Atmospheric Fuel Cell Power System for Transportation

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Presentation Agenda

- Objective
- Technical Targets and Barriers
- Background/Approach
- Project Safety
- Program Schedule
- Technical Accomplishments/Progress
- Testing Progress
- Interactions and Collaborations
- Summary
- Future Challenges & Opportunities
Objective

To determine the feasibility of a on-board gasoline reforming 50 kW fuel cell power plant for commercial transportation applications based on the industry and DOE targets for commercialization.
Technical Targets and Barriers

*Develop a 45% efficient reformer-based fuel cell power system for transportation operating on clean hydrocarbon or alcohol-based fuel that meets emissions standards, a start-up time of 30 seconds, and a projected manufactured cost of $45/kW by 2010 and $30/kW by 2015*. 

- Transportation Fuel Processors Technical Barriers (3.4.4.2)*:
  
  I. Start-up/Transient operation
  J. Durability
  K. Emissions
  L. H2 Purification/CO clean-up
  M. Integration/Efficiency
  N. Cost

* Excerpts from: “Multi-Year Research, Development and Demonstration Plan, HFCIT, June 3, 2003”
S400 Gasoline FCPP Phases

- Development in Two Phases (FY02 - FY04)
  - Integrated Gasoline Fuel Processor (FY02 - FY03)
    - Gasoline in, fuel cell-quality reformate out
    - Data shown here
  - Integrated Fuel Cell Power Plant (FY03 - FY04)
    - Assembly completed
    - Started testing in December 2003
    - ANL to conduct verification testing June 2004
    - Available data and projections shown here
Approach

Current S400 Development 2001-2004

System Concept 2001:

Program Steps
2001: Down-select optimum system
2002: Fuel Processor Focus: Start Time, Controllability & Volume
2003: Power Plant Focus: Start Time Controllability, Emissions & Efficiency

FPS - Fuel Processor System
CSA - Cell Stack Assembly
BOP - Balance of Plant

PPIR 2003-2004
FP1 testing completed June 6, 2003

FP1 2002-2003
System Overview

Simple System Schematic

FPS - Fuel Processor System
CSA - Cell Stack Assembly
BOP - Balance of Plant
Project Safety

• Safety reviews of product and test equipment design, and of test processes
  – Codes and Standards, Hazard Analysis, FMEA, FTA, HAZOP

• Standards for Areas with Hazardous Fluids
  – Ventilation and Ventilation Monitoring
  – Gas detection and Fire Suppression
  – Selection of electrical components in potentially hazardous locations

• Out of Limits Conditions
  – Burner and reactor controls
  – Ground fault detection
  – High Temperatures and High Pressures
Project Safety – Safety Analyses

Potential Situations

Mitigation Approaches

Hazard Analysis (HA)

Resultant Events

Failure Modes of Parts and Process

Failure Mode and Effects Analysis (FMEA)

Events

Mitigation Approaches

Fault Tree Analysis (FTA)

Procedures

Operation Approaches

Reviewing Procedures for Hazardous Operation (HAZOP)

Analysis Risk Ranking

Likelihood

Very Likely

Extremely remote

Severity

Inconsequential

Severe

Corrective Actions Acceptable

Corrective Action Required

Special Approvals Required to Proceed

1 2 3 4 5

1 2 3 4 5

1 2 3 4 5
Project Safety – Management of Change

• UTC change process applied to product & test equipment
  – IPD team members review and approve
  – Safety Engineer involvement in IPD
  – Functional checkout of hardware/software changes

• Operating procedures under revision control

• Readiness reviews required for 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
Two Lessons Learned Examples:

- **Gasoline Heater Control Failure**: Failed solid state relay used for primary control of heater, secondary relays were part of sequential control instead of being continuous. Corrective action: change to continuous and adding further over-temperature redundancy.

- **Unintended Flow Path**: Failed active component creates unintended flow path, i.e. blower fails to start, other flows find unintended path. Corrective action: improved flow confirmation and backflow prevention.

Other Insights:

- Perform more safety analysis early in project design to identify and resolve safety issues.

- Off normal states used for engineering or diagnostic purposes can create challenges. Consideration of all operating states (start-up, shutdown, transitions and off-design) in safety analyses.
Accomplishments/Progress

Series 400 CPO-based FPS

• Benefits
  – No steam generator (smaller)
  – Fuel flexibility (Low sulfur gasoline, naphtha, diesel, F-T diesel, CNG, ethanol…)
  – Reformer durability on CA RFG II / III gasoline (desulfurization by UTC FC)
  – Faster start (lower mass) than ATR

• Start Time: 10 sec CPO ignition, ~5 min FPS
• Volume: 78L Packaged FPS
• Emissions: SULEV
• H₂ Production efficiency:
  ~75% FPS
## Accomplishments/ Progress – iFPS Results

### Summary of S400 FP1 Testing

**Performance Data versus Targets**

<table>
<thead>
<tr>
<th>Data</th>
<th>Target</th>
<th>FP1 Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPS Volume, liters</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td>Heat up time, s</td>
<td>165</td>
<td>171</td>
</tr>
<tr>
<td>Number of start/stops</td>
<td>500</td>
<td>111</td>
</tr>
<tr>
<td>Duration of operation (total hrs)</td>
<td>2000</td>
<td>232 hrs</td>
</tr>
<tr>
<td>- Longest single run, hrs</td>
<td></td>
<td>10 hrs</td>
</tr>
<tr>
<td>Range of equivalent power, kWe</td>
<td>10-50</td>
<td>10-50</td>
</tr>
<tr>
<td>LHV efficiency, % at rated</td>
<td>≥75</td>
<td>69%</td>
</tr>
<tr>
<td>LHV efficiency, % below rated</td>
<td>≥70</td>
<td>69-72%</td>
</tr>
</tbody>
</table>
## Accomplishments/ Progress – Powerplant Results

