System Architectures for Solid Oxide Fuel Cell-Based Auxiliary Power Units in Future Commercial Aircraft Applications

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Recent advancements in fuel cell technology through the auspices of the Department of Energy, the National Aeronautics and Space Administration, and industry partners have set the stage for the use of solid oxide fuel cell (SOFC) power generation systems in aircraft applications. Conventional gas turbine auxiliary power units (APUs) account for 20% of airport ground-based emissions. Alleviating airport ground emissions will continue to be a challenge with increased air travel unless new technology is introduced. Mission fuel burn and emissions can be significantly reduced through optimal systems integration of aircraft and SOFC subsystems. This study examines the potential total aircraft mission benefits of tightly integrating SOFC hybrids with aircraft subsystems using United Technologies Corporation Integrated Total Aircraft Power Systems proprietary methodologies. Several system concepts for optimal integration of the SOFC stack with aircraft subsystems are presented and analyzed in terms of mission fuel burn for technologies commensurate with 2015 entry into service. The performance of various hybrid SOFC-APU system architectures is compared against an advanced gas turbine-based APU system. In addition to the merits of different system architectures, optimal SOFC system parameter selection is discussed. The results of the study indicate that despite the lower power density of SOFC-based APU systems, significant aircraft fuel burn (5–7%) and emission reductions (up to 70%) are possible. The majority of the fuel burn savings are realized during aircraft ground operations rather than in-flight mission segments due to the greater efficiency difference between the SOFC system and the advanced APU technology. [DOI: 10.1115/1.3008037]

Introduction

Interest in fuel cells as an advanced auxiliary power unit (APU) technology alternative for aircraft has been receiving increased attention in the past five years and is being driven by several factors, including emissions, costs, and evolving application requirements. Conventional gas turbine APUs account for 20% of airport ground-based emissions [1]. Alleviating airport ground emissions will continue to be a challenge with increased air travel unless new low-emissions technology is introduced. Conventional APU technology and secondary aircraft systems are also responsible for 50% of the aircraft maintenance cost and some 12% of the delays [2]. The APU system itself represents the third highest aircraft system cost in terms of repair and replacement. Airlines are also experiencing increased operating costs associated with higher fuel prices and, on a typical day, greater than 5% of the total fuel consumed during daily operation is due to the APU [3]. Furthermore, new aircraft development programs are increasingly evolving toward more-electric aircraft (MEA) designs, such as the Boeing 787. These drivers coupled with the general need for high specific power and high efficiency power and propulsions systems for a variety of aerospace applications are promoting interest in fuel cell-based power systems.

To address these challenges, the National Aeronautics and Space Administration (NASA) formulated a plan to advance solid oxide fuel cell capabilities for a wide range of aircraft power and propulsion applications [4]. The plan builds on the Department of Energy's (DOE) Solid State Energy Conversion Alliance (SECA) program by complementing SECA's program objectives on cost reduction to address power density (kW/l) and specific power (kW/kg) challenges critical for aircraft applications. As part of this plan, NASA issued several contracts to conduct studies targeting a jet fuel-based fuel cell with a 2015 Entry-Into-Service (EIS) application. One such study is the one conducted by United Technologies Research Center (UTRC) for the NASA RASER program [5] which concluded that most of the benefits of a solid oxide fuel cell (SOFC) APU system would be realized during ground operations, for a long-range mission. A preliminary analysis of the short-range mission (1000 NM (nautical mile)) conducted as part of that study showed that the SOFC system provided about 3% mission fuel burn (FB) savings for the short-range mission as compared to only 0.7% mission fuel burn savings for the long-range mission (3000 NM). The present work was intended to look into the potential short-range mission benefits of tightly integrating the SOFCs with aircraft subsystems using UTC Integrated Total Aircraft Power Systems (ITAPS™) proprietary methodologies.

Objectives

The objectives of this work were threefold: (1) define SOFC-based APU system concepts with high specific power (kW/kg) for a future short-range aircraft, (2) evaluate the propulsion and power system benefits of these system concepts, and (3) identify the key technology gaps that need to be closed to enable these systems to enter the marketplace.

The scope of the study targeted technologies that would be commensurate with a year 2015 EIS. This generally means that hardware needs to be demonstrated at full scale in a relevant environment at least three years prior to EIS. This milestone corre-

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sponds to a NASA technology readiness level (TRL) of 6 and would theoretically need to be reached by 2012 at the latest. Thus, balance-of-plant (BoP) hardware for the studies was selected with these timeline and readiness constraints. Furthermore, the study was focused on technologies and systems integration concepts for short-range missions (<1000 NM). The study also includes an assessment and development of lightweight SOFC stack/system concepts for high specific power for aircraft APU applications but limits system architecture simulation and evaluation to a conceptual level of fidelity. Nevertheless, the uniqueness of this study is the utilization of Integrated Total Aircraft Power Systems (ITAPS™) methodologies to examine the performance benefits from tight aircraft systems integration. ITAPS™ is a United Technologies Corporation (UTC) concurrent engineering and analysis package that leverages systems integration approaches with proprietary aircraft component and system modeling tools, databases, and design processes to generate synergistic system-level solutions [6]. As Joyner and McGinnis noted [7], "the objective of ITAPS™ is to provide an accurately defined model or system of models that represent a system-of-systems to provide quantitative solutions early in the design process. It also is employed to evaluate architectural solutions based on the system requirements during the functional analysis step."

Methodology

Metrics. The basic approach taken in this study was to compare the performance of advanced SOFC-APU system concepts for 2015 EIS to a baseline APU system that was comprised of advanced but conventional gas turbine technology. The future SOFC systems were designed to exceed the DOE SECA program goals for high specific power. The primary metrics that quantified the technology benefits were captured as reductions in total aircraft fuel burn, emissions, and overall efficiency performance. SOFC-gas turbine (SOFC-GT) APU system efficiency is defined as

$$\eta_{\text{SOFC-APU}} = \frac{\dot{W}_{\text{SOFC,Netdc}} + \dot{W}_{\text{GT,Netdc}}}{\text{LHV}_{\text{Fuel,in}}} \tag{1}$$

where the aircraft power distribution in this study is high voltage dc power.

Simulation Tools. Modeling and simulation of the SOFC-APU subsystem draw upon the large library of fuel cell and combined heat and power (CHP) proprietary models developed by UTRC and its sister division, UTC Power. This library has been developed using the commercially available gPROMS software, which stands for general process modeling system. gPROMS is an equation-oriented modeling system typically used within the process industry for building, validating, and executing first-principles models within a flowsheeting framework [8]. The software employs user-specified ordinary differential equations and differential algebraic equation simultaneous equation solvers to enable process modeling, simulation, parameter estimation, and optimization.

Basic Modeling Approach. The UTRC SOFC stack model is based on a lumped single-node thermodynamic representation that accounts for internal reforming and water-gas shift equilibrium, electrochemical polarizations and the associated heat generation, mass transfer via cell reactions, and overall energy balances within a single-cell repeat unit. Reactant gas supply is assumed to be uniformly distributed among the cells within the cell stack and among the channels within each repeat unit. Thus, single-cell performance is extrapolated to produce SOFC stack performance. This representation can be readily constructed as quantities, such as stack voltage and stack power that are scaled versions of single-cell voltage and power. Thus, a single-cell model forms the heart of stack model. The cell model is comprised of three compartments—the anode, the cathode, and the electrolyte. Mass balances are written individually for the anode and the cathode compartments. The consumption of H_2 in the anode and O_2 in the cathode is governed by Faraday's law and is proportional to the current density.

