<td>9.7</td>
</tr>
<tr>
<td>Expander power [MW]</td>
<td>9.7</td>
<td>8.1</td>
</tr>
<tr>
<td>Total produced power [MW]</td>
<td>132.5</td>
<td>124.4</td>
</tr>
<tr>
<td>Air blower [MW]</td>
<td>-1.7</td>
<td>-1.9</td>
</tr>
<tr>
<td>Recycle blower [MW]</td>
<td>-1.9</td>
<td>-2.1</td>
</tr>
<tr>
<td>Refrigeration [MW]</td>
<td>-0.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>Cooling [MW]</td>
<td>-1.8</td>
<td>-1.7</td>
</tr>
<tr>
<td>Parasitic ASU [MW]</td>
<td>-8.0</td>
<td>-5.9</td>
</tr>
<tr>
<td>Parasitic other [MW]</td>
<td>-1.6</td>
<td>-1.5</td>
</tr>
<tr>
<td>Total parasitics</td>
<td>-15.7</td>
<td>-13.6</td>
</tr>
<tr>
<td>Net AC Power [MW]</td>
<td>116.9</td>
<td>110.8</td>
</tr>
<tr>
<td>Coal massflow (dry) [kg/h]</td>
<td>27511</td>
<td>25005</td>
</tr>
<tr>
<td>Gross coal input power [MW]</td>
<td>233.3</td>
<td>212.1</td>
</tr>
<tr>
<td>IGFC efficiency [HHV %]</td>
<td>50.1</td>
<td>52.2</td>
</tr>
</tbody>
</table>
IGFC Power Block Design

Atmospheric SOFC/ST

Gasifier

Coal Feed
233.3

Raw Coal Gas
207.8

Clean Coal Gas
204.2

Sulfur Removal 3.6

Gasifier Loss 25.5

AGR

Expander 9.7

Turbine 16.3

SOFC DC
109.9

Clean Coal Gas

SOFC AC
106.6

Waste Heat 71.7

Parasitics

Cooling 2.4

AGR 1.6

ASU 8.0

Blower 4.0

Parasitics

Net AC
116.9

Efficiency (HHV)
- 50.1% net
- 56.8% gross

SOFC AC
106.6

Gross AC
132.5

Inverter 3.3

UTC Power
A United Technologies Company
Gas turbine integration offers significant efficiency gain

<table>
<thead>
<tr>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC AC power [MW]</td>
</tr>
<tr>
<td>FT8 net power [MW]</td>
</tr>
<tr>
<td>Steam cycle net power [MW]</td>
</tr>
<tr>
<td>Expander power [MW]</td>
</tr>
<tr>
<td>Total produced power [MW]</td>
</tr>
<tr>
<td>Recycle blower [MW]</td>
</tr>
<tr>
<td>Refrigeration [MW]</td>
</tr>
<tr>
<td>Cooling [MW]</td>
</tr>
<tr>
<td>Parasitic ASU [MW]</td>
</tr>
<tr>
<td>Parasitic other [MW]</td>
</tr>
<tr>
<td>Total parasitics</td>
</tr>
<tr>
<td>Net AC Power [MW]</td>
</tr>
<tr>
<td>Coal mass flow (dry) [kg/h]</td>
</tr>
<tr>
<td>Gross coal input power [MW]</td>
</tr>
<tr>
<td>IGFC efficiency [HHV %]</td>
</tr>
</tbody>
</table>
## IGFC Power Block Design

### Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOFC/ST $U_{f,p} = 70%$</td>
<td>SOFC/ST $U_{f,p} = 80%$</td>
<td>SOFC/GT/ST $U_{f,p} = 80%$</td>
</tr>
<tr>
<td><strong>Net Efficiency</strong> [% HHV]</td>
<td>50.1</td>
<td>52.2</td>
<td>57.2</td>
</tr>
<tr>
<td><strong>Net AC Power</strong> [MW]</td>
<td>116.9</td>
<td>110.8</td>
<td>122.0</td>
</tr>
<tr>
<td><strong>SOFC DC</strong> [% gross]</td>
<td>80.4</td>
<td>85.7</td>
<td>80.1</td>
</tr>
<tr>
<td><strong>Steam Cycle</strong> [% gross]</td>
<td>12.3</td>
<td>7.8</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Coal-gas Expander</strong> [% gross]</td>
<td>7.3</td>
<td>6.5</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Gas Turbine</strong> [% gross]</td>
<td>—</td>
<td>—</td>
<td>11.2</td>
</tr>
</tbody>
</table>

### Model Assumptions

- Cold gas efficiency = 89.1%
- Steam turbine efficiency** = 34.3%
- Gas turbine efficiency = 85%
- Inverter efficiency = 97%

