2005 DOE Hydrogen Program Review

150 kW PEM Fuel Cell Power Plant Verification

Tom Clark
UTC Fuel Cells
May 26, 2005

Project ID # FC46
Contract # DE-FC36-04GO14053

This presentation does not contain any proprietary or confidential information
Overview

Timeline
• Jan. 2, 2004  Start Date
• Dec. 31, 2009  End Date
• 20% Complete

Budget
• Total project funding
  – DOE share $11,617,821
  – Contractor share $10,165,096.
• Funding FY04 $1,337,306
• Funding FY05 $1,562,694

Barriers
• Components
  – O. Stack Material & Manufacturing Cost
  – P. Durability
  – Q. Electrode Performance
  – R. Thermal & Water Management
• Distributed Generation Systems
  – E. Durability
  – F. Heat Utilization
  – G. Power Electronics

Partners
United Technologies Research Center
• CT Light and Power
• EPRI
• Austin Energy
• New York Power Authority
• San Francisco Public Utilities Commission
Objectives

• The UTC Fuel Cells DOE Stationary Power Plant Program will resolve critical cell component, cell stack, and power plant reliability issues. Testing will be conducted in 20-cell stacks, and 150 kW power plants.

1. Improve PEM CSA durability to achieve lifetimes >40,000 Hrs
2. Verify reliability of low cost PEM cell stack components
3. Verify the Design, Durability, and Reliability of Natural Gas Fueled PEM Power Plant
4. Complete a Fuel Cell Stationary Power Plant Market Assessment
5. Waste Heat Thermal Integration Assessment
CSA Technology Approach

• Improve PEM CSA durability to achieve lifetimes > 40,000 hrs by:
  – Determine root cause and corrective action for high severity / frequent CSA failure modes
  – Develop a mathematical modeling to optimize inlet flow channel design for maximum humidification
  – Identify seal materials with chemical and mechanical stability in a fuel cell environment
  – Verify accelerated test conditions that demonstrate representative failure modes
  – Endurance verification of durability improvements

• Cost reduction of PEM CSA components by validating low-cost plate and UEA components
  – Performance in single cell tests and
  – Durability in 20-cell tests
CSA Technical Accomplishments

• Improved components and accelerated testing for CSA durability
  – Accelerated testing shows advanced reinforced membrane life-times of > 20-kh
  – Non-silicone materials for advanced designs down-selected
  – Seal accelerated testing suggests sealability maintained up to 40,000 Hrs

• Low cost component verification
  – Single cell performance verification of low cost plates and UEAs

• Endurance Testing
  – 11,500 hours on 20-cell stack with unreinforced membrane
  – 4,000+ hours on S900 20-cell stack
Seal Durability Accomplishment

Improved compression set resistance
15,000 → 43,000 hours

Interfacial gasket CSR

Fabrication Stress

Compressive stress, kPa

Normalized Compression Set

Time, hours

$k = A \exp\left(\frac{-E}{RT}\right)$

UTC Non-Proprietary
Membrane Durability Accomplishment

Cyclic accelerated testing

Reinf1  84~100 h
Reinf2  130 h
Reinf5  180 h

Unreinf  100 h
Reinf3  ~160 h
Reinf4  ~163 h

UTC Non-Proprietary
Endurance Demonstration Accomplishment

4.5-kh on S900 20-cell and 11.5-kh on N111 20-cell

S900

Unreinforced

UTC Non-Proprietary
Performance comparison

S900 H2Air_IV_8060
Load Calibration Comparison
Peak Load Hours

- H2/Air 80/60
- dry/dry
- Air Exit = 63 °C
- Coolant Flow = 400 ccm
- Coolant P = -14 kPa

Current Density (mA/cm²)
Cell Voltage (Volts)

X-811D
H2Air_IV_8060.xls
Run Began Fri, 10-08  11:47 am

UTC Non-Proprietary
UTCFC Non-proprietary
Power Plant Approach

- Verify the specification, durability, and reliability of natural gas fueled PEM power plant
  - Operate PEM Beta Stationary power plant as a 150 kW baseline
  - Dynamic Controls Testing
  - Use Beta Test Article Results as a Baseline for Next Generation Verification Design
  - **Compete Improved Integrated System Design for Reliability**
  - Construct and Evaluate a PEM-150kW that incorporates significant improvements in Power Plant Controls, Fuel Processor Design, Balance of Plant Components, and Grid Operation

