10kWe SOFC Power System Commercialization Program Progress

May 11, 2004
Boston, MA

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Manager Advanced Development
Cummins Power Generation
• Cummins Power Generation
• Cummins - SOFCo Team
• SECA Program Progress
  – System Design & Application
  – Cell and Stack
  – Hot Box
  – Balance of Plant
  – Controls & Power Electronics
Cummins Inc.

Power Generation

May 11, 2004
SECA Annual Workshop Boston
Cummins Power Generation
World Headquarters and Manufacturing
Minneapolis, Minnesota
Cummins Power Generation

Developing and manufacturing a wide range of power generation equipment...
Energy Solutions

- **Containerised Diesel & Gas GenSets**
  - 1005 to 2000 kW
  - 50 & 60 Hz prime & standby rating
- **Projects mainly 2 to 30 MW**
  - prime mover sales
  - turnkey solutions
  - O&M contracts
  - equity-based full servicing
  - financing
- **Key Drivers**
  - power availability (mainly off-grid)
  - power reliability (high-quality or critical)
  - price insurance/arbitrage
  - energy optimization
- **Customer Types**
  - industrial end-users
  - commercial/public-sector end-users
  - utilities
  - developers
  - energy service companies (ESCOs)
  - regional authorities/government
Small Scale Fuel Cell Applications and Fuels

- **Recreational Vehicle**
  - Diesel

- **Truck APU**
  - Diesel

- **Marine**
  - Diesel

- **Military**
  - Diesel

- **Residential DG**
  - Diesel

- **Commercial Mobile**
  - Diesel

- **Telecommunications**
  - Natural Gas or Propane
• Electronic controls
• Power electronics
• Fuel systems
• Air handling systems
• Noise and vibration
• System integration
• Manufacturing
• Marketing, sales, distribution

• Planar SOFC technology
• Reformer technology
• Material science
• Heat transfer
• Computational fluid dynamics
• Numerical modeling
• Multilayer ceramic manufacturing
## Progress to Plan

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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<tr>
<td>1</td>
<td>Product Profile Development</td>
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<tr>
<td>2</td>
<td>Develop Steady State Model</td>
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<tr>
<td>3</td>
<td>Develop Transient Model</td>
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<tr>
<td>4</td>
<td>Validate single cell test methodology</td>
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<tr>
<td>5</td>
<td>C1 Hot Box Mechanical Design Complete</td>
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<td>6</td>
<td>Deliver C1 reformer components to Hotbox</td>
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<tr>
<td>7</td>
<td>Fuel Cell Boost Hardware ready for application</td>
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<tr>
<td>8</td>
<td>Deliver C1 Hot Box to Cummins</td>
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<tr>
<td>9</td>
<td>C1 simulated fuel cell system test</td>
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<tr>
<td>10</td>
<td>Preliminary 15cm components available</td>
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<tr>
<td>11</td>
<td>Deliver 2 Power Cell Units for C1</td>
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<tr>
<td>12</td>
<td>C1 Prototype - stable steady state operation</td>
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<tr>
<td>13</td>
<td>Deliver C2 reformer components to Hot Box</td>
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<tr>
<td>14</td>
<td>C2 control system ready for application</td>
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<tr>
<td>15</td>
<td>Deliver C2 Hot Box to Cummins</td>
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<tr>
<td>16</td>
<td>C2 Control &amp; Power Electronics Integration</td>
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<tr>
<td>17</td>
<td>Start development testing on C2</td>
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<tr>
<td>18</td>
<td>Start DOE test sequence on C2</td>
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<td></td>
</tr>
<tr>
<td>19</td>
<td>Finish DOE test sequence on C2</td>
<td></td>
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</tr>
</tbody>
</table>
Commercial target: same size envelope as Diesel RV Genset

0.49 m³ (17.4 ft³)
Fuel Cell System Mock-Up
Fuel Cell System Mock-Up
Staged prototyping -- C1 and C2

**C1 Prototype**
- Development tool
- 10cm x 10cm cells
- 2 x 47 cell stacks
- Not packaged
- DC output
- Characterization testing
- Limited operating hours
- Operational June 2004

