Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft

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Overview

Timeline
► Start: July 19, 2010
► End: September 30, 2011
► Percent complete: 45%

Barriers
► Identify and quantify barriers to deployment of fuel cell power systems on commercial aircraft.

Budget
• Total project funding
  – DOE share: $400K
  – Contractor share: $0
• Funding received in FY10: $400K
• Funding for FY11: $150K

Partners
• Collaborator: Boeing Commercial Aircraft Division
• Project Lead: PNNL
Objectives-Relevance

- Assess approaches to provide electrical power from solid oxide fuel cells (SOFC) on board commercial aircraft.

- Focus on more-electric airplanes, with the Boeing 787 as a case study for comparison.

- Assess optimum sizing, location and configuration of the SOFC power system.

- Identify and quantify barriers to deployment of fuel cell power systems on commercial aircraft.
Approach

- Obtain detailed understanding of current 787 electrical system, including generators, power conversion and loads.
  - Milestone: Determine reference load profile. Completed Q1, FY11

- Develop a model to determine the expected performance and fuel efficiency of various SOFC power system configurations. Use PNNL stack performance model and ChemCAD.
  - Milestone: Complete system model. Completed Q1, FY11

- Perform a trade study using the modeling tool. Assess various SOFC system configurations. Assess optimum system operating conditions, including stack voltage, system pressure and single-pass fuel utilization.
Approach, cont.

- Quantify the benefits of the optimum fuel cell power system relative to fuel savings and emissions reduction.
  - Milestone: Quantify benefits of fuel cell system, Q4, FY11. On schedule.

- Identify near-term demonstration project(s) that would decrease barriers to commercial use on airplanes.
  - Milestone: Demonstration project(s) identified, Q3, FY11. Not yet started.

- Prepare a final report to DOE.
  - Milestone: Complete final report Q4, FY11. Not yet started.
Technical Accomplishments and Progress

- Obtained extensive information from Boeing on the 787 electrical system, including generation and distribution systems, load profiles and fuel consumption.

![Diagram of aircraft engine components]

- Efficiency of converting Jet-A fuel to 230 VAC: 34%
- 918 kW

<table>
<thead>
<tr>
<th>System</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN ENGINES</td>
<td>59%</td>
</tr>
<tr>
<td>GEARBOX</td>
<td>96%</td>
</tr>
<tr>
<td>GENERATORS</td>
<td>60%</td>
</tr>
</tbody>
</table>

230 VAC BUS

- 432 kW
- 230 VAC to +/- 270 VDC
  - 75%
- ATRU
- 230 VAC to +/- 270 VDC
  - 75%
- TRANSFORMER 230 TO 115 VAC
  - 85%
- 180 kW
- 230 VAC to 115 VAC
  - 85%
- TRU 30 VAC TO 28 VDC
  - 80%
- 34 kW
- 230 VAC to 28 VDC
  - 80%

/+ 270 VDC BUS

- Total +/- 270 VDC Loads (kW): 324
- ECS/Pressurization: 240
- Hydraulics: 30
- Equip. Cooling: 30
- ECS Fans: 24

115 VAC BUS

- Total 115 VAC Loads (kW): 153
- ICS: 34
- Various: 119

28 VDC BUS

- Total 28 VDC Loads (kW): 27
- Flight Controls: 11
- Various: 16
- Ice Protection: 60
- Galleys: 120
- Fuel Pumps: 32
- Forward Cargo AC: 60

226 kg fuel consumed per hour to generate electricity (~5% of fuel used for propulsion at 40,000 feet).
Technical Accomplishments and Progress

Conceived electrical system using SOFC on DC bus that will save ~100 kW in power conversion losses and almost 200 kg in conversion equipment.

- Efficiency of converting Desulfurized Jet-A fuel to 230 VAC: 70%
- Efficiency of 270 VDC to 115 VAC: 80%
- Efficiency of 270 VDC to 28 VDC: 80%

Total +/- 270 VDC Loads (kW) 596

- ECS/Pressurization 240
- Hydraulics 30
- Equip. Cooling 30
- ECS Fans 24
- Ice Protection 60
- Galleys 120
- Fuel Pumps 32
- Forward Cargo AC 60

Loads moved from 230 VAC to 270 VDC: 98 kg fuel consumed per hour to generate electricity

- Total 115 VAC Loads (kW) 153
  - ICS 34
  - Various 119

- Total 28 VDC Loads (kW) 27
  - Flight Controls 11
  - Various 16
Modeled a matrix of SOFC power systems to determine anticipated fuel efficiencies. Most promising system uses steam reforming, anode recycle and compressor/expander.
Technical Accomplishments and Progress

- Determined breakeven weight change vs flight distance for various SOFC system efficiencies: A system with 70% conversion efficiency can add up to 4600 kg and still break even on fuel consumed.
Technical Accomplishments and Progress

- Generated estimates of system weights (not yet complete) for SOFC system with steam reformer, anode recycle and compressor/expander.