In the case of reformate fuels, it is assumed that hydrocarbons and/or CO are not electrochemically active but are consumed rather through reactions, such as reforming and water-gas shift. For example, if CH_4 and CO are also fed to the anode, then the following reactions govern the consumption of the two species:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \text{(water-gas shift)} \tag{2}$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \text{(methane reforming)} \tag{3}$$

Thus, the H_2 needed for the electrochemical oxidation at the triple-phase boundary in the anode is supplied by the above reactions. The above reactions are assumed to be at equilibrium in the anode. This assumption is generally valid for high voltage low current operating conditions, i.e., longer anode gas residence times [9]. Furthermore, for externally reforming SOFC systems where catalytic partial oxidation and autothermal reforming of liquid jet fuel occur, the reformate products consist of primarily hydrogen and carbon monoxide, not methane. Thus, the primary global reactions are the electrochemical oxidation of hydrogen and the water-gas shift, where water-gas shift is in equilibrium. Quantities such as fuel utilization and O_2-stoichiometry are calculated from the mass-balance equation framework.

An overall system energy balance is implemented as a part of the model. The total enthalpy flow into the system has two components: the anode inlet flow and the cathode inlet flow. Similarly, the enthalpy flow out of the system has the anode outlet and cathode outlet flow components. The lumped system produces power and rejects thermal energy to both the surroundings and the cathode cooling air stream. All of these respective terms figure into the cell energy balance.

Aircraft Application Challenges for SOFC Technology

There are several technical challenges encountered in using SOFC technology for aircraft applications. One critical challenge is that the SOFC system specific power (kW/kg) is at least four times lower than that of a conventional gas turbine APU and the corresponding weight penalty increases the amount of fuel burned by the aircraft during a mission. To operate a SOFC-based APU during flight operations requires an input air stream, and providing this air stream from the ambient (ram-air) introduces ram-drag penalties. These ram-drag penalties increase the amount of fuel burned by the aircraft. Another challenge is associated with the power electronics with onboard aircraft electrical systems. The SOFC system (which is a hybrid system comprising the SOFC cell stack and a turbogenerator) produces both ac and dc power. The dc power is from the SOFC cell stack, while the ac power is from the turbine driven generator. The management of the power (ac and dc) generated by the SOFC system requires additional power electronics (power converters, etc.), which, in turn, increase the amount of fuel burned by the aircraft due to their additional weight and inherent inefficiencies. Conventional ceramic-based SOFC systems require a relatively long time (much more than 30 min) for startup. Therefore, designs that can enable rapid startup and provide good thermal cycling capability are desired. Another challenge is utilization of the high temperature (>300–550°C) exhaust gas leaving the SOFC system.

Jet A fuel specifications indicate that sulfur levels can range from 300 ppm 1000 ppm by weight. SOFCs generally require sulfur levels to be less than 1 ppmv (<15 ppm by weight) at the anode inlet. Sulfur removal can be accomplished with either ground-based or on-board methods. The first approach assumes that sulfur levels will be reduced to the required SOFC and reformer levels either at the refinery or on-site at the airport using ground-based hardware. However, the availability of low-sulfur jet fuel may not be ubiquitous for some time and our view is that a transitional period will exist where on-board desulfurization will

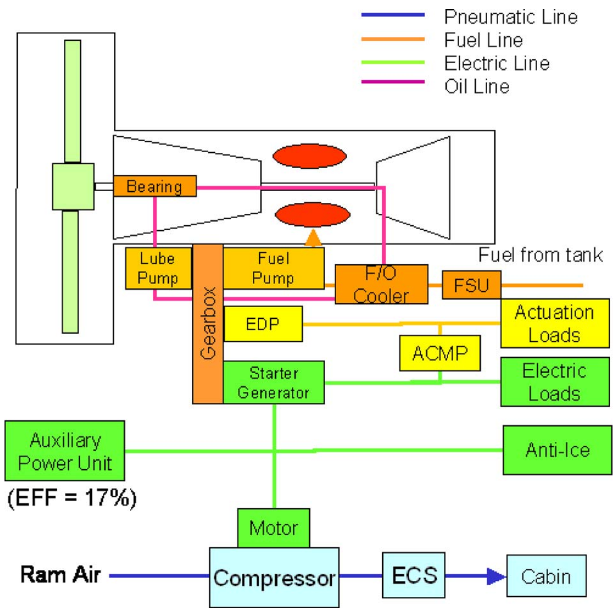

Fig. 1 Schematic baseline engine and power system architecture

be required. Thus, ground-based desulfurization is not examined in this study. To remove the sulfur on-board requires a bulky desulfurizer, which restricts the fuel processing options for aircraft applications.

In short, the addition of weight to the aircraft, ram-air consumption, and long start-up times can all increase the fuel burn of the aircraft. To realize any potential benefit from the SOFC system for aircraft APU applications, system integration concepts for the SOFC system should provide substantial compensating benefits to overcome penalties imposed by the above requirements and technical challenges. The current study uses some advanced and proprietary concepts for the SOFC cell stack and system design, desulfurization, and heat utilization to maximize the benefits of integration of a SOFC system as an APU for short-range more-electric aircraft.

Baseline APU System Description and Performance

System Description and Aircraft Electric Load Profiles. The baseline aircraft system is a short-range twin engine aircraft that employs ultra-efficient engine technology (UEET). The overall engine and power system architecture is shown in Fig. 1. The more-electric architecture aircraft features electric engine start, electric environmental control system (ECS) sourced by ram air, hydraulic and electric actuation, gearbox-driven accessories, and electric anti-ice. The baseline APU is an advanced bleedless APU with ceramic materials utilized in some static components. The main functions of the APU are to provide electric power to start the main engines, to drive the generator for ground-based electric loads, the compressor for the ECS, and for wing anti-ice at altitudes beneath 10,000 ft. (~3 km).

The baseline system performance analyzed is for a 162 passenger aircraft, sized for a 3200 nautical miles (NM) mission at a cruise Mach number of 0.8. The take-off gross weight (TOGW) of the aircraft was 153,471 lbs (69,600 kg). The mission analyzed for this study is a 1000 NM mission for which the optimum cruise altitude was 39,000 ft (11.9 km). The flight mission consists of ground operations, taxi-out, climb-cruise-descent, and taxi-in segments. The conventional gas turbine-based APU is typically operated only during the ground segment of flight missions and after the main engine starts, it proceeds to an idle condition (zero load) during the taxi-out and taxi-in segments. The main engines are operational from the beginning of the taxi-out (engine start) to the end of taxi-in (engine stop).

All baseline APU power requirements are electrical, and the auxiliary generator mounted on the main engine gearbox is considered to be part of the APU. APU electric load requirements and the ground operation times are shown in Fig. 2. During regular operation, the APU remains operational until the "taxi-out." During the flight segment, the APU is reduced to a zero-load condition (idle) during take-off and then is normally shutdown or is operated only for emergency and anti-ice conditions. The APU was sized for 300 kW or rated power to meet electrical loads (auxiliary and emergency operation and also to satisfy anti-ice loads) and operates with an efficiency of about 17% (low heating value (LHV) basis) during standard ground day conditions (15°C/68°F). Ultimately, the size of the APU is determined by the peak electrical power demand on a hot day (40°C/105°F) for ground conditions.

