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Fuel Cell Airframe Integration Study for Short-Range Aircraft

Volume 1: Aircraft Propulsion and Subsystems Integration Evaluation

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Summary

The objective of this contract effort was to define the functionality and evaluate the propulsion and power system benefits derived from a Solid Oxide Fuel Cell (SOFC) based Auxiliary Power Unit (APU) for a future short-range commercial aircraft, and to define the technology gaps to enable such a system. The study employed technologies commensurate with Entry into Service (EIS) in 2015. United Technologies Corporation (UTC) Integrated Total Aircraft Power System (ITAPS) methodologies were used to evaluate system concepts to a conceptual level of fidelity. The technology benefits were captured as reductions of the mission fuel burn, emissions, noise and life cycle cost.

At the system level, the overall integration of a fuel cell power unit, turbine engines and power subsystems for a short-range commercial transport was evaluated and the associated enabling technologies were identified. The baseline aircraft considered is a 162 PAX airframe with more electric subsystems, Ultra Efficient Engine Technology (UEET) engines, and an advanced, increased efficiency, electric output APU, which includes an auxiliary generator. In addition to the baseline architecture, two architectures using an SOFC system to replace the conventional APU were investigated.

Architecture-A included the best concepts from a previous [NASA RASER study conducted under NAS3–01138, Task Order 20] SOFC gas turbine (GT) hybrid system, which operated for all phases of the mission, including the flight climb-cruise-descent operation, thereby reducing the engine shaft extractions substantially. A specific power SOFC system tightly integrated with aircraft systems is used for the analysis. Architecture-B comprised greater integration between the SOFC system and aircraft Environmental Control System (ECS), Thermal Management System (TMS), and Electrical Power System (EPS), and led to improved overall system efficiency and hence reduced the mission fuel burn.

System integration is critical to maximize benefits from the SOFC APU for aircraft application. The mission fuel burn savings for Architecture-A, which had the best concepts from previous study, was 4.7 percent. Architecture-B with high efficiency SOFC system and reduced weight, due to greater functional integration, resulted in 6.7 percent fuel burn savings in total. A substantial part of the savings is from ground operations. The second contributing factor to the savings is the more efficient electricity production in flight and reduced shaft extractions from the engine, during the idling, taxi, climb, cruise and descent segments of the mission. The impact of shaft power extraction on fuel burn is most severe at low power settings where the engine is operating at low efficiency.

The SOFC system has higher capital cost than a conventional APU. However, the maintenance costs and operational costs are lower. With benefits from Architecture A, the payback time for the SOFC is 5 years, and for Arch B is 2 years, at fuel cost of $0.9/gal.

The SOFC APU produces zero emissions, thus eliminating the emissions from the conventional APU. The reduction in engine fuel burn (partly due to reduced extractions, and efficient electricity production) also results in a reduction in emissions from the engines. For Architecture-B, the engine emissions in flight decreased by 1.8 percent for oxides of nitrogen (NO_X), 5.6 percent for carbon monoxide (CO) and 10.5 percent for unburned hydrocarbons (UHC). The landing and take-off (LTO) emissions from the engines were reduced by 3 percent for NO_X, 11 percent for CO, and 13 percent for UHC.

The noise level of the baseline APU during ground operations is 77 dBA, with a silencer. The Architecture-A SOFC APU produces a noise level of 65 dBA, needing no silencer.

While the benefits of integration of a high specific power SOFC APU have been evaluated at a conceptual level, the impact of location, volumetric size of the SOFC, safety and reliability concerns with certain integration concepts and transient electrical system compatibility remain as open issues.

1. Introduction

Recent advancements in fuel cell technology from the Department of Energy (DOE) and industry have set the stage for the use of SOFC systems in aircraft applications. Conventional gas turbine APUs account for 20 percent of airport ground based emissions. Airport ground emissions will only worsen with increased air travel unless new technology is introduced. To address these issues, NASA formulated a plan to advance solid oxide fuel cell capabilities for a wide range of aircraft power and propulsion applications (ref. 1). The plan builds on the DOE's 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 is the UTC NASA study (NASA Raser study conducted under NAS3–01138, Task Order 20) which indicated 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 conducted as part of that study showed that the SOFC system provided about 3 percent mission fuel burn savings for the short-range mission as compared to only 0.7 percent mission fuel burn savings for the long-range mission. This present NASA study is intended to look into the potential short-range mission benefits of tightly integrating the SOFC fuel cell with aircraft subsystems using UTC ITAPS proprietary methodologies.

1.1 Objective

The objective of the 'Aircraft Propulsion and Subsystems Integration Evaluation' (NAS3–01138: Task Order 28) contract effort is to define the functionality of a high specific power SOFC system concept as an Auxiliary Power Unit (APU) for a future short range aircraft, evaluate the propulsion and power system benefits derived and define the technology gaps to enable such a system.