**C2 Prototype**
- Program deliverable
- 10cm x 10cm cells
- 4 x 70 cell stacks
- Integrated hot box assembly
- Power conditioning
  - Load sharing
  - 120VAC output
- Complete SECA test plan
- 1500+ operating hours
- Operational June 2005
SOFC Stack Technology

• “All-Ceramic” stack design
  – Cells and multi-layer interconnect are CTE matched
  – No ceramic-to-metal seal
  – No metal interconnect corrosion
  – Compatible with MLC manufacturing methods

• Co-flow design advantages
  – Improved temperature distribution
  – Simplified manifold and improved sealing
  – Improved reactant distribution

Co-Flow Multi-layer Ceramic (MLC) Interconnect
SOFC Stack Development

2002
Short Stacks
(2-5 cells)

- ASR ~ 2.5 ohm-cm²
- PD ~ 75 mW/cm²
- Power Deg > 20% / 500 hrs
- Fuel Utilization > 70%

2003
Medium Stacks
(20 cells)

- ASR ~ 1.5 ohm-cm²
- PD ~ 125 mW/cm²
- Power Deg < 4% / 500 hrs
- Fuel Utilization > 75%
SOFC Stack Development

Q1 2004
Tall Stacks
(45-50 cells)

- ASR ~ 1.5 ohm-cm²
- PD ~ 125 mW/cm²
- Power Deg < 4% / 500 hrs
- Fuel Utilization > 75%

Q4 2004
PCU (50-70 Cells)

- ASR < 0.75 ohm-cm²
- PD > 250 mW/cm²
- Power Deg < 2% / 500 hrs
- Fuel Utilization ~ 80%
SOFC Stack Scale-up

- Achieved acceptable short stack performance Q3 2003
- Began transition to tall stacks
  - Horizontal orientation for assembly and operation
  - New manifold arrangement
  - No change to sealing materials, current collector, or cell-to-interconnect contact materials
Tall Stack Development

• First build in early 2004
  – > 200 hrs operation on hydrogen with FU >70%
  – > 200 hrs operation with reformed natural gas with FU >75%

• Second test underway
  – Objective: Demonstrate C1 operating parameters (FU, air flow, etc)

• Two stacks for C1 prototype will be assembled in June
Performance Improvements

- Instrumented short stack allows isolation of contributions to stack resistance
- Significant non-cell contributions to stack ASR and power degradation eliminated
  - Non-cell ASR contribution reduced to < 0.2 ohm-cm²
  - Short stack power degradation reduced to < 3% / 500 hrs
2002 Short Stacks – Degradation Reduced

- Anode-to-interconnect contact largest contributor
- Implemented new anode contact ink
- Significant reduction in degradation rate
- Major non-cell contributor to degradation is now the cathode-to-interconnect contact

300 hr Relative Resistance

- Cell, 40%
- Anode-to-interconnect, 54%
- Cathode-to-interconnect, 1%
- Current collector, 4%

1000 hr Relative Resistance

- Cell, 68%
- Cathode-to-interconnect, 15%
- Interconnect, 4%
- Anode-to-interconnect, 1%
- Current collector, 4%
- Collector, 12%
Calculated average degradation from 0 to 1175 hours = 2.9% per 500 hours,
Initial ASR = 1.36 ohm-cm²
SOFC Cell Development

• 2002 cell development outcomes
  – Reached performance plateau with YSZ electrolyte-supported cells
  – Identified significant problem with integrity of co-fired cells

• 2003 cell development shifted to “dual path” approach
  – External sources for cells and cell technology
    • Baseline 3YSZ post-fired cell for stack development
    • Improved electrolyte-supported cell using ScSZ electrolyte
    • Anode-supported cells
  – Internal cell development focused on co-fired interconnect-supported cells
SOFC 2003 Cell Performance Progress

- Baseline 3YSZ electrolyte-supported cell for stack development
  - Stable, repeatable performance (ASR ~ 1.2 ohm-cm²)
- Evaluated ScSZ electrolyte-supported cells produced by SOFCo and several external sources
  - ASR = 0.7 – 0.8 ohm-cm²
  - Degradation exceeds target
- Evaluated anode-supported cells from external suppliers
  - ASR ~ 0.45 – 0.6 ohm-cm²
  - Degradation exceeds target
  - Limited short stack testing
- Work planned for 2004
  - Cooperative development working with suppliers to improve cell performance
  - Aggressive insertion of new cells into stack development
Driving ASR down