- Complete a Fuel Cell Stationary Power Plant Market Assessment
  - Identify Market Segments, Drivers and Size
  - Identify Energy Credits and Incentives
  - Explore Domestic and International Opportunities

- Waste Heat Thermal Integration Assessment
  - Concepts,
  - Value Proposition Studies
  - Regional Needs Summary
P/P Accomplishments

• Demonstration Testing of Beta Power Plant
  – Multiple daily runs: Typical 1 to 4 hour runs
  – Controls tuned for hands off automatic startup
  – Achieved maximum power of 139 kW DC / 117kW AC Net.
  – CO performance from FPS less than 10 ppm
  – FPS thermal management optimized
  – Debugged subsystems and BOP (balance of plant) components
  – P/P Start time reduced to 25 minutes
  – Cathode Humidification/Energy Recovery Device Verified

• Dynamic Tests Completed & Data Collected.
  – Tests conducted on 8 major loops: Power, Cathode air, CPO fuel & air flows, Prox air & thermal, Vaporizer water, CPO air blower
  – Tests conducted at 2 power levels: 40 kW and 75 kW.
  – Excitations used are step, sine-sweep and PRBS (pseudo random binary signal)
  – Dynamic data acquired at 10 Hz from the controller via CANalyzer
Power Plant FPS Approach

• Design and test a Fuel Processor System (FPS) capable of delivering high purity $H_2 (> 90\%)$ to a PEM fuel cell

• Design FPS to resolve critical component durability and cost issues using UTCFC experience

• Design validation will be accomplished via a full scale (150 kW) integrated FPS test
FPS Design Approach

High Pressure Fuel Train

Start Burner

Steam System

Air Train

PrOx Assembly

CO₂ Membrane

PSA

Pd Membrane

WGS Assembly (ILS)

HDS Assembly (ILS)

Reformer Assembly

PC 25 Configuration

Non UTCFC Hardware

PC35 Configuration
FPS Accomplishments

• 4 FPS design concepts were evaluated
• Reformer design based on Catalytic Steam Reforming (CSR)
• Examined the impact of reformate clean-up
  1. CO₂ Membrane (CO₂ Separation)
  2. Pd Alloy Membrane (H₂ Separation)
  3. Pressure Swing Adsorption (PSA)
  4. Preferential Oxidation (PROX)
## FPS Concept Options

<table>
<thead>
<tr>
<th>Concept</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F PA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>4 bar</td>
<td>6 bar</td>
<td>10 bar</td>
<td>1 bar</td>
</tr>
<tr>
<td>CH₄ Conversion</td>
<td>90%</td>
<td>85%</td>
<td>75%</td>
<td>90%</td>
</tr>
<tr>
<td><strong>Purification</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td>CO₂ Membrane</td>
<td>H₂ Membrane</td>
<td>PSA</td>
<td>NONE - PROX</td>
</tr>
<tr>
<td>H₂ Purity</td>
<td>97% dry</td>
<td>&gt;99%</td>
<td>&gt;99.9%</td>
<td>78% dry</td>
</tr>
<tr>
<td><strong>CSA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSA Type – S900</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode Recycle</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Power Plant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPS Efficiency</td>
<td>73.9%</td>
<td>62.2%</td>
<td>73.9%</td>
<td>73.8%</td>
</tr>
<tr>
<td>Mech. Efficiency</td>
<td>97.0%</td>
<td>95.5%</td>
<td>94.9%</td>
<td>98.7%</td>
</tr>
<tr>
<td>CSA Efficiency</td>
<td>52%</td>
<td>52%</td>
<td>52%</td>
<td>51%</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>37.2%</td>
<td>30.8%</td>
<td>36.4%</td>
<td>37.0%</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>Membrane</td>
<td>Membrane</td>
<td>Reformer</td>
<td>CSA - Reformate</td>
</tr>
</tbody>
</table>
150 kW Conceptual Layout


CSR/PSA Concept (2006)

- WTS, TMS, APS, NG Compressor, Steam, Other
- PSS (S900 CSAs)
- HEX 400 (PC35)
- ECS/PCS (PC35)

