SECA
Solid Oxide Fuel Cell Program

Nguyen Minh

3rd Annual SECA Workshop
Washington, DC
March 21-22, 2002
Program Objective

• Overall objective
  – Demonstrate a fuel-flexible, modular 3-to-10-kW solid oxide fuel cell (SOFC) system that can be configured to create highly efficient, cost-competitive, and reliable power plants tailored to specific markets

• Approach
  – System approach
  – Development focus
    • High performance
    • Low cost
    • Reliability
    • Modularity
    • Fuel flexibility
SOFC System Concept

Honeywell

3rd SECA Workshop
March, 2002
Key System Features

• **SOFC**
  – High-performance reduced-temperature cells
  – Operation on light hydrocarbons
  – Tape calendaring manufacturing process

• **Fuel processor**
  – Low-cost, fuel-flexible fuel processor design
  – Catalytic process
  – Pre-reforming function

• **Other subsystems**
  – Integrated thermal management
  – Flexible control subsystem
**Program Features**

**Phase I**
- Key Technology Development
  - Design, Stack Development, Fuel Processing, Thermal Management, Controls/Sensors, Power Electronics

**Phase II**
- Technology Improvement and Cost Reduction
  - Improved performance, yields, efficiency
  - Enable increased manuf. automation
  - Design packaging

**Phase III**
- Advanced Materials/Processes
  - Enable full manuf. automation
  - Optimize packaging

- Field Test of Packaged System
- Market Analysis and Cost Estimates

**Selected Application for Phases II, III**
- Field Test of Packaged System for Selected Application
- Market Analysis and Cost Estimates
Phase I Work Elements

- System analysis
- Cost estimate
- Stack technology development
- Fuel processing
- Thermal management
- Control and sensor development
- Power electronics
- System prototype demonstration
Schematic of Method for Cost Estimation

1. Define System Identify Components
2. Establish Performance Specifications
3. Size Components
4. Identify BOP Suppliers/Manufacturers
5. Solicit Cost Information
6. Perform System Cost Estimation
7. Map Manufacturing Process
8. Design Stack, Fuel processor
9. Determine Production Rates
10. Calculate Costs

Vendors: Honeywell Businesses, Engineering Judgement

Costs:
- Raw Materials Cost
- Equipment Cost
- Labor Cost
- Facilities/Utilities Cost
- Assembly Costs
Key Assumptions

• Main system design assumptions
  – 5 kW stationary system operating on natural gas
  – Fuel processor as pre-reformer

• Key manufacturing assumptions
  – Production rate of 250 MW/year
  – Single plant located in Southwest
Cost Estimates

- Projected system cost when fully developed: $388/kW
- Stack Costs

![Cost Breakdown Diagram]

- Materials (50.5%)
- Equipment (18.7%)
- Labor (12.1%)
- Utilities (17.8%)
- Land & Building (0.9%)
System Concept

NOTES:
1. Optional liquid fuel feed for non-stationary applications
System Design and Analysis Approach

System Requirements
- Propose Conceptual Design
- Steady-state Model
- Assume Components & Performances
- Detailed Thermal/Transient System Model

Technology Base
- Design Components
- System Analysis
- Trade Studies

Conceptual System Definition
- Compare to Requirements
- Identify Gaps

Technology Gaps

System Definition

Technology Development
## Performance Estimates

<table>
<thead>
<tr>
<th></th>
<th>Stationary</th>
<th>Mobile</th>
<th>Military</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>Natural Gas</td>
<td>Gasoline</td>
<td>Diesel</td>
</tr>
<tr>
<td><strong>Stack</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage, V</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Utilization</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cell, kW</td>
<td>5.7</td>
<td>5.9</td>
<td>6.1</td>
</tr>
<tr>
<td>Net, kW</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net, %</td>
<td>40</td>
<td>33</td>
<td>30</td>
</tr>
</tbody>
</table>
Low Cost Manufacturing Process