Single-Cell Performance Testing

- 3YSZ Electrolyte-supported
- ScSZ Electrolyte-supported
- Anode-supported

Graph showing the ASR (ohm-cm²) over time (hours) for different electrolyte-supported systems.
Manufacturing Status - Background

Interconnects
- Manufacturing processes established
  - Production moved to new facility in 2003
  - Over 450 interconnects produced YTD in 2004
- In-house prototyping demonstrated for 10 and 15-cm interconnects

Cells
- Developing commercial sources
  - 2 established
  - 1 under development
- SOFCo development work for improved performance
  - PNNL
  - NASA Glenn
Scale-up to 15 cm Interconnects

- Scale-up work began Q1 2003
  - No major problems
  - Current engineering processes applied
- Design engineering
  - Flow / channel common to 10 cm
  - Channel depth increased for delta P
  - Via density preserved
  - I/O manifolds scaled for flow
- Modeling
  - Parallel channel pressure modeled with AFT-FATHOM
  - Electro-chemical model being developed from 10 cm baseline (2 dimensional EZ-Thermal)
- Produced preliminary 15 cm prototype parts in December 2003
- Prototype parts available for short stack testing in October 2004
SOFC Stack Development - Summary

- **Stack Scale-up**
  - Successful scale-up to tall stack for C1
  - On track with 70-cell PCU for C2 (mid 2005)

- **Performance and Cost**
  - Significant reduction in non-cell contributions to stack ASR and degradation
  - Stack performance largely driven by cells
  - Dual path approach to evaluating anode-supported cells and advanced ScSZ electrolyte-supported cells
  - On track to meet Phase 1 performance targets
  - Achieving cost target = meeting performance targets + implementing low-cost materials
Fuel Processor Development

CPOX Propane/NG Reformer for 10 kWe SOFC System

• High capacity: 40 kW / liter
• Waterless
• Rapid start-up: < 1 minute
• Turndown ratio: > 5:1
• Lightweight, compact design
  - Weight < 2 kg
  - Volume ~ 0.25 liter
• Efficient reformer
  - 70% on LP
  - 80% on NG
Fuel Processor Success

- Scaled-up waterless CPOX meets performance goals
- Completed transition from LP to Natural Gas for SECA demonstration
- Reformer operated on natural gas for >2500 hrs at 1.5 kWe equiv
- Stack operated on NG reformate for >1800 hrs
  - Carbon free operation verified through post-test exams of stack and manifolding
  - No performance issues
### Natural Gas Reformer Status vs. Targets

<table>
<thead>
<tr>
<th>TARGET</th>
<th>CURRENT VALUE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>1 kWe</td>
<td>1.3 kWe</td>
</tr>
<tr>
<td></td>
<td>5 kWe</td>
<td>TBD (5-10 kWe)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complete for C1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On-going for C2</td>
</tr>
<tr>
<td>Reformer Efficiency</td>
<td>~88%</td>
<td>85 %</td>
</tr>
<tr>
<td></td>
<td>(at equilibrium)</td>
<td>67 %</td>
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<tr>
<td></td>
<td></td>
<td>High load, Low load</td>
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<tr>
<td>Slips (%) Methane C₂⁺</td>
<td>0</td>
<td>0.4 – 4.0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0 – 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₄ converted in SOFC stack</td>
</tr>
<tr>
<td>Turndown</td>
<td>5 : 1</td>
<td>4.3 : 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not an issue</td>
</tr>
<tr>
<td>Carbon Deposition</td>
<td>No</td>
<td>No issues</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No C deposits in stack after &gt;1,800 hrs test</td>
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<tr>
<td>Cost</td>
<td>$60/kW</td>
<td>On target</td>
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<tr>
<td></td>
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<td>Based on C1 experience</td>
</tr>
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</table>
## Fuel Flexible CPOX Design

**Fuel Design/Size**
- LP: 25mm D x 150mm L
- Natural Gas: 25mm D x 150mm L

### Operation
- **Feed Preheat**: 200°C (LP), 300°C (Natural Gas)
- **Turndown (% load)**: 100% to 20% (LP), 100% to 25% (Natural Gas)

