Development Update on Delphi’s Solid Oxide Fuel Cell Power System

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Acknowledgements

Battelle

Pacific Northwest National Laboratory
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DELPHI
Fuel Cell Development Team

SECA

NETL
Outline

• Market Opportunities
• Systems Development
• Cell and Stack Development
• Reformer Development
• Cost Analysis
• Summary
SOFC Market Opportunities

- European micro –CHP & CHCP
  Natural Gas

- US Stationary – APU & CHP
  Natural Gas, LPG

- Commercial Power
  Natural Gas

- FutureGen Powerplant
  Coal Gas

- Heavy Duty Truck
  Diesel

- Recreational Vehicles
  Diesel, LPG

- Truck and Trailer Refrigeration
  Diesel

- US Military
  JP-8
Development Strategy

Each application adjusted for:
- Fuel Type
- Electrical Configuration
- Application Environment
- User Interface

Core
Fuel Cell
System Technologies
“Building Blocks”
- SOFC Stack
- Heat Exchangers
- Process Air
- Controls

Automotive
Military
Commercial Vehicle
Mobile Power
Stationary Power
Marine
Outline

• Market Opportunities
• Systems Development
• Cell and Stack Development
• Reformer Development
• Cost Analysis
• Summary
2002
Gen 2A (Level 0)
0.270 kW_{\text{gross}}

Control Cabinet

SOFHC Hot-Zone Module
Delphi Systems Developed During Phase I

- **Gen 2A**
  - 0.220 kW\(_{\text{gross}}\)

- **Gen 2B/2C**
  - 0.423 kW, 3.3% efficiency

- **SPU 1A**
  - 1.18 kW, 17% efficiency

- **SPU 1B**
  - 2.16 kW, 38% efficiency
SOFC System Mechanization

HIGH EFFICIENCY
INTERNAL REFORMING MODE

SOFC SYSTEM
Integration of SPU 1B SOFC System

2x30-cell SOFC STACKS

CATHODE AIR HEAT EXCHANGER

CPOX NATURAL GAS REFORMER
SPU 1B SOFC System

2x30-cell SOFC Stacks

Cathode Air Heat Exchanger

Recycle Cooler
SECA Phase I Test Plan

TYPICAL 24 HR CYCLE

Rated (Peak) Net Power Point
Normal Operating Condition (NOC) Point
Minimum NOC operating Point

24 HR CYCLE: STEADY STATE

(9) LOAD CYCLES

(1) FULL THERMAL CYCLE

TEST TIME=Tc

NP 1000
NP 1001

DELPHI
Delphi Phase I Demo System A Test
# Delphi Phase I System Performance

<table>
<thead>
<tr>
<th>System Metrics</th>
<th>Target</th>
<th>Set 2</th>
<th>Set 3</th>
<th>2 &amp; 3 Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Net Power</td>
<td>3 kW</td>
<td>2.08</td>
<td>2.16</td>
<td>4.24</td>
</tr>
<tr>
<td>System Efficiency (Peak)</td>
<td>35%</td>
<td>35.1%</td>
<td>38.9%</td>
<td>37.0%</td>
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<tr>
<td>Factory Cost</td>
<td>$800/kW</td>
<td></td>
<td></td>
<td>$767</td>
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<tr>
<td>Durability Test</td>
<td>1500 hours</td>
<td>4660</td>
<td>2240</td>
<td>&gt;1500</td>
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<tr>
<td>Temp Cycles</td>
<td>1 cycle</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Power Cycles</td>
<td>9 cycles</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Net Power Degradation</td>
<td>7% / 1500 hours</td>
<td>4.5%</td>
<td>10.1%</td>
<td>7.3%</td>
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<tr>
<td>Operational Availability</td>
<td>80%</td>
<td>99%</td>
<td>99%</td>
<td>99%</td>
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</tbody>
</table>
Delphi Phase I Durability Performance Demonstration System

![Graph showing power output over test time with specific events labeled: Stand Shut Down, Full Self, Thermal Cycle, and Station Shut Down. The graph illustrates the total net power (kW) over the Phase I test period.]
Delphi Phase I Durability Performance
SPU 1B – Set 2

Phase I Test Period
Continued Durability Testing

Thermal Cycle

Stacks Retired

Test Time (hours)

Power, kW
Delphi Team SECA Phase I Success

<table>
<thead>
<tr>
<th>SECA Phase I Goals</th>
<th>Delphi Demonstration Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>3 to 10 kW</td>
</tr>
<tr>
<td>Cost</td>
<td>&lt; $800/kW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>35 – 55%</td>
</tr>
<tr>
<td>Degradation</td>
<td>&lt;7%/1500 hours</td>
</tr>
</tbody>
</table>
Delphi SOFC Power System Operation at NETL

- Delphi SOFC Power System operated at NETL Test Facility in Morgantown, WV from May 2, 2006 through June 17, 2006
- Testing conducted at Normal Operating Condition of 1.0 kW, average net electrical output
- 610 hours of operation using methane
Outline

• Market Opportunities
• Systems Development
• Cell and Stack Development
• Reformer Development
• Cost Analysis
• Summary
Delphi is fabricating anode supported cells with LSCF cathode
- Current footprint is 140mm x 98mm (active area 105 sq cm)
- Currently producing ~80 cells per week
- A typical microstructure is shown below

**Microstructure Details:**
- **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)
Key process development for cells have included:

- Improved tape characterization, improvement of lamination parameters
- Electrolyte processing optimization (solids loading optimized)
- Bi-layer sintering operation development using Design for Six Sigma (DFSS) - significantly increased yields

Key focus on developing specification for materials, tapes and inks for high volume manufacturing – includes identifying and developing relationship with high volume manufacturing suppliers

Delphi is also exploring viability of manufacturing cells with larger footprints for application in large power plants for stationary markets
Long Term Stability of Cell Materials

- Button cell tests ongoing for materials development
- Stable performance from LSCF cathode based cell demonstrated
- No degradation in 1500 hours after initial stabilization

![Graph showing specific power vs. time with no degradation observed after initial stabilization.](image-url)
Coating Development for Interconnects

- Low cost coating being developed for Cr retention – data shown below on a button cell test with Crofer 22 sample (coated and uncoated) in the cathode environment.