Overall Aircraft Fuel Burn Performance Using Baseline APU. Aircraft electrical loads during ground operations were shown in Fig. 2. In-flight aircraft electrical loads for the climb-cruise-descent segment, which includes the aircraft electrical service load, ECS electrical load, and the electrical portion of the actuation load, are depicted in Fig. 3. The electric anti-ice load requirement was taken into account while designing/sizing the APU/engine-mounted generators for different architectures. However, the anti-ice performance/benefits were not evaluated in the ITAPS™ environment, since the standard day performance mission does not include the icing condition. To satisfy the overall electrical load, two engine-mounted generators of 250 kW are required. Using the UTC ITAPS™ tools, the baseline aircraft system was evaluated. The total aircraft fuel burned during ground operations was 1996 lb/day (905 kg/day) and the total aircraft fuel burn (including the main engines) during the climb-cruise-

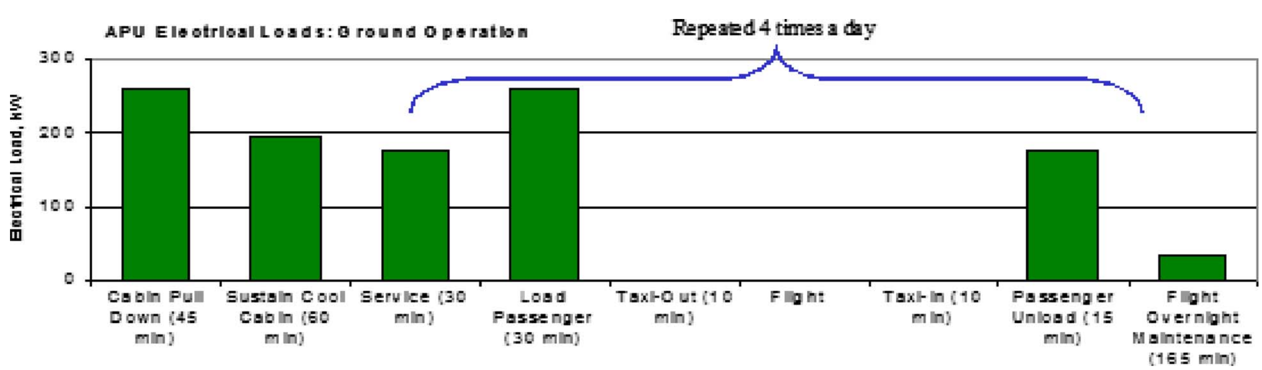

Fig. 2 Baseline APU electrical loads for ground operation

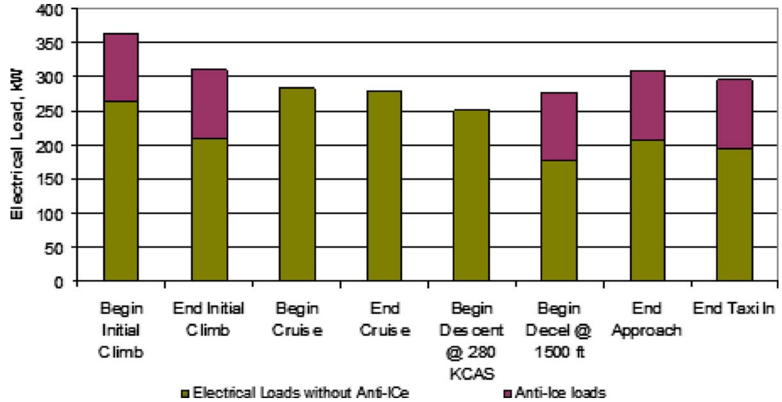

Fig. 3 Baseline electrical loads for climb/cruise/descent mission

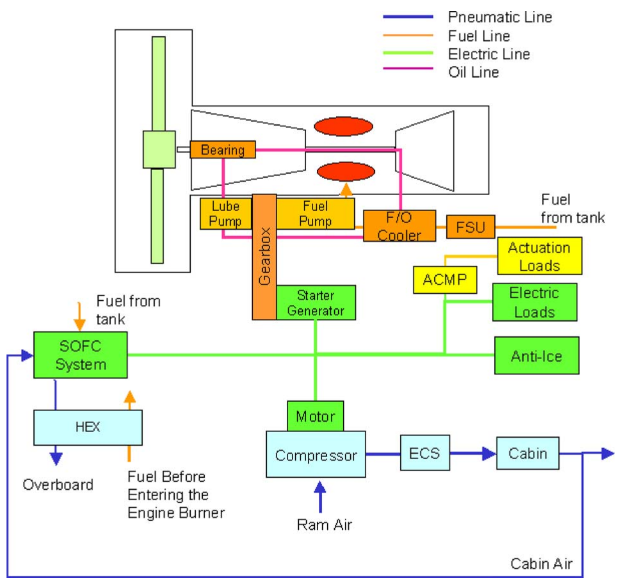

Fig. 4 Schematic of aircraft systems with SOFC-APU Architecture A

descent segments was 41,216 lb/day (18,690 kg/day). Additional performance summaries are provided in the subsequent section.

SOFC-APU System Architecture A

System Description. Two different SOFC system architectures (denoted as "A" and "B") were examined for integration into the aircraft systems. Architecture A includes the features of the baseline system and the best features from a previous study [5] and is depicted in Fig. 4. Twin 150 kW hybrid SOFC systems serve as an APU in place of the gas turbine APU. The efficiency advantage of the SOFC-gas turbine hybrid system also enables operation during the flight climb-cruise-descent segment, thereby reducing the engine shaft extractions substantially. The jet fuel is processed in a Pratt & Whitney proprietary fuel stabilization unit (FSU) to deoxygenate the fuel prior to receiving waste heat from the SOFC system, and air is supplied to the system using the overboard flow from the ECS.

The SOFC-APU is a pressurized gas system that is comprised of four basic subsystems: a fuel processing subsystem, cell-stack module and hot gas recycle components, a turbine bottoming cycle, and the power conditioning subsystem (PCS), as shown in Fig. 5. The fuel processing subsystem (FPS) consists of a single fuel pump, an on-board and athermal regenerative desulphurizer (DS), an autothermal reformer (ATR) (FR in Fig. 5), one air blower, and a fuel heat exchanger (HEX) to cool the reformate gas stream to the fuel cell-stack requirements. Jet A fuel enters the

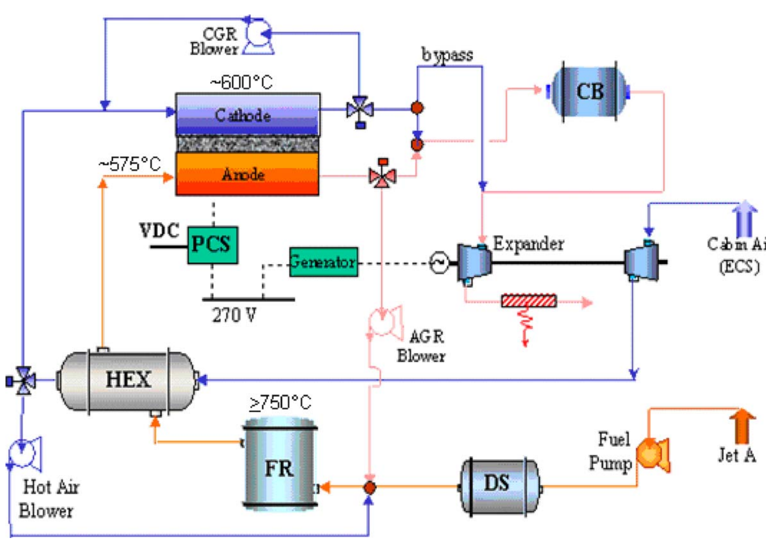

Fig. 5 Process schematic of SOFC-APU

Table 1 SOFC stack technology

Characteristic	Requirement	Approach
Life	⩾40 k-h	Operating temp. ~600°C
Robustness	0.01% mV/thermal cycle	Metal-supported cell
Specific power	>1 kW/kg	• Metal-supported cell • 20×30 cm^2 platform • ultrathin layers (⩽5 mm unit cell height)
Fuel utilization	>80%	Assumed via optimized manifold design
Fuel	Jet A reformate	ATR reformer ensures low coke forming potential at anode inlet via proper H_2O/C and O_2/C ratios

