X.10 Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft

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Fiscal Year (FY) 2011 Objectives

- Examine electrical power generation for commercial aircraft using solid oxide fuel (SOFC) technology.
- Determine amount of weight reduction required to make SOFC power systems net fuel efficient on aircraft.

Technical Barriers

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

FY 2011 Accomplishments

- Obtained extensive information from Boeing on the 787 electrical system, including generation and distribution systems, load profiles and fuel consumption.
- Conceived electrical system using an SOFC on a direct current (DC) bus that will save ~100 kW in power conversion losses and almost 270 kg in conversion equipment.
- Modeled a matrix of SOFC power systems to determine anticipated fuel efficiencies. Most promising system uses steam reforming, anode recycle and compressor/expander.
- Determined breakeven weight change vs. flight distance for various SOFC system efficiencies: a system with 70% conversion efficiency can add up to 4,600 kg and still break even on fuel consumed.
- Generated estimates of system weights (not yet complete) for SOFC system with steam reformer, anode recycle and compressor/expander.

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Introduction

This study examines electrical power generation for commercial aircraft using SOFC technology. The focus of this study is “more-electric” airplanes with the Boeing 787 used as a case study. More-electric airplanes minimize extraction of bleed air from the engine compressor stages and instead run electrical generators driven by the engines to satisfy loads. More-electric airplanes have higher electrical generation rates and thus stand to show greater benefit from an increase in the efficiency of electrical generation.

SOFC technology can generate electrical power at higher efficiency than is achieved by using power from the main engine shaft to run a generator. Hence, unlike the existing auxiliary power unit (APU), which is turned off once the main engines are started, a fuel cell power unit would operate throughout the flight to maximize fuel savings. Fuel cell power units are expected to be somewhat heavier than turbine APUs resulting in a heavier aircraft. For an SOFC power unit to be feasible, the fuel savings for electrical generation must exceed the increase in fuel consumption due to weight.

Approach

System flowsheets were analyzed to estimate weight and efficiency. Mass and energy balance was modeled using ChemCAD software coupled with a PNNL stack performance model of a planar anode-supported SOFC. The stack performance model is calibrated to actual data for a promising new materials set that yields about 75% higher power density than previous cells. Based on input values for pressure, inlet temperature, flow rates, compositions, and cell voltage, the SOFC model predicts the power density achieved. All systems modeled were assumed to operate using desulfurized jet fuel that is loaded into a dedicated tank. Approaches to the flowsheet included auto-thermal reforming, steam reforming and anode recycle steam reforming. All systems included a compressor/expander to compress air drawn in from the atmosphere and then expand the exhaust gases to recover work. System pressures were examined at 0.835 atm (cruise cabin pressure), 3 atm and 8 atm. Operating cell voltages of 0.70, 0.75, 0.80 and 0.85 V were analyzed.

A revised 787 electrical distribution system was considered to take advantage of the SOFC power being generated as DC rather than alternating current (AC) power. An estimate of the electrical power required was developed based on an understanding of the Boeing 787 loads. The impact of the addition of the SOFC APU weight on main engine fuel consumption was determined using a PianoX (http://www.lissys.demon.co.uk/index2.html) model of the 787-8. Flight profiles for trips of 1,000, 3,000, 5,000 and 7,000 nautical miles were calculated for a range of payloads. The PianoX model was allowed to select appropriate parameters for each flight such as rate of climb, initial cruise altitude, rate of descent, etc., and provided fuel consumption data as a function of payload. A breakeven weight for the APU was calculated by determining the point at which the fuel saved during the flight due to the efficiency of the SOFC would be offset by the increase in main engine fuel consumption required to carry the additional APU weight. Estimates of APU weight were compared to the breakeven weight.

Results

Key factors in the comparison of SOFC power system weights to break even values include:

Modification of Power Distribution - For the SOFC-based electrical system, the aircraft distribution system was modified so that the SOFC directly produces the +/-270 VDC power used for major loads. The existing 230 VAC loads are moved to +/-270 VDC bus and 80% efficient DC/DC and DC/AC power conversions are used to provide power to 115 VAC and 28 VDC loads. This approach reduces the conversion losses, reducing the required gross power generation from 918 kW to 821 kW. The weight saved in power conversion equipment is estimated to be 268 kg.

Elimination of Turbine APU - It is expected that the SOFC power system would be divided into multiple independent units to provide redundancy. In this configuration, the turbine APU could be eliminated, saving 245 kg. The ram air turbine was assumed to still be present. Engine generators cannot be eliminated since they double as starters for the main engines.