<table>
<thead>
<tr>
<th>Efficiency*/Added Mass (kg)**</th>
<th>SOFC Cell Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.85</td>
</tr>
<tr>
<td>0.8 atm</td>
<td>75%/9130</td>
</tr>
<tr>
<td>3 atm</td>
<td>75%/5961</td>
</tr>
<tr>
<td>8 atm</td>
<td>75%/4652</td>
</tr>
</tbody>
</table>

- Efficiency increases with cell voltage, not much affected by pressure.
- Stack mass decreases as pressure increases because power density increases.
- Below 0.8 volts/cell BoP mass increases because gas flow rates increase.

*Efficiency = Net Electrical Energy Supplied to Bus / LHV of Kerosene

**Net change in aircraft mass does not yet include insulation, supporting structure, piping, ducting or instrumentation.
Proposed Future Work  
(Now till 9/30/2011)

- Develop pre-conceptual design for most promising system and refine weight estimates based on this design. Split total load between 2 or 3 systems for redundancy.

- Develop weight estimate for on-board de-sulfurization system. Current estimates assume low sulfur fuel is available at airports.

- Test effect of elevated pressure on state-of-the-art SOFC performance. Publish the results.

- Compare alternatives to provide peaking power.

- Assess benefits of condensing water for lavatories from SOFC system.

- Identify opportunities for reducing weight of SOFC power systems.
Collaborations

- Boeing has been very helpful in explaining how modern airplane electrical systems work with relevance to fuel cell applications and in providing data on loads, power conversions and system efficiencies.

- Williams International has offered (as of 3/31) to develop a conceptual design for a custom turbo expander/compressor.

- Aviation Working Group, with members from Boeing, Cessna, Airbus and others has provided useful information.
Summary

- Preliminary analysis indicates current state-of-the-art technology is near or just under breakeven weight.
- Weight reduction has potential to increase fuel savings to significant levels.

![Graph showing weight and flight distance relationship](graph.png)

- Breakeven weight for most promising system
- Weight limit for insulation, supporting structure, piping, ducting and instrumentation
- Net weight added due to major SOFC system components minus equipment eliminated
- ~1250 kg
Technical Back-Up Slides
Efficiency Boost from Steam Reforming

• Steam reforming is endothermic

• Heat from SOFC stack is converted into ~25% increased chemical energy of reformate:

Steam Reformation of $n$-Dodecane:

\[ \text{C}_{12}\text{H}_{26} + 12\text{H}_2\text{O} + \text{heat} \rightarrow 12\text{CO} + 25\text{H}_2 \]

\[
\begin{align*}
7552 \quad &\text{kJ/mole} \\
9421 \quad &\text{kJ/mole (125%)}
\end{align*}
\]

• **System yields >60% net efficiency**

• Steam and heat for reforming obtained from SOFC stack exhaust
Partial Oxidation (POx) Reforming

• Some systems use POx reforming.

• POx is exothermic.

• POx reformate has less chemical energy than original fuel.

• Example, dodecane: $C_{12}H_{26} + 6O_2 = 12CO + 13H_2 + \text{heat}$

\[
\begin{align*}
7552 \text{ kJ/mole} & \quad \quad \quad \quad \quad \quad \quad \quad 6618 \text{ kJ/mole (87%)}
\end{align*}
\]
Preliminary Mass Estimate

- Number of cells based on required gross power and state-of-the-art cell power density at pressure.

- Mass of anode recuperator, reformer and anode blower based on fuel consumption rate and scaled to 3.6 kW system.

- Mass of cathode recuperator based on air flow rate and scaled to 3.6 kW system.

- Compressor/Expander mass based on small jet engine specifications (Williams International) and scaled to number of compressor stages required.

- Mass of pressure vessel based on actual design calculation. Assumes titanium.

- Mass of supporting structure, insulation, piping and ducting to be determined based on pre-conceptual design.
Preliminary Mass Estimate, cont.

- Calculation of “net mass added to aircraft”:
  - Mass of SOFC power system components
  - Minus mass of AC/DC power converters (196 kg)
  - Minus mass of turbine APUs (245 kg)

- Existing generators cannot be removed because they also serve to start the main engines.

**Preliminary Mass (kg) Estimate for Most Promising Configuration**

*at 8 atm. and 0.8 volts/cell*

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC cells</td>
<td>1333</td>
</tr>
<tr>
<td>cathode recuperator</td>
<td>770</td>
</tr>
<tr>
<td>anode recuperator</td>
<td>392</td>
</tr>
<tr>
<td>reformer</td>
<td>510</td>
</tr>
<tr>
<td>anode blower</td>
<td>760</td>
</tr>
<tr>
<td>compressor/expander</td>
<td>45</td>
</tr>
<tr>
<td>pressure vessel</td>
<td>31</td>
</tr>
<tr>
<td><strong>subtotal for major system components</strong></td>
<td><strong>3842</strong></td>
</tr>
<tr>
<td>credit for elimination of conversion equipment</td>
<td>-196</td>
</tr>
<tr>
<td>credit for elimination of turbine APU</td>
<td>-245</td>
</tr>
<tr>
<td><strong>net change in aircraft mass</strong></td>
<td><strong>3401</strong></td>
</tr>
</tbody>
</table>