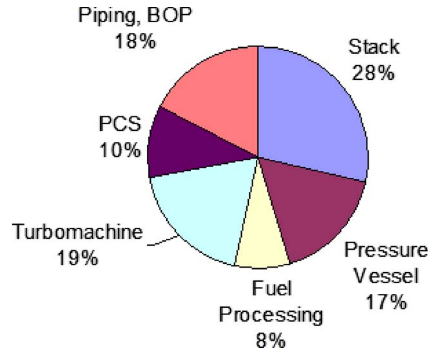

Fig. 6 2015 weight distribution goals of SOFC-APU system—Architecture A

system via the fuel pump, is delivered to the low-temperature regenerative DS, and then mixes with a fraction of recycled anode tail gas and fresh air to achieve the necessary oxygen-to-carbon and steam-to-carbon ratios for the reformer. The air requirements for the SOFC-APU system can be met entirely with the available cabin air. The SOFC stack is pressurized to 3 atm and operates at a temperature near 615°C and with a fuel utilization near 80%. In the twin 150 kW SOFC systems, each fuel cell stack typically generates dc power in excess of 125 kW at the design condition with a power density of 0.25 W/cm^2. A substantial amount of excess air is supplied to the SOFC to maintain the stack operating temperature. The depleted reactant gases exit the SOFC module and a portion of these gases are recycled via the cathode gas recycle (CGR) and anode gas recycle (AGR) blowers. The remainder of the depleted gas flows are mixed and sent to the catalytic burner (CB). In order to minimize the size and weight of the catalytic burner, not all of the SOFC cathode air flow is mixed with the anode exhaust and sent to the combustor. A significant fraction of the cathode exhaust gas bypasses the catalytic burner and mixes with the burner exhaust achieving a turbine inlet temperature below 800°C (<1380°F). The system exhaust gas passes through the expander, generating ac power and then provides thermal energy for fuel preheating via the waste heat recovery heat exchanger before being dumped overboard. High temperature fuel preheating of liquid hydrocarbon without coking and thermal decomposition is made possible by the FSU, as shown in Fig. 4. The efficiency of the fuel cell system is 45% (LHV) under ground conditions when delivering 300 kW of net power and 64% (LHV) at cruise conditions.

Sizing of the gas turbine power output occurs at cruise conditions as the pressure ratio of the expander increases from 3 to 14 when moving from operation at sea level to 39,000 ft (11.9 km). In contrast, the SOFC is sized at ground conditions and is responsible for over 80% of the electric power production during this mission segment. The SOFC-GT power split during cruise conditions changes to 63% SOFC-37% gas turbine. Thus, the efficiency increase during cruise operation is largely due to the increased power production from the gas turbine as well as an increase in SOFC efficiency due to the part-load operation.

SOFC Stack Technology. The SOFC is based on metal-supported stack technology to achieve high specific power. A list of stack requirements and a viable approach toward meeting these requirements are summarized in Table 1. The SOFC stack technical challenges are quite severe, especially in terms of robustness to thermal cycling, and the approaches envisioned in this study are conceptual. To achieve the high stack and system specific power and robustness requirements, a departure from the current anode-supported SECA stack technology development efforts is required. The approach envisioned herein is the development and use of metal-supported SOFC stack technology that will enable fast dynamic response, thinner cell layers, high specific power, and reduced performance degradation due to thermal cycling.

Figure 6 shows the weight distribution for the SOFC system consisting of twin 150 kW systems, providing power up to 300 kW. The weights are based on the following:

(i) proprietary light weight high specific power stack design
(ii) proprietary desulfurizer design using microwave-based regenerative concepts
(iii) pressure vessel design with minimum weight and minimum tolerance to withstand the pressure differentials across it
(iv) power conditioning for SOFC dc power regulation only (ac power is regulated with electrical power system (EPS) equipment weighing 54 kg)

The system weight projections are based on the best guess in some cases and these estimates should be considered as the minimum weight of the equipment to meet the performance requirements. The SOFC stack comprises 28% of the total system weight even with the high specific power of the metal-supported stack design. The turbomachinery is the next largest weight contributor at 19% of the total, followed closely by the piping, balance-of-plant (BoP) and the pressure vessel. The pressure vessel is based on an integral shell design at ground temperature (rather than elevated temperature) and the weight should be considered as a lower bound estimate. Clearly, the pressure vessel cannot be neglected as it represents a significant fraction of the system weight and is strongly coupled to the system operating pressure, as will be seen in the parameter sensitivity analysis in a subsequent section of this study.

SOFC Parameter Sensitivity Study. The operating parameters for Architecture A are based on several simulations carried out to optimize the performance for aircraft specific applications. Significant SOFC system design parameters include stack operating pressure, voltage, temperature, and fuel utilization. The proper selection of these design operating parameters involves a trade-off between system efficiency performance, system weight, heat available, and drag penalties on the airframe. An objective function that incorporates these effects into an equivalent fuel burn metric was developed and utilized to evaluate the sensitivity of each operating parameter. An exploration of each of the design parameters to changes in efficiency, weight, and fuel burn objective follows. In each of the analyses, all stack operating parameters were held fixed at their baseline values (615°C cell temperature, 80% fuel utilization, and 3.1 bar pressure operation) except for the parameter of interest. The results that are depicted in Figs. 7–13 are inclusive of the SOFC-based APU weight (and any concomitant drag penalties) and generally represent an increase in total aircraft weight due to the lower power density fuel cell-based APU versus the baseline APU system.

System Operating Pressure. Figure 7 shows the relationship be-

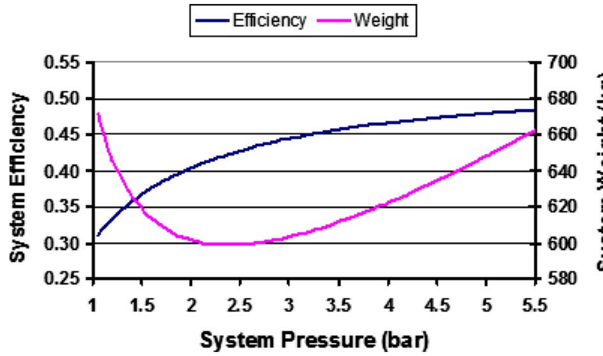

Fig. 7 System efficiency and weight versus system operating pressure

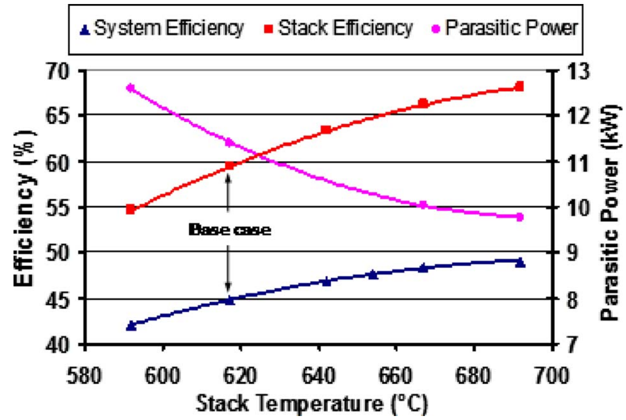

Fig. 10 Effect of stack temperature on system efficiency and parasitic power

tween system efficiency and weight to a variation in design pressure. A minimum in system weight near a system design pressure of 2.5 bar reflects the trade-off of the SOFC stack weight and the weight of the stack pressure vessel. As system pressure increases from atmospheric operation, the number of cells required to generate a specified dc power output decreases more rapidly than the increase in the weight of the pressure vessel. Above 2.5 bar operation, the increase in pressure vessel weight can no longer be offset by improvements in SOFC stack performance. Figure 7 also shows that the largest system efficiency gains are in the range of 1–3 bar operation. Above 3 bar operation, the gain in system efficiency tapers off while the system weight increases exponentially. This is in agreement with a related SOFC-GT hybrid system study for aircraft applications [10].