SOFC System Configuration - The extent of fuel savings depends on the flowsheet for the SOFC system. Key system features include the air compression/expansion, the fuel cell itself and the approach to reforming the fuel.

Air Compression - In all cases, ram air is compressed to SOFC pressure in a compressor (80% efficient) and exhaust gases expanded through a turbine (85% efficient) to ambient to recover mechanical energy. Weight and performance of the compressor/expander was based on a Williams WR2 jet engine. Adjustments were made to scale the estimated weight based on the air flow and compression ratio required for each flowsheet. Shaft power is balanced by either using electrical power as input or generating AC power and converting it to +/-270 VDC. Cabin air is not used as input to the compressor to avoid concern over upsetting normal cabin venting.

Fuel Cell - The fuel cell is based on a Delphi Gen 4 stack with a new material set which is capable of higher power density than the more established materials currently used. The new materials set has been tested in small button cells, but has not yet been scaled up. The weight of the stack was taken to be 62 kg for a 100-cell stack. This weight represents the current weight of a 100-cell Gen 4 stack design minus a relatively heavy base plate and frame (33.5 kg). It is believed that a much lighter weight solution to the base plate and frame can be developed. The power density in the stack is a function of anode gas composition, fuel utilization, excess air, operating pressure and voltage. Stack electrical conversion efficiency is purely a function of stack voltage.

Reforming Approach - Autothermal reforming, single anode pass steam reforming and anode recycle steam reforming flowsheets were modeled. Figure 1 shows the logical layout of the anode recycle flowsheet. Figure 2 shows that the anode recycle steam reforming provided significantly higher system efficiency than other approaches. In this approach all steam required for reforming is generated on the SOFC anode and waste heat from the fuel cell is used to drive the enothermic steam reforming reaction. Net power from the compressor-expander provided only a small contribution (3.2% to 4.7% at 3 atm) to total net power output. Since the SOFC offers higher efficiency than a turbine, efficiency is improved with more power from the SOFC and less from the turbine as long as electrical power is not required as input to drive the compressor. Also, the decision to configure the system to directly generate DC power penalizes the turbine for losses in AC/DC conversion.

Weight Estimates - The system was assumed to be placed in a titanium vessel designed for a safety factor of 1.5 on yield stress. The heat exchangers, anode blower and