### Performance
- **Fuel Conversion (%)**: 75 - 85 (LP), 90 - 98 (Natural Gas)
- **CPOX Efficiency (%)**: 65 - 72 (LP), 75 - 85 (Natural Gas)
- **H₂ + CO (Dry mole %)**: 40 - 45 (LP), 47 - 50 (Natural Gas)
- **H₂ / CO Ratio**: 1.2 (LP), 2.0 (Natural Gas)
- **Methane Slip (dry mole %)**: 0.5 - 2.0 (LP), 0.4 - 4.0 (Natural Gas)
- **C₂+ Slip (Dry mole %)**: 0 - 2.0 (LP), 0 - 0.04 (Natural Gas)
Fuel Conversion vs. Turndown

Conversion = \frac{[CO_2 + CO]_{product}}{[Fuel Carbon]_{in}}

Catalyst B with Natural Gas

Catalyst A with LP Gas
Reformer Efficiency vs. Turndown

Eff = \frac{[H_2 + CO]_{LHV}}{[Fuel \text{ In}]_{LHV}}

Catalyst B with Natural Gas

Catalyst A with LP Gas
C1 Development Unit

- Component and sub-system operation/control development
- Stack simulators utilized prior to stack installation
C1 Prototype in Cell 21 at CPG

- Ignition Control
- Exhaust
- Startup Burner
- Combustor
- Controls
- Hot Box
C2 Phase I Demonstration Unit

- Full thermal integration
- Prototype level packaging
- 4 x 70-cell (10 cm) stacks
- Hardware design nearing completion
- Long-lead hardware orders placed
- Overall size targets on track for APU product goal
  - 4-stacks
  - 85cm L x 64cm W x 41 cm H
Balance of Plant

• Balance of Plant concept translated into functional C1 systems
  – Components selected to meet the functional requirements
  – Functional checks completed on
    • Anode air and fuel supply systems
    • Cathode air supply and bypass subsystems
  – First operational testing of the C1 system with simulated stacks conducted 12/17/03
  – Test cell up-fit for fuel cell specific instrumentation, safety, and controls completed

• C1 analysis and experience will be factored into C2
Purpose of controls and power electronics

- Thermal and fluid management
  - Control stack average temperature.
  - Control temperature gradient across the stack.
  - Control flows to match current demand and fuel utilization

- Load management
  - Buffer required load power and fuel cell dynamics.
  - Ramped stack loading
  - Managed energy storage
BOP controls hardware architecture

• Controls hardware
  – Designed Q1-Q2 2003
  – Implemented Q3-Q4 2003

• Controls sited on CPG production master control unit (MCU) for development purposes
  – Adapts existing software platform and tools.

• Distributed architecture based on a CAN serial bus.
  – Provides flexibility in choice of actuators.
  – Simplified interface to power electronic controls.
SOFC Controls and Power Electronics

- Master Control Interface: Completed Q3 2003
- Master Control Unit: CAN Bus Implemented Q3 2003
- CAN Bus: Q3 2003
- CAN/O Modules: Completed Q2 2003
- Sensors & Actuators: Completed Q4 2003
- Power Electronics: Sensors/Actuators Completed Q4 2003
Balance of Plant Controls Hardware

- Cathode Blower
- Mass Flow Controls
- CAN I/O Modules
- MCI
- MCU
- Cathode Blower
- Mass Flow Controls
SOFC Controls and Power Electronics

Master Control Interface Board

• 11 Type K thermocouple channels.

• 11 filtered analog input channels.

• 7 discrete digital outputs, each rated to 7.5A.
Power Electronics Architecture

- Two options for Power Electronics architecture.
  
  - **Option 1** initially selected based on lowest cost
  
  - **Option 2** selection driven by control dynamics – cost impact reduced in parallel commercial project
SECA Program Progress -- Summary

- Matrixed development of all-ceramic cells and interconnects demonstrating progress consistent with Phase 1 targets
- First generation prototype on schedule consistent with product goals
- Parallel paths in place to evolve systems and components
- Demonstrated performance of CPOX reformer
- BOP, controls, and power electronics available to support system development
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