Figure 8 shows a reciprocal relationship between the system efficiency and fuel burn objective function during ground operations. From this plot, it is apparent that the fuel efficiency term in the objective function is dominant. As operating pressure is increased, the fuel burn objective function rapidly decreases until about 3 bar, after which the function approaches an asymptotic minimum near 5 bar. Increasing the system pressure from 1 bar to 3 bar produces a nearly 15 percentage point increase in system efficiency. Only another 3 percentage points in efficiency are gained by further increases in system pressure. Based on the results from Figs. 7 and 8, a system design pressure of 3.1 bar was selected.

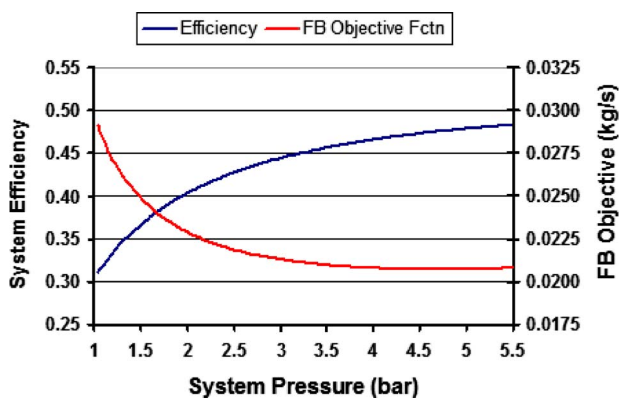

Fig. 8 System efficiency and FB objective versus system pressure

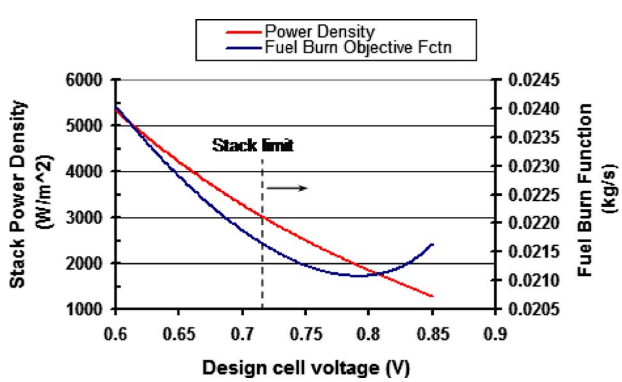

Fig. 9 System efficiency and weight versus design cell voltage

Operating Voltage. Stack power density decreases linearly with increasing cell voltage in the range of interest, as shown in Fig. 9 (system efficiency increases in direct proportion to cell voltage).

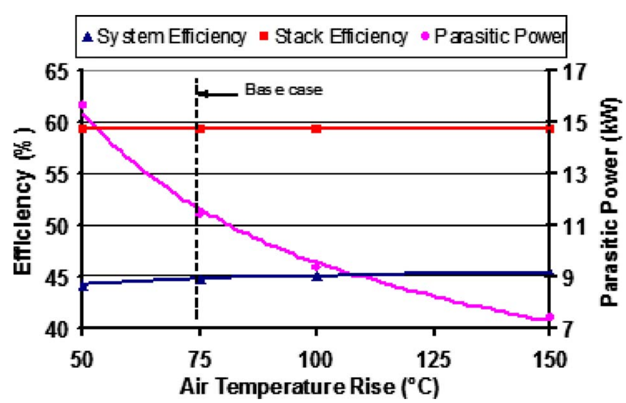

Fig. 11 System efficiency and parasitic power versus cathode air temperature rise

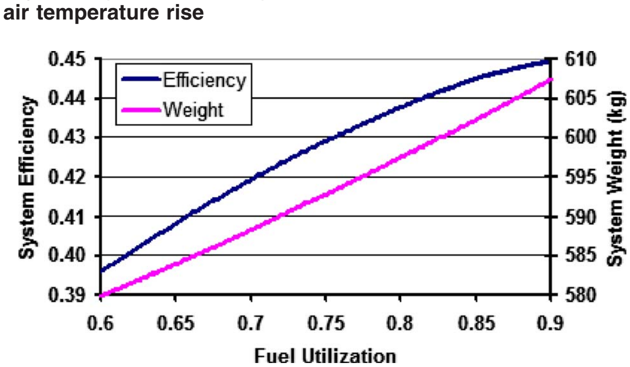

Fig. 12 System efficiency and weight versus fuel utilization

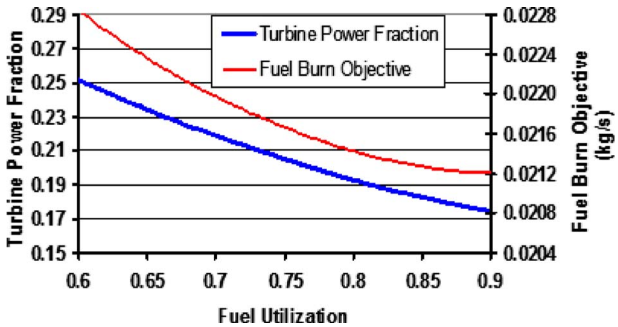

Fig. 13 Turbine power fraction and fuel burn objective versus fuel utilization

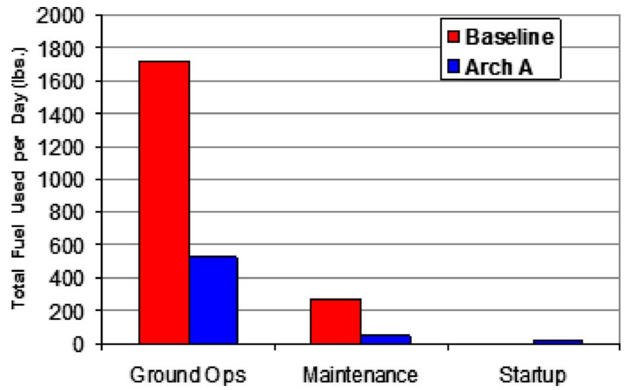

Fig. 14 Fuel savings for Architecture A during ground operations

The fuel burn objective function is shown to reach a minimum near 0.8 V/cell operation and a power density of 180 mW/cm^2. Interestingly, the nonlinear behavior of the fuel burn function is related to the system weight and system efficiency. As cell voltage is increased, system efficiency increases (fuel burn is reduced) and net system weight (due to the combined effect of the pressure vessel and the SOFC stack) also increases. As the cell voltage increases, the number of cells required to deliver a specified stack dc power output increases exponentially and eventually overrides benefits in system efficiency. However, while the fuel burn objective is shown to have a minimum, the economics of the SOFC-APU system must also be considered and thus, a higher power density design point (250 mW/cm^2 at 0.745 V) was chosen for the analyses to accommodate lower system costs.

Cell Temperature and Cathode Air Temperature Rise. A study of the effect of cell operating temperature and cathode air temperature rise on system performance revealed that the stack temperature is the more influential parameter. Figs. 10 and 11 depict this result. In Fig. 10, increases in stack temperature increase stack (and system) efficiency due to lower cell polarizations. When maintaining the net system power output at a fixed value, the effect of an increase in fuel cell-stack efficiency has two primary consequences: (1) it lowers the amount of cooling air that the compressor must supply to the fuel cell system, and (2) it enables a higher system efficiency by operating at a higher stack voltage (and lower current density) and hence reduced fuel input to produce the same amount of power. Thus, while parasitic power is reduced by 20% (~2.5 kW) over the range investigated in Fig. 10, the more significant effect is an increase in stack efficiency of nearly 25%, which translates into an increase in system efficiency of 7 percentage points.

While air flow in the system is influenced by the magnitude of the cathode air temperature rise, only slight changes in system efficiency are realized as the blower parasitic power requirements represent only 3% of the net system power output. From Fig. 11, it is evident that neither gain nor loss in stack efficiency occurs as cathode air temperature rise is altered and cell temperature is held fixed. Only a small increase in system efficiency due to the lower blower parasitic power is observed.