- Fabrication process with tape calendering

- Multilayer electronics fabrication process
Thin Electrolyte Cell

Fracture Surface

LaMnO$_3$ Cathode
ZrO$_2$ Electrolyte
NiO/ZrO$_2$ Anode
Stack Configurations

- Thin film electrolytes
- Thin foil metallic interconnects
- Gas manifold options
- Gas flow configuration flexibility

Crossflow Design  
Radial Flow Design  
Unitized Cell Design
SOFC Performance

- 800°C operation
- Open circuit voltages in agreement with theoretical values
- Peak power density:
  - 1.3 W/cm² in hydrogen
  - 0.85 W/cm² in JP-8 syngas
High power densities (e.g., 0.9 W/cm² at 650°C) achieved at reduced temperatures (<800°C) with anode-supported thin-electrolyte cells
Cell Fuel Utilization

- Fuel: Hydrogen
- Oxidant: Air

75% Fuel Utilization, \( J = 1.72 \text{A/cm}^2 \)
Power Density = 1.1 \( \text{W/cm}^2 \)

80% and 85% markers on the graph.
Other Cell/Stack Accomplishments

- Demonstration of high cell performance (1.8 W/cm² at 800°C) with high utilization (50%)
- Operation of a stack module for more than 3000 hours
  - Identification and modeling of degradation rate
- Fabrication scaleup and improvement
Reforming Options

STEAM REFORMING
Fuel
Steam
Fuel Reformer
H$_2$, CO$_2$

PARTIAL OXIDATION
Fuel
Air
Fuel Reformer
H$_2$, CO, CO$_2$, H$_2$O, N$_2$

AUTOTHERMAL REFORMING
Fuel
Steam
Air
Fuel Reformer
H$_2$, CO, CO$_2$, H$_2$O, N$_2$
Fuel Processing Approach

• Fuel processor as a pre-reformer for hydrocarbon fuels
• Approach: Catalytic partial oxidation (CPOX) as baseline and process modifications as required for different types of fuels
CPOX for Processing Hydrocarbon Fuels

- Fuels: propane, butane, octane, JP-8, and diesel
- Duration: 700 hours to date
- Thermal cycles: 10
- Sulfur tolerance: 1000 ppm dibenzothiophene in JP-8
- Yield: 70-80% of LHV in JP-8
Control System Functions

- Control system functionality drives integration
- Coordinate subsystems for shared resources and efficient operation
- Efficiently regulate over a wide operating range
  - Flow / Composition
  - Temperature
  - Pressure
  - Power
- Provide safe system operation through built-in test
- Perform process and component health monitoring for improved life cycle
- Provides user interface and automated system operation
  - Startup/Shutdown
  - Scheduled operation
  - Status indicators/alarms
  - Emergency Shutdown
Control & Sensing Approach

- Honeywell’s proprietary *Fuel Cell Dynamic Component Library* allows for rapid development of dynamic system models and prototyping of control systems through simulation.

- **Rapid prototyping** capabilities allow for direct transfer of controls designed in simulation to control of fuel cell system.

- **Advanced control and sensing** techniques can investigated through simulation trade studies and then the most promising approaches easily implemented in hardware system.
Controls Analysis and Design Process

Control Requirements Definition
- Model Development
- Subsystem Analysis
- Control Loop Analysis
- Cell Monitoring

Preliminary Control Design
- Simulation Based Design
- Assume Component Performance
- Controllability of System Addressed

Control Evaluation and Development
- Control Design Trade Studies
- Focus Control Design for Application
- Built-In Test and Health Monitoring
- Final Control Design for Phase I
- Develop Sensor Requirements
- Develop Actuator Requirements

Sensor and Actuator Evaluation
- Sensor Trade Studies
- Sensor Testing
- Actuator Trade Studies
- Actuator Testing

Sensor and Actuator Development
- Sensor Development
- Actuator Development

Control System Integration
- Rapid Prototyping System Implementation of Control Strategy
- Hardware Selection and Procurement
- Software Development
- Hardware/Software Implementation

“Design for Control”

Current Effort

System Design
- FMEA
- Event Ledger

3rd SECA Workshop
March, 2002
Concluding Remarks

- SECA SOFC system concept
- System features
  - High performance
  - Low cost
  - Flexibility
- Various activities to support system development