---

* Efficiency includes CO$_2$ separation (but not compression) parasitics

** Based on utilized heat. Based on available heat, efficiency is 19.6%
50kW Test Stand

Capabilities

• Fully automated, lights-out operation

• Provide anode gases up to
  – 50 kW using coal syngas, or
  – 30 kW using 50%/50% H₂/N₂
    • 70% fuel utilization and up to 775°C
  – 5000 sl/min cathode air up to 775°C and -40°C dewpoint

• Provide loads up to 60 kW
  – Up to 400 amperes
  – Up to 600 volts

• Recuperate up to 52 kW cathode energy
50kW Test Stand

Test Facility
50kW Test Stand

Test Facility
50kW Test Stand

Test Room

- Test Article (in Hot Box)
- Cathode Heater
- Cathode Recuperative Heat Exchanger
- Anode Constituent Heaters (obscured)
- Anode Supply
- Anode Exhaust
- Cathode Exhaust
- Test Article Room (doors not shown)

Piping, heat exchanger and heater insulation not shown
50kW Test Stand

Test Room
Test of Delphi ≥ 25kW Stack

- Comprises four 40-cell stacks using the Gen 4 cassette
# Verification Testing Goals

## PHASE I MINIMUM REQUIREMENTS

**SECA Coal-Based Systems**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DELIVERABLE POWER RATING</strong></td>
<td>$\geq 25kW$</td>
</tr>
<tr>
<td><strong>COST (fuel cell system, 2002 dollars)</strong></td>
<td>$400 / kW$</td>
</tr>
<tr>
<td><strong>STEADY STATE TEST</strong> (Normal Operating Conditions)</td>
<td>$\Delta$ Power $&lt; 2.0%$ degradation/1000 hours</td>
</tr>
<tr>
<td><strong>TEST SEQUENCE</strong></td>
<td>1) Start-up</td>
</tr>
<tr>
<td></td>
<td>2) Peak Power Test</td>
</tr>
<tr>
<td></td>
<td>3) Steady State Test</td>
</tr>
<tr>
<td></td>
<td>4) Shut-down</td>
</tr>
<tr>
<td><strong>TEST DURATION</strong></td>
<td>5000 hours (1500 hours in Phase I)</td>
</tr>
<tr>
<td><strong>FUEL TYPE</strong></td>
<td>Simulated (subject to DOE concurrence, up to 25% CH$_4$, dry basis)</td>
</tr>
</tbody>
</table>
Outline

• Summary Highlights

• Cells
  – Scale up
  – Cell microstructure
  – Process improvements
  – DFMEA-based accelerated test development
  – Cathode development

• Gen 4 and Gen 3 stacks
  – Electrochemical performance of Gen 4
  – Comparison of Gen 4 performance data to Gen 3 data
  – Stack voltage tracking run chart

• Durability
  – Constant current durability test
  – Thermal cycling
  – Stack tested with real hydrocarbon fuel reformate
Performance Highlights Summary for SECA Coal Based System Stack Development

- Continued scale up of cells from 105 cm$^2$ (active area) cells to 403 cm$^2$ without increasing cell thickness for Gen 4 stacks
- Expanded cell and stack fabrication and testing capability for large footprint Generation 4 stacks
- Fabricated and tested Gen 4 stacks
- Completed design for 25 kW SECA Phase 1 test article
- Demonstrated 5kW Gen 4 stack module
  - Produced 5064 Watts (506 mW per cm$^2$) @ 0.81 Volts per cell
  - Fuel = 48.5% H$_2$, 3% H$_2$O, rest N$_2$
- Developed low cost, high volume manufacturable processes for Gen 4 stack components – stamping, laser welding
- Demonstrated greater than 8000 hours continuous durability in Gen 3.2 stack
- Demonstrated 200 thermal cycles in Gen 3.2 stack
Delphi SOFC Unreduced Cell Microstructure

- Gen 3.2 cell footprint is 140 mm x 98 mm (105 cm² active area)
- Gen 4 cell footprint is 300 mm x 158 mm (403 cm² active area)

Cathode: LSCF (~30 µm)
Interlayer: Ceria Based Layer (~4 µm)
Electrolyte: 8 mol. YSZ (~10 µm)
Active Anode: NiO – YSZ (~10 µm)
Bulk Anode: NiO – YSZ (~500 µm)
Cell Process Engineering Achievements Using Quality Tools

• **Design for Six Sigma – Includes Functional Modeling, Axiomatic Design, FMEA, Designed Experiments**
  - Optimized cell firing techniques to improve cell electrochemical performance by about 7%
  - Implementing cell manufacturing processes that reduce raw material costs by about 35% and capital investment by about 60%
  - Devised improved lamination method that incorporated high volume manufacturing process, significantly reducing lamination cycle time
  - Developed optimized process strategy for controlling screen printed thick film cell layers
  - Developed cell to retainer seal material, process, and design approach using axiomatic design principles that increases durability and eliminates active degradation mechanisms