Operating Fuel Utilization. Figure 12 shows that system weight is nearly linear with the amount of fuel utilization and is only mildly sensitive, changing by less than 5% over the range of interest. Changes in SOFC-based APU system weight with fuel utilization are largely due to changes in the power distribution between the small gas turbine and SOFC stack. In order to maintain a fixed SOFC power density of 250 mW/cm^2 and an overall APU power output of 300 kW, the number of cells within the fuel cell stack (and therefore the weight) increases as fuel utilization increases. The increase in SOFC stack cell count raises the fuel cell's portion of total system power output and lowers the power output of the small gas turbine, thereby also increasing the net system efficiency. However, the system efficiency versus fuel utilization trend contains some nonlinearity due to the nonlinear component efficiency responses.

The amount of power generated in the expander is of interest when evaluating the selection of system fuel utilization. Figure 13 shows the impact of system fuel utilization on the fraction of turbine-to-total system power and fuel burn objective. The turbine power fraction decreases with increasing utilization as less fuel energy is provided to the catalytic combustor. The fuel burn objective function also decreases as fuel utilization and system efficiency increase. The fuel burn objective function is shown to decrease less rapidly with increasing fuel utilization due to the larger decrease in drag associated with system air input. A value of 88% fuel utilization was selected based on the minimum fuel burn objective function achieved near that value.

APU System Performance Comparisons

Ground Operations. The efficiency advantage of the SOFC-APU Architecture A system over the baseline APU during ground operations is about 28 percentage points (45% versus 17%). This increase in APU efficiency results in a fuel savings of about 70% (1397 lb/day) over the course of one day of aircraft ground operations. The distribution of savings is depicted in Fig. 14, where ground operations consume most of the fuel and therefore offer most of the daily fuel savings. Additional savings occur during the maintenance portion of the daily operations. A small penalty in fuel burn can also be observed for the fuel consumed during SOFC system startup. As previously indicated, the total aircraft fuel consumed during daily operations (including main engine flight operations) is on the order of 41,000 lb (18,594 kg). Thus, about 3.3% fuel burn savings are possible from efficiency improvements during ground operations.

In-Flight Operations. The efficiency of the SOFC-APU system is higher than the engine-mounted electric generator and therefore enables some fuel burn savings to be realized during the mission flight segments, whereas the conventional APU is not typically operated during the in-flight segment due to its poor efficiency. As previously shown in Fig. 3, aircraft electrical loads range from about 170 kW to 280 kW during flight. It is during in-flight aircraft operation that the SOFC exhaust gas heat recovery to the main engine fuel supply is possible. The result of operating the SOFC-based APU during the climb-cruise-descent portion of the mission is a 1.3% savings in total aircraft fuel burn. The distribution of the net savings is illustrated in Fig. 15. The SOFC system weight and ram-air drag penalty adds about 1.5% more fuel burn to the flight mission. This increase in fuel consumption is offset by 2.9% fuel burn savings in electric power generation for aircraft hotel power and an increase in main engine efficiency by preheat of the engine fuel supply. A net savings of 1.3% in fuel burn over

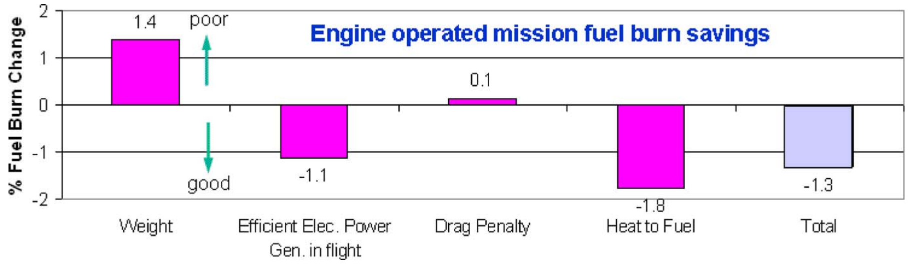

Fig. 15 Architecture A fuel burn savings during climb-cruise-descent

an entire day of operations is achieved. The total fuel consumption savings from both ground and flight operations amounts to nearly 4.7%.

Architecture B: More Integrated SOFC System

A second system architecture (B) was explored that achieves greater integration between the SOFC and aircraft systems, and includes technologies that target higher performance but are associated with greater perceived technological risks. Greater integration is achieved between the SOFC and aircraft subsystems with smart sizing of the components. Architecture B includes all the features of the Architecture A system and three additional architecture concepts:

(i) SOFC-gas turbine and ECS turbocharger on the same shaft
(ii) SOFC sized for ground operations on a normal day
(iii) a more efficient SOFC system

The first concept decreases the weight of the power electronics equipment, the second one provides a lower weight SOFC system while not compromising the efficiency on a typical day, and the third improves the operating efficiency and hence decreases the overall mission fuel burn. By sizing the SOFC-APU for typical day conditions, the power requirements for hot day operations are met by the engine-mounted generator. The SOFC efficiency increases to nearly 70% at cruise conditions and 53% at ground conditions. Architecture B APU electric loads during the ground operation remain the same as in the baseline and Architecture A cases; however, due to the different sizing strategiey of the components, the in-flight climb-cruise-descent operation mission performance changes. In addition, the engine-mounted generators provide the electrical power for the anti-ice loads, similar to that of the Architecture A system. Higher efficiency of the SOFC system was obtained by increasing the fuel processing efficiency by operating the ATR at lower O_2/C and H_2O/C ratios than the current technology allows, increasing the cell-stack temperature, and by cracking a portion of the fuel to enable some internal reforming to take place within the SOFC.

Using the UTC ITAPS™ tools, the Architecture B system performance for the aircraft mission was evaluated. The overall system weight increased by 560 kg (1% mission fuel burn penalty from baseline) relative to the baseline system. The tighter integration also enabled a 10% weight reduction over Architecture A. Figure 16 shows the benefits or the penalties of the Architecture B concepts relative to Architecture A. While system efficiency increased and reduced the air input requirements, the ram-air drag decreased by only 2 kg (negligible fuel burn savings). The daily fuel consumption decreased by 1.3% due to the more efficient electricity production during climb-cruise-descent operation and by 0.2% from more efficient ground operations. Another 0.2% savings are associated with the reduced capacity SOFC stack arising from sizing for typical day ground operations rather than the hot day condition. Integration of the SOFC and ECS turbomachinery enabled an additional 0.3% fuel consumption savings due to the concomitant weight reduction. Together, an additional 2% point efficiency benefits can be achieved with Architecture B relative to A (as shown in Fig. 16) and 6.7% fuel burn savings relative to the baseline.

Economic and Emission Performance

Economic Performance. The economic impacts of the changes embodied in the two architectures studied are shown in Fig. 17 in 2006 U.S. dollars. Replacing the conventional gas turbine APU with an SOFC system resulted in a weight increase of 847 kg for Architecture A and 560 kg for Architecture B.

The benefits from SOFC integration can be broadly classified in terms of either APU ground or APU flight operations. Benefits from ground operation arise from more efficient electricity production and are debited for fuel used for starting up the APU. Benefits from flight operations are found in the net gain from certain credits, like improved electric power production efficiency, reduced shaft extractions, improved engine cycle with heat addition to fuel, and certain debits, such as drag incurred for supplying air to operate the SOFC and increased fuel burn due to additional weight for the SOFC system and its aircraft integration.