![Graph showing power retention over time for different conditions.]

- Baseline (750°C, 0.7V)
- With low cost conductive coating (750°C, 0.7V)
- With uncoated Crofer
Effect of 1.0 ppm H₂S on Standard Cell

- Development ongoing to understand and minimize degradation mechanisms due to H₂S
- Data below shows lowering in power due to addition of 1ppm H₂S in hydrogen at 750°C
Generation 3.1 30-Cell Stack

- 30-cell modules are the building blocks for Delphi’s power systems
- These 30-cell modules were integrated into the system and operated to meet SECA Phase 1 targets
Generation 3.1 30-Cell Stack Data

*Power*
- Data below shows a 30-cell Generation 3.1 stack tested in the stack laboratory (furnace, no insulation)
- Produced max power of 2.62 kW (833 mW/cm²) @ 22.6 Volts with 48.5% H₂, 3% H₂O, rest N₂ (53 % utilization, measured anode outlet temperature: 800°C)
  - Current development ongoing to map cell temperature and optimize conditions for adequate internal cooling of stack for high power operation in systems
- Fuel utilization studies show a 30-cell stack producing 522 mW/cm² @ 75% utilization @ 0.8 V per cell, power density of 470 mW/cm² @ 85% utilization @ 0.8 V per cell
Cassette Variation in a 30-Cell Stack

- Consistent performance between cassettes in a 30-cell stack (@ 60 Amps, 48.5% H₂, 3% H₂O, rest N₂)
  - Voltage difference between best and worst cassette is 0.07 Volts
Post-Mortem Analysis of Stacks

- Focus is on understanding degradation and failure mechanisms from autopsy of stacks after long term operation in the system
- Key lessons learned on seals, interconnects and cell durability
- Picture below shows an optical micrograph of center slice of 30-cell stack prior to SEM examination.
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Delphi is developing reforming technology for Natural Gas, Gasoline and Diesel/JP-8 for SOFC applications

Two main designs are being developed:

- **CPOx Reformer**
  - Moderate efficiency
  - Simplicity of design
  - Not recycle capable

- **Recycle Based (Endothermic) Reformer**
  - High efficiency
  - Use of water in anode tailgas to accommodate steam reforming
  - Recycle capable
CPOx Fuel Reformer Durability on Systems Test – Reformate Composition

Data

- Average of H2
- Average of CO
- Average of CH4
- Average of H2O
- Average of CO2

Plot

Time on Test [hrs] by Set

- 6 set 2
- 9 set 3
- 1501
- 508 set 3
- 1516

Product Species Concentration [mol%]

Average of H2
Average of CO
Average of CH4
Average of H2O
Average of CO2

Time on Test [hrs] by Set

Set 1 Time on Test
Tubular Endothermic Fuel Reformer

Reformate Out

Cathode Tailgas Air

Anode Tailgas Fuel

Recycle

Ref Air

Fuel
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Delphi Factory Cost Analysis

- Establish a standard Bill of Material
- Perform Component Review Meetings (These meetings identify the differences between prototype and production intent designs)
- Identify and Document Assumptions and Justifications
- Submit Quote Request Forms through Delphi’s Supply Management Team for all purchased components
- Estimates were developed for all manufactured and assembled parts using Delphi’s extensive manufacturing experience
- Cost analysis audited by outside consultant
- Audited Phase I Cost Analysis submitted to SECA
Cost Breakdown by Subsystem

- Stack, 39%
- Balance of Plant, 33%
- System Integration, 15%
- Electronics and Controls, 8%
- Fuel Reformer, 5%
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Next Steps:

- SECA Phase II:
  - Conversion to Line Natural Gas with Fuel Desulfurizer
  - System integration of output power electronics including A/C inverter
  - Aggressive cost reduction and manufacturability improvement
  - Continued improvement in power, efficiency, and reliability
  - Diesel-fueled APU System Development
  - Improve thermal cycle capability of Stack and System
  - Meet Phase II targets
# SECA Phase II System Target Metrics

<table>
<thead>
<tr>
<th>Target Metric</th>
<th>Current</th>
<th>DOE/SECA Ph I (CONTRACT)</th>
<th>DOE/SECA Ph II (CONTRACT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Production&quot; Date</td>
<td>SPU 1B</td>
<td>2005</td>
<td>2005/2006</td>
</tr>
<tr>
<td>Fuel</td>
<td>Methane</td>
<td>Methane</td>
<td>Nat Gas</td>
</tr>
<tr>
<td>Net Rated Power kW</td>
<td>2.2</td>
<td>3-10</td>
<td>3-10</td>
</tr>
<tr>
<td>Fuel to Electric Efficiency (Peak) %</td>
<td>38%</td>
<td>35%</td>
<td>40%</td>
</tr>
<tr>
<td>System Start-Up Time (25C - 750C) min</td>
<td>180</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cycle Durability cycles</td>
<td>2</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Operation Life hrs</td>
<td>4660</td>
<td>1500*</td>
<td>1500*</td>
</tr>
</tbody>
</table>

* -1.5% / 500 hours  -2% / 500 hours  -1% / 500 hours