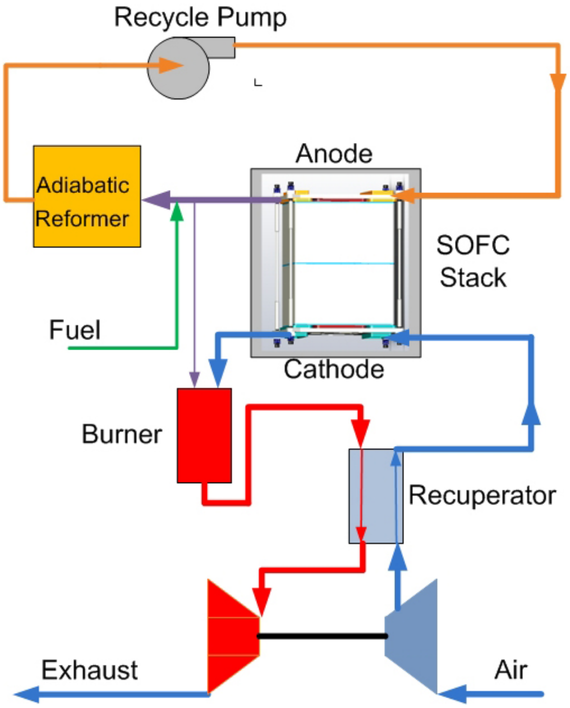

FIGURE 1. Logical Flowchart for Anode Recycle Steam Reforming Flowsheet

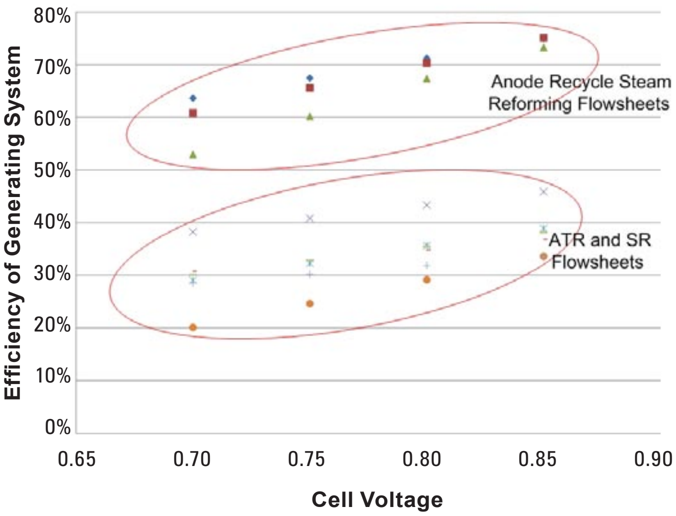

FIGURE 2. Efficiency as a Function of Cell Voltage Flowsheet Configuration

reformer were scaled based on an existing SOFC power system operating at 6.3 kW. Stacks were estimated at 62 kg/100 cells. Current weight estimates do not account for the insulation, connecting pipes, support structure, instrumentation and controls. Table 1 shows a summary of the estimated net efficiency and weight for analyzed anode recycle cases. Highlighted cells indicate the most attractive regions for operation.

TABLE 1. Net Efficiency and Weight Added by SOFC Power Unit (kg)

Pressure	SOFC Cell Voltage			
	0.85	0.80	0.75	0.70
0.8 atm	75%	71%	68%	64%
	8,956	5,264	4,392	4,163
3.0 atm	75%	70%	66%	61%
	4,828	3,901	3,729	3,825
8.0 atm	73%	67%	60%	53%
	3,709	3,510	3,726	4,135

Breakeven Weights - The breakeven weight as a function of power unit efficiency is shown in Figure 3. The breakeven weight indicates the SOFC power unit weight at which the aircraft fuel consumption would be the same as the current engine generators due to weight added. The highest breakeven weights occur for shorter flights. This occurs because the electrical generation is assumed constant but aircraft velocity during climb and descent is lower causing more fuel to be saved per mile compared to the higher velocity cruise phase. Figure 4 shows that current weight estimates are below breakeven weights indicating a potential to save fuel compared to engine generators. However, current weight estimates do not yet include insulation, connecting ducting and tubing and support structure which will possibly impact on the fuel savings.

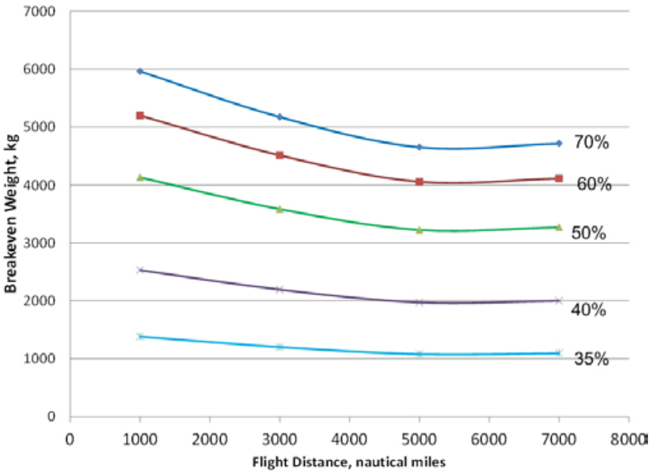

FIGURE 3. Breakeven Weights as a Function of Efficiency

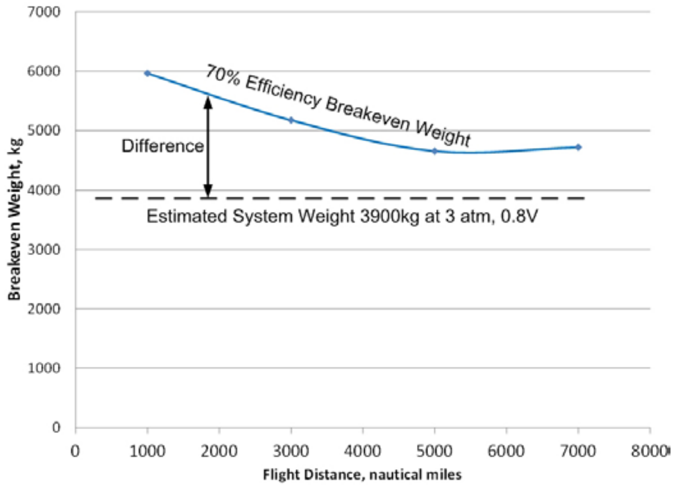

FIGURE 4. Comparison of Breakeven Weight to Estimated System Weight (3 atm, 0.8 V/cell)

Conclusions and Future Directions

- Existing SOFC technology is potentially capable of saving fuel during flight.
- Measurements of SOFC performance at high pressure will be made to support predictions of performance at high pressure.
- Additional modeling in the region of best performance will be conducted.
- A conceptual design will be developed to improve estimates of system weight.

FY 2011 Publications/Presentations

1. Chick, LA., May 2010, "*Assessment of Solid Oxide Fuel Cell Power System for Greener Commercial Aircraft.*"