Length (15.5 ft)

Length (20 ft)
## Fuel Cell Stationary Power Plant Market Assessment

### Market Segments/ Drivers

<table>
<thead>
<tr>
<th>Market Drivers</th>
<th>Segments / Applications</th>
</tr>
</thead>
</table>
| Economic                      | **Commercial** • ~ 3 year payback  
|                               | • Energy Savings  
|                               | • ~ 3 - 5 year payback  
|                               | **Utility** • ~ 3 - 5 year payback  
|                               | • Lost productivity costs (varies)  
|                               | • Up to 10 year payback  
|                               | • US Military bases  
|                               | **Industrial** • Longer paybacks possible  
|                               | • Municipal ADG  
|                               | **Government** • Longer paybacks possible  
|                               | • Municipal buildings  
|                               | **Commercial** • ~ 3 year payback  
|                               | • Energy Savings  
|                               | **Utility** • ~ 3 - 5 year payback  
|                               | • Lost productivity costs (varies)  
|                               | • Up to 10 year payback  
|                               | • US Military bases  
|                               | **Industrial** • Longer paybacks possible  
|                               | • Municipal ADG  
|                               | **Government** • Longer paybacks possible  
|                               | • Municipal buildings  

### Combined Heat & Power (CHP)

- Assured Power
- • Power Supply
- • T & D Upgrade Avoidance
- • Conventional
- • Specialty (H2)

### Economic

- • Large power requirements (1+MW)
- • High power density
- • Low Emissions

### Technical

- • Emissions / Noise
- • Heat Quality
- • Footprint
- • Reliability
- • Multi MW needs

### Regulatory / Other Factors

- • Availability of Incentives /Subsidies
- • Utility Interconnection rules/tariffs
- • State PUCs RPS Standards
- • Costs captured in regulated base
- • Grid Constraints

UTCFC Non-proprietary
Accomplishments

Fuel Cell Stationary Power Plant Market Assessment

– Domestic US Market
  • Direct Generation
  • Renewables (ADG)
  • On-Line Emergency Power
  • Assured Power
  • Micro-grid Power
  • Green Power / Cogeneration

– International Market Opportunities
  • **Germany**
    – Nuclear Power Phase out
    – Reduce CO2 Emissions Reduction levels by 25%
    – German Energy Agency Promoting (DENA) Renewable Fuels
    – CHP Incentives for Operators
  • **Korea**
    – Government Focus on Fuel Cells
    – Government Looking to Move to H2 Economy
  • **China**
    – Pollution-7 of 10 most polluted cities are in China
    – 10% of World Energy Consumption
## Accomplishments

### Fuel Cell Power Plant Market Assessment

### Identified Energy Credits and Incentives

<table>
<thead>
<tr>
<th>State</th>
<th>Program Description</th>
<th>Rate</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA SGIP – Level 1 Renewable</td>
<td>$4.50 / W</td>
<td>$900,000</td>
<td></td>
</tr>
<tr>
<td>CA SGIP - Non-Renewable</td>
<td>$2.50 / W</td>
<td>$500,000</td>
<td></td>
</tr>
<tr>
<td>CA LADWP – Renewable Fuel</td>
<td>$2.20 – 2.40 / W</td>
<td>$440,000 - $480,000</td>
<td></td>
</tr>
<tr>
<td>CA LADWP – Non Renewable</td>
<td>$1.20 – 1.90 / W</td>
<td>$240,000 – 380,000</td>
<td></td>
</tr>
<tr>
<td>CT CT Project 100</td>
<td>10 Year contract for 5.5 cents/kwhr + wholesale pricing</td>
<td>Must be 1MW project</td>
<td></td>
</tr>
<tr>
<td>DE Green Energy Program Grant - Renewables</td>
<td>Lesser of 50% cost or $250,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NJ Clean Energy Program - Renewables</td>
<td>$360,000 - $855,000</td>
<td>Formula dependent on product size (100 kW – 1 MW)</td>
<td></td>
</tr>
<tr>
<td>NJ Renewable Energy Advanced Power Program</td>
<td>20% of total construction cost</td>
<td>Minimum of 1MW in size. Undergoing revisions, new solicitation in summer 2005</td>
<td></td>
</tr>
<tr>
<td>MD Corporate Tax Credit – Both Renewable and non-Renewable</td>
<td>30% of installed cost, max of $1.00 / W</td>
<td>$200,000 – credit carry forward for 10 years</td>
<td></td>
</tr>
<tr>
<td>MA Commercial, Industrial &amp; Institutional Initiative (C31)</td>
<td>$3.00 - $4.50 / W</td>
<td>$650,000 or 50% of construction cost.</td>
<td></td>
</tr>
<tr>
<td>OR Business Energy Tax Credit</td>
<td>35% tax credit taken over 5 years</td>
<td>$350,000</td>
<td></td>
</tr>
</tbody>
</table>
Accomplishments
Power Plant Thermal Integration Study