All SOFC system architectures analyzed required an air source during flight when a conventional APU would be shut down. The

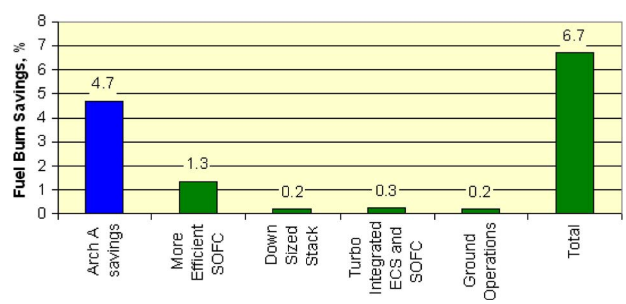

Fig. 16 Architecture B: Benefits of included concepts achieve 6.7% overall fuel burn savings

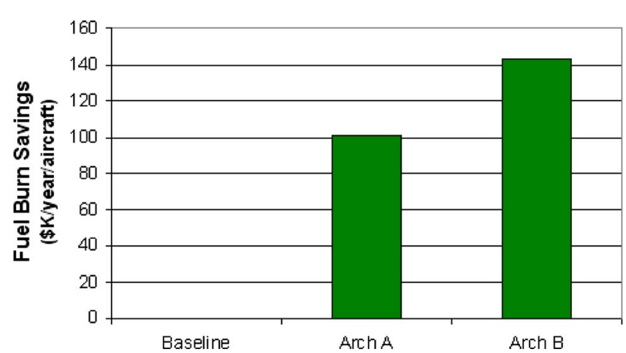

Fig. 17 Financial impact of fuel burn savings of architectures investigated

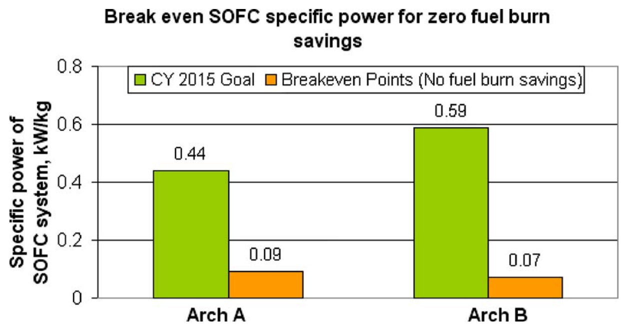

Fig. 18 Year 2015 EIS SOFC system weight goals and break even points (no fuel burn savings)

ram-air drag incurred due to the uptake of air, and the loss in cabin air thrust recovery for Architectures A and B resulted in increased mission fuel burn.

The net fuel burn benefit due to the sum of all of the individual factors above provides the primary influence on operational savings. The net fuel burn savings is 922 kg/day for Architecture A and 1315 kg/day for Architecture B. Figure 17 shows the financial benefits of these architectures and illustrates that the annual savings are on the order of \$100,000–\$140,000 per aircraft. The assumptions for this estimate are the price of aviation fuel at \$0.9/gal, which is substantially less than fuel prices at the time of this writing, and 365 days a year of operation. At a system cost of \$1300/kW for Architecture A, the simple payback is less than 4 years. (Note that simple payback would be <2 years at current fuel prices.) It is clear that the greater consideration of integration of the SOFC system into the aircraft systems is beneficial.

Achieving the required system specific power is critical to realizing the fuel burn benefits discussed above. Figure 18 depicts the year 2015 SOFC system weight goals and the break-even point in terms of fuel burn savings for Architectures A and B. To realize any fuel burn benefit from a SOFC system for a short-range commercial aircraft, the SOFC system specific power should be >0.07 kW/kg (best case SOFC system—Architecture B). The SOFC system specific power will not affect the ground APU emission benefits. However, the engine emissions will increase due to the increased fuel burn from the gain in SOFC system weight. Furthermore, the value proposition for the fuel cell system results in many years to achieve payback (although this economic outlook is strongly dependent on fuel prices). At specific powers higher than the breakeven point, but greater than 0.09 kW/kg SOFC system, the payback time is more than 5 years. At a system specific power of 0.59 kW/kg the payback is achieved in 2 years. As fuel prices climb, the payback economics will only improve the economic viability of SOFCs for APU systems and thus, gains in system specific power will be increasingly valuable.

Emission Performance. Figure 19 depicts the emissions and emission reductions for both Architectures A and B during different mission segments. None of the SOFC systems studied produces any oxides of nitrogen (NO_x), carbon monoxide (CO), or unburned hydrocarbons (UHC), thus the reductions are 100% during ground operations as Figure 19(*a*) shows. The use of a SOFC system in place of a conventional APU impacts the emissions from the engine in a number of ways. The main impact is through the reduction in fuel burn as previously discussed. The changes in engine extractions cause some changes in the temperatures and pressures inside the engine for a given thrust level; hence, the emissions do not track exactly with fuel burn. Furthermore, a portion of the fuel used for electric power generation by the fuel cell APU burns clean, reducing the overall emissions. Thus, in Architectures A and B, the engine emissions decrease by 3.5–6% for NO_x, by 8–10% for CO, and by 12–14% for UHC, as Figure 19(*b*) shows.

The total aircraft emissions for the two architectures relative to the baseline are shown in Fig. 20(*a*) during engine operation and in Fig. 20(*b*) during the landing and take-off (LTO) cycles, which

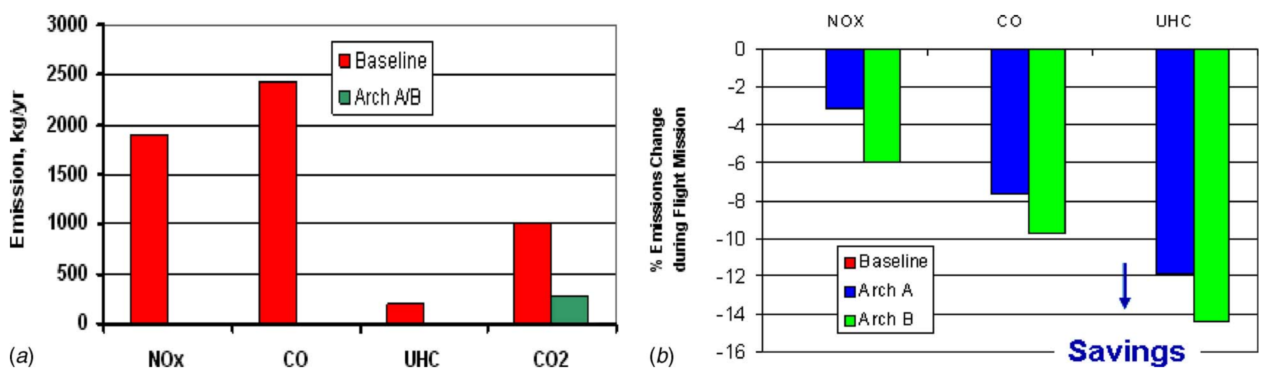

Fig. 19 Emission/emission reductions for Architectures A and B during (*a*) ground operations and (*b*) flight operations

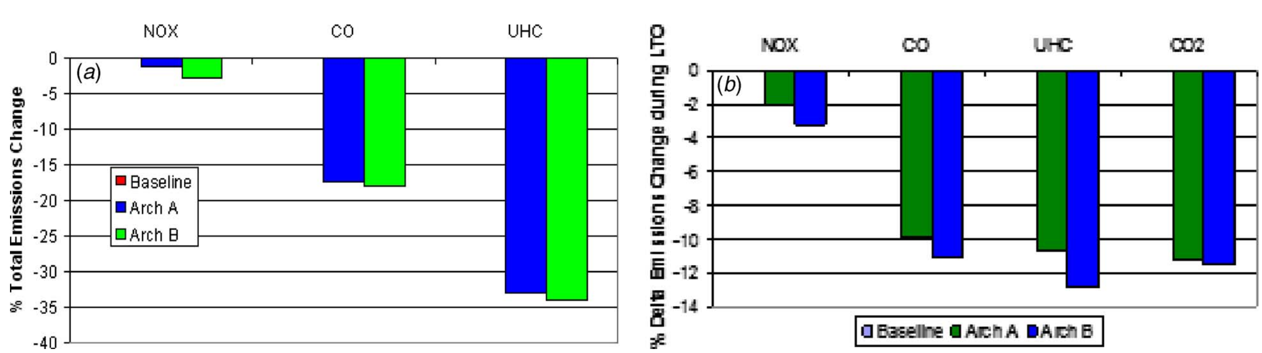

Fig. 20 Total aircraft emissions for entire mission relative to baseline for (*a*) engine operations and (*b*) LTO cycle

occur below 3000 ft (0.9 km) altitude. Ground emissions and LTO emissions are of particular interests at airports, where air quality requirements are increasingly difficult to meet. As Fig. 20(*b*) shows, substantial reduction in CO and UHC is achieved by operating the fuel cell during the LTO cycle.