• **Shainin Red X – Strategy for Cell Defect Reduction**
  - Identified defect sources, elimination strategies currently under evaluation to increase first time quality
Develop DFMEA

Develop Validation Testing Plan to Address DFMEA Issues and Observations from Stack Testing

Develop Accelerated Testing to Address Failure Mechanisms Identified in DFMEA and Stack Testing
Cell Accelerated Degradation Testing

![Graph showing degradation cycles over Ohmic Impedance (mohm) for Old and Improved Cell Material Set and Architecture.](image)

Old Cell Material Set and Architecture

Improved Cell Material Set and Architecture
### Cathode Development

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Power (From Button Cell Performance Testing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>Standard</td>
</tr>
<tr>
<td>Cathode Improvement 1 (HPC1)</td>
<td>Typically &gt; 25% Higher Than Standard Cathode</td>
</tr>
<tr>
<td>Cathode Improvement 2 (HPC2)</td>
<td>Additional 20% Higher Than Cathode Improvement 1</td>
</tr>
<tr>
<td>Cathode Improvement 3 (HPC3)</td>
<td>Additional 10% Higher Than Cathode Improvement 2 in 4ppmv H₂S</td>
</tr>
</tbody>
</table>

#### Power density, (W/cm²)

- **750°C 50-50 H₂ in N₂ 0.7V**

- **HPC1**
- **HPC2**
- **Standard**

#### Time, (h)

- 0
- 5
- 10
- 15
- 20
- 25

- **Power density (W/cm²)**
  - 1.2
  - 0.8
  - 0.4
  - 0

- **HPC1**
- **HPC2**
- **Standard**
Seal and Interconnect Development

- Improvements in glass/ceramic seals and substrate coatings have demonstrated good results for repeating unit to repeating unit sealing in a stack
  - Coupon level testing has demonstrated higher shear strength and thermal cycling stability
  - Multiple stacks tested with the improved repeating unit to repeating unit seals confirmed improved thermal cycling capability with no measurable leakage in the seals

- Low cost coatings and interconnects have been developed and implemented in stacks
  - Coupon level tests have demonstrated stable and acceptable ASR
  - Tested for > 8000 hours in Gen 3.2 stack durability
  - Tested for thermal cycling
  - Process improvements ongoing
Gen 4 Stack

- Delphi is developing its Generation 4 stack with larger footprint cell
- Key stack features are:
  - 4x active area increase
  - Very low pressure drop (less than 4kPa, anode and cathode)
  - Laser welded cassette repeating unit configuration
  - Stamped metallic cassette components including interconnects
  - Reduced part count
  - Low cost, conventionally processed balance of stack components
Gen 4 Stack

- Gen 4 stack fabrication ongoing for meeting SECA requirements
• 25-cell Gen 4 stack demonstrated predicted power density
  – Produced 5.064 kW (506 mW per cm²) @ 0.81 Volts per cell with 48.5% H₂, 3% H₂O, rest N₂
  – Data shows comparison of Gen 3.2 and Gen 4 electrochemical performance
Gen 4 Stack Performance

- Fuel utilization evaluation has demonstrated good results
- Current density of 600 mA per cm$^2$
- Fuel 48.5% H$_2$, 3% H$_2$O, rest N$_2$
  - Data below shows minimal lowering of power density up to 85% utilization
  - Data shows a power density of 403 mW per cm$^2$ at 70% fuel utilization
- Gen 3.2 stacks is our baseline platform for evaluation of technology and components as we scale up Gen 4 fabrication
- Improvements in design and process parameters have led to consistent performance in stack to stack builds – translates to lessons learned for Gen 4
Gen 3.2 30-Cell Stack Durability

- Fuel = 48.5% H2, 3% H2O, rest N2; current = 333 mA per cm²
- > 8200 hours, continuing to run
- Total degradation is 1.20% per 500 hours
- Degradation after initial lowering of power and stabilization is 0.66% per 500 hours
- Implementing solution to mitigate initial lowering of power
Thermal Cycling

- Gen 3.2 30-cell stacks evaluated for thermal cycling with improved seals
- 200 thermal cycles demonstrated with minimal degradation
  - 2 hour heat-up
  - Performance evaluated at each thermal cycle
  - Constant current load of 285 mA per cm² at operating temperature
  - Fuel of 48.5% H₂, 3% H₂O, rest N₂
Stack tested with real hydrocarbon reformate

- Gen 3.2 5-cell stack evaluated with real reformate based on different O:C mapping from hydrocarbon fuel reforming
- 1000+ hours on actual hydrocarbon fuel reformate (20% H₂, 24% CO, 7% H₂O, 6% CO₂, rest N₂) at optimized operating conditions
- Voltages and pressure drop stable

Stack Voltage and Power Density for Constant Current Test

Fuel: Zero Sulfur Diesel Reformate with Simulated Recycle
Flows: Approx 10 slpm** (A) 25 (C)
Acknowledgements

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