Reviewed several thermal integration concepts, markets, regional aspects and evaluation methodologies to select **4 primary concepts, 5 markets and 8 regions for systematic evaluation** and identification of high value concepts

- **CHP Markets Identified:**
  - **Hospitals** - Chilling needs throughout the year and clean environment requirement
  - **Supermarkets** - Dehumidification needs
  - **Data Centers** - Requirements for reliable power and chilling needs
  - **Hotels** - Swimming pools would need dehumidification
  - **Labs/Clean rooms** - Reliable power and 24 hour conditioned air

- **Regions Selected:**
  - **San Francisco, Los Angeles, Chicago, Boston, New York City, Long Island, Miami Washington D.C.**
  - Density of Potential Customers
  - Spark Spread (Delta between Natural gas and Electrical costs)
  - Geographic Zones, Hot and Humid Areas
  - Areas with $ Incentives for CHP Applications
Project Future Work

• FY 2005
  – Continue to develop and demonstrate low cost, cell stack components with high durability and reliability
  – Design and manufacture of advanced seals
  – Performance verification of low cost plates and UEAs
  – Complete improved PEM stationary natural gas fueled power plant design based on Lessons Learned
  – Proceed with PSA system (Concept #3) as primary option unless further data from Concepts #1 and #4 suggest otherwise
    • Monitor technological progress as it relates to Concepts #1 and #4
    • Transition Concept #3 to the preliminary design phase
    • PSA purification technology
    • Complete Reformer development tasks
      ➢ Noble metal catalysts
      ➢ Modified tube structure
  – Finalize Thermal Integration study for the useful application of PEM power plant heat
Project Future Work

- FY 2006 – 2009
  - Validate PEM stack components and power plant design concepts in Field Evaluation Power Plant on Grid
  - Begin quantified accelerated testing of advanced membranes to show 40,000 hr durability
  - Continue 20-cell stack demonstration of long life stacks (15,000 Hrs).
  - Stack testing under accelerated, aggressive conditions for lifetime estimation and robustness.
  - Validate PEM power plant performance on feeder systems located in three areas of the U.S: Austin, TX; Albany, NY; and San Francisco CA.
  - Develop predictive base for PEM power plants on various distribution feeders
Backup Slides
Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

Hydrogen leakage within the power plant fuel compartment leads to explosion.

1. Requires multiple failures
2. Multiple layers of protection
3. Very low probability of occurrence
Our approach to deal with this hazard is based on CSA FC1, NFPA 496, and NEC:

1. Design equipment for pressure capability and leakage.
2. Actively monitor hydrogen flow to limit fuel leakage.
3. Ventilate the compartment to less than 25% LFL.
5. If necessary,
   - Monitor ventilation exhaust for combustibles
   - Fuel Compartment Fire Detection
   - Provide fail-safe isolation of hydrogen via multiple shutoffs and Normally-closed valves
Design Process for Safety

• Safety reviews of product design and product operation
  Codes and Standards, Hazard Analysis, FMEA, HazOps

• Layers of Protection Approach
  Passive, Active, Reactive Mitigations
  Ventilation, Monitoring of Fuel Enclosure, Fuel Interlocks,
  Selection of electrical components in Zone 2 areas

• Engineering change process applied
  Cross functional team members review and approve
  Functional verification of hardware/software changes
  Operating procedures under revision control
  Readiness reviews required for major changes, new equipment and chemicals. Highlights:
  » Hazards analysis and FMEA
  » Equipment functional checkout
  » Identification of preventative maintenance
  » Procedures and Energy Control
  » PPE assessment, training and communication