Technology Gaps. Technology gaps that need to be closed to realize the fuel burn benefits discussed in this study are summarized for the SOFC stack and fuel processing hardware. A key gap is associated with SOFC stack and system specific powers. To achieve the EIS 2015 goal metrics (weight, life, etc.) required for aerospace applications, a paradigm shift is needed in SOFC stack concepts and technology development. This is based on the four times improvement needed for the stack weight and seven times improvement needed for the SOFC system weight, using current state-of-the-art fuel cell and BoP technologies. Additionally, the startup time required for SOFCs is longer by several hours rather than the minutes required. While system startup strategies have been evaluated [3], the metal-supported SOFC stack hardware needed to enable startup times to less than 30 min are not currently available. Stack durability (e.g., thermal cycling) and lifetime also need to be substantially improved. SOFC system cost has been estimated at \$1300/kW (current study) and stack and BoP technology will need to be substantially reduced from current levels to reach this requirement.

Desulfurization of Jet A fuel is critical for operation of the SOFC system and is a nontrivial challenge. The assumption in this study has been that ground-based desulfurization solutions will not be readily and universally available at all airports and therefore, a low maintenance and compact regenerative scheme for sulfur removal down to <1 ppmv S for aerospace applications is desirable. An athermal microwave adsorbent regeneration process [11] has been employed in conjunction with sulfur removal sorbent beds in the present analysis. Proof-of-concept testing has successfully been performed [11], but sorbent capacity for replacement every 10,000 h must be developed and sorbent weight must decrease by two times to obtain <0.9 kg/L. Furthermore, aircraft integration issues will need to be resolved with the desulfurization process.

Fuel reformer requirements include a lifetime of 10,000 h or greater while achieving at least 95% fuel conversion and assembly into a compact package that is less than 3 kg/L. In order to obtain these requirements at aggressively low O_2/C and H_2O/C operating conditions without carbon deposition, highly active and stable catalyst development will be required. The size of ATR will also have to decrease by a factor of 2.

Integration of the SOFC-APU into the airframe to achieve the stated benefits also has some challenges. Arguably, the SOFC-APU location should be closer to wing roots (or engines) rather than the customary tail cone position to take advantage of many integration benefits. For example, the benefits that arise from the waste heat recovery and the exhaust gas utilization concepts will not be realized if the SOFC-APU is located in the tail cone. Aside from pinpointing the location of the SOFC-APU, future efforts should be prioritized to the development of advanced stack, reforming catalyst, and desulfurization concepts that have the potential to realize the benefits identified in this study.

Conclusions

This study selected an aggressive year 2015 EIS aircraft for baseline systems (UEET engines, advanced more-electric APU and more-electric aircraft subsystem concepts). Two different aircraft system architectures (A and B) integrated with SOFC-based APUs were evaluated relative to this short-range commercial aircraft baseline system. The basic process design of the Architecture A SOFC system was discussed and parameter sensitivity explored. The features of a more efficient SOFC system design in Architecture B were highlighted and the potential benefits (emissions and fuel burn) of both SOFC-based APU system architectures were quantified. The key technology development areas and SOFC stack requirements were also presented.

The hybrid SOFC system architectures featured efficiency performances ranging from 45–53% during ground operations and 64–70% during the cruise flight segment. Optimal system operating parameters were explored using an objective function strongly correlated with fuel consumption. While an optimal system pressure with respect to minimum system weight was found, the fuel burn objective function pointed toward an asymptotic minimum of near 5 bar. SOFC stack limits set a constrained optimal system pressure of about 3.1 bar.

System integration is critical to maximize benefits from the SOFC-APU for aircraft applications and will help to minimize the technology development cost/time. The mission fuel burn savings for Architecture A, with integrated design concepts from the best architecture of a previous study, is 4.7%. Architecture B, with a higher degree of system integration and higher risk technologies, delivered fuel burn benefits of 6.7%. The per aircraft savings are greater than \$100,000 k/yr and emission reductions of 70% or more are possible during ground operations. Total emission reduction ranges from 2% (NO_x) to 33% (UHC) per one day of operations.

While the benefits of integration of a high specific power SOFC-APU has been evaluated at a conceptual level, the impact of location, the volumetric size of the SOFC, safety and reliability concerns with certain integration concepts, and electrical system integration remain as open issues. These areas would be the foci for further studies.

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References

[1] Liang, A. D., 2003, "Emerging Fuel Cell Developments at NASA for Aircraft Applications," Fourth Annual SECA Meeting, Seattle, WA, Apr. 15–16.

[2] Daggett, D., 2003, "Commercial Airplanes, Fuel Cell APU Overview," Fourth Annual SECA Meeting, Seattle, WA, Apr. 15–16.

[3] Gummalla, M., Pandy, A., Braun, R. J., Carriere, T., Yamanis, J., Vanderspurt, T., Hardin, L., and Welch, R., 2006, *Fuel Cell Airframe Integration Study for Short-Range Aircraft, Vol. I: Aircraft Propulsion and Subsystems Integration Evaluation*, prepared by United Technologies under Contract NAS3-01138 Task 28 for NASA Glenn Research Center, NASA CR-2006-214457/VOL1.

[4] Liang, A. D., 2004, "NASA Fuel Cell Power System Development for Aerospace Vehicles," 2004 Fuel Cell Seminar, San Antonio, TX, Nov. 1–5.

[5] Srinivasan, H., Yamanis, J., Welch, R., Tulyani, S., and Hardin, L., 2006, *Solid Oxide Fuel Cell APU Feasibility Study for a Long Range Commercial Aircraft Using UTC ITAPS Approach, Volume I—Aircraft Propulsion and Subsystems Integration Evaluation*, prepared by United Technologies under Contract NAS3-01138 Task 20 for NASA Glenn Research Center, NASA CR-2006-214458 VOL1.

[6] Kaslusky, S. F., Sabatino, D. R., and Zeidner, L. E., 2007, "ITAPS: A Process and Toolset to Support Aircraft Level System Integration Studies," 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 8–11, Paper No. AIAA 2007-1394.

[7] Joyner, C. R., and McGinnis, P. M., 2004, "The Application of ITAPS for Evaluation of Propulsion and Power at the System Level," 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, Jul. 11–14, Paper No. AIAA 2004-3849.

[8] Process Systems Enterprise, Ltd., 2006, http://www.psenterprise.com/gproms/index.html, as accessed on 11/15/2006.

[9] Hecht, E. S., Gupta, G. K., Zhu, H., Dean, A. M., Kee, R. J., Maier, L., and Deutschmann, O., 2005, Appl. Catal., A, **295**, pp. 40–51.

[10] Mak, A., and Meier, J., 2007, *Fuel Cell Auxiliary Power Study, Volume 1: RASER Task Order 5*, prepared by Honeywell Engines, Systems & Services, under Contract NAS3-01136 for NASA Glenn Research Center, NASA CR-2006-214461/VOL1.

[11] Emerson, S., Arsenault, S., Campbell, T., MacLeod, J., Ma, Z., and Vanderspurt, T., 2006, "Desulfurization of Logistic Fuels Using Athermal Adsorbent Regeneration," Sixth Annual Logistics Fuel Processing Conference, Panama City, FL, May 16–17.