### Summary of S400 PP1R Testing

**Performance Data versus Targets**

<table>
<thead>
<tr>
<th>Data</th>
<th>Target</th>
<th>PP1R Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP1R Volume, liters</td>
<td>570</td>
<td>582</td>
</tr>
<tr>
<td>PP1R Mass, kg</td>
<td>455</td>
<td>690</td>
</tr>
<tr>
<td>Start Time (to 10kW Power), min</td>
<td>15</td>
<td>TBD</td>
</tr>
<tr>
<td>Number of start/stops</td>
<td>500</td>
<td>TBD</td>
</tr>
<tr>
<td>Duration of operation (total hrs)</td>
<td>1000</td>
<td>TBD</td>
</tr>
<tr>
<td>Maximum Net Power, kW</td>
<td>25-50</td>
<td>TBD</td>
</tr>
<tr>
<td>System Efficiency at 25% of rated (12.5kW)</td>
<td>≥35</td>
<td>TBD</td>
</tr>
<tr>
<td>Ambient Operating Temperature</td>
<td>4 - 40°C</td>
<td>TBD</td>
</tr>
</tbody>
</table>
**FP1 Test Results: Start Time**

- Start time <5 minutes. Based on stability, H₂ and CO Concentrations

![Graph showing fuel flow and concentrations over time](image-url)
FP1 Test Results: FPS $H_2$ Production Efficiency

- $H_2$ Production Efficiency at 10kWe is $\sim$70%

![Graph showing FPS Efficiency at 10kW Run 1; June 3, 2003]

FPS H2 Production Efficiency = LHV H2/LHV Gasoline

Where LHV is Lower Heating Value
FP1 Test Results: Small Transient Performance

3.5 kW/s small transient. All stable, CO levels as desired
FP1 Test Status: Large Transient Performance

3.5 kW/s large transient. All stable, except CO levels high
FP1 Test Status: SULEV Emissions

- Power plant emissions design goal was to be equal to or less than the 2004 Super Ultra Low Emissions Vehicle (SULEV) standards for vehicles <8500lbs, for CO, NOx and NMHC.

- The SULEV emission limits are specified in terms of g/mile. The emissions for FP1/PP1R were apportioned as total mass amounts for start up, and as concentrations during on-load based on the SULEV limits and the LA4-CH driving mode.

- A methane target of 700 ppm at the powerplant exhaust (3100ppm at FPS exit) and a NMHC target of 1ppm at the FPS exit were additional goals.

- The CSA limit for CO is 20ppm, which is lower than SULEV. The 20ppm target was used herein.

<table>
<thead>
<tr>
<th>Steady State Goal</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx ≤ 2.1ppm (dry volume)</td>
<td>&lt; 1ppm at all power levels</td>
</tr>
<tr>
<td>CO ≤ 20ppm (dry volume)</td>
<td>≤ 20ppm at power levels below 30 kW</td>
</tr>
<tr>
<td>CH4 ≤ 3100ppm (dry volume)</td>
<td>&lt; 3100ppm at all power levels</td>
</tr>
<tr>
<td>NMHC ≤ 30ppm (dry volume)</td>
<td>≤ 30ppm at all power levels except 50 kW</td>
</tr>
<tr>
<td>Aromatics ≤ 1ppm (dry volume)</td>
<td>Average ~ 2ppm; Range: 0.1 to 10ppm</td>
</tr>
</tbody>
</table>
FP1 Test Results: FPS Exit Emissions and H2

FP1 Test FPS Exit Emissions vs. Power Level
All on Dry Volume Basis

Equivalent Power Level (%)

Concentrations: H2 (%); NMHC (ppm); NOx (ppm)

H2 Target (%)  Measured H2 (%)
NMHC Target (ppm)  Measured NMHC (ppm)
NOx Target (ppm)  Measured NOx (ppm)
CO Target (ppm)  Measured CO (ppm)
CH4 Target (ppm)  Measured CH4 (ppm)
FP1 Test Status: Speciated Hydrocarbon Emissions

• In addition to the emissions testing was done to determine the unreacted non methane hydrocarbons (NMHCs) in the FPS exhaust.

• The total amount of NMHCs in the exhaust is very low

• Data is shown for three samples at 50 kW equivalent FPS operation. Data from 50 kW was used since the most species were measurable.
Test Results: NMHC Speciation at FPS Exit (~CSA inlet)

Speciated NMHC Results
March 19, 2003
50 kW - Gasoline

Concentration (ppb (wet volume))

Sample 1  Sample 2  Sample 3
Summary/Future

- Significant progress made from S200 to S400
  - Weight
  - Volume
  - Start time
  - FPS Technology
  - CSA Technology

- Program ends in FY 04, remaining testing will be completed followed by complete teardown and analysis.
Future Challenges

Gasoline reformer fuel cell power plants

ATR

Current FPS

Next generation FPS

• 250 L
• 45 min start

• 78 L
• <10 min start

Goal

• 35 L
• < 30 sec start
Future Opportunities

FPS Technology Advancement

• Focus on Fuel Processor System (FPS) technology to:
  – Improved catalyst
  – Reduce start time
  – Evaluate membrane separation technology
  – Evaluate PSA technology
  – Reduce weight and volume
  – Improved controllability

• Focus on smaller applications, 5 kW APU size demonstrations and development