1.2 Scope

The project scope is defined by the following:

- The technologies would be commensurate with the year 2015 Entry into Service (EIS)
- The 162 passenger (PAX) aircraft short-range mission requirements and the United Technology Corporation UTC Integrated Total Aircraft Power System (ITAPS, United Technology Corporation) methodologies were used to evaluate technologies as elements of complete system concepts.
- The future SOFC systems were designed to exceed the Department of Energy (DOE) program Solid-state Energy Conversion Alliance (SECA) goals to achieve high specific power.
- The system architectures were evaluated to a conceptual level of detail and fidelity.
- ***Metrics***: The technology benefits were captured as reductions in emissions, noise, and life-cycle cost, while highlighting the fuel burn savings where applicable.
- ***Baseline System***: A "rubber" 162 PAX Short-Range Commercial Aircraft with
    - More electric subsystems
    - Ultra Efficient Engine Technology (UEET) engines
    - Advanced, more electric APU (with ceramics)

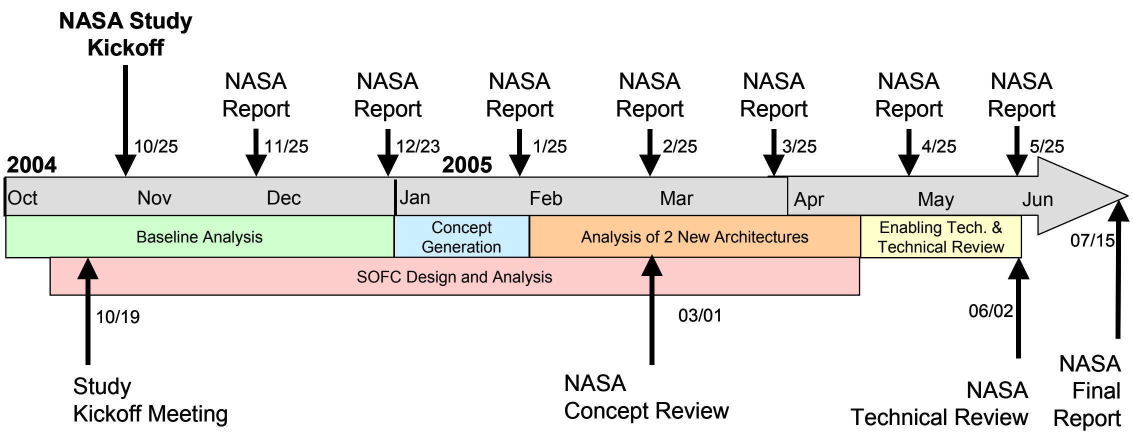


Figure 1.—Tasks and events.

1.3 Tasks

At the system level, the overall integration of a fuel cell power unit, turbine engines and power subsystems for a short-range commercial transport were evaluated and the associated enabling technologies were identified. The work covered the following general areas of activity:

- Establish Baseline Short-Range Airplane (Task-1),
- Steady State and Transient Analysis of a SOFC System (Task-2),
- Generate Integrated SOFC System Concepts (Task-3),
- Evaluate Future SOFC Powered Architectures (Task-4), and
- Study Results and Technology Planning (Task-5).

Figure 1 shows the key events and the tasks executed for this project.

1.4 Study Challenges

Technical challenges encountered in using the SOFC system for aircraft application are listed below:

- The SOFC system specific power (kW/kg) is about three times lower than that of a conventional gas turbine APU. The corresponding weight penalty increases the amount of fuel burned by the aircraft (equivalent of 1.4 percent aircraft mission fuel burn).
- The SOFC system operation during flight cruise conditions requires an input air stream, and providing that air from the ambient (ram air) introduces ram-drag penalties. These ram-drag penalties increase the amount of fuel burned by the aircraft (equivalent of 0.1 percent aircraft mission fuel burn).
- The SOFC system (which is a hybrid system with the SOFC stack and the turbo-machinery) produces both ac and dc power. The dc power is from the stack and 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 inefficiencies.
- The ceramics based fuel cell technology of the SOFC system requires a relatively long time (more than 30 min) to startup the SOFC system. Therefore, designs that can enable rapid start-up and provide good thermal cycling capability are desired.
- The processing of the Jet-A fuel, with sulfur levels between 300 to 1000 ppm, requires a bulky de-sulfurizer, which restricts the de-sulfurization options for the aircraft applications.

- The exhaust gas coming out of the SOFC system is at rather high temperature (> 600 °F) and utilization of this hot stream is a challenge.

To realize any potential benefit from the SOFC system for aircraft APU application, system integration concepts for the SOFC system should provide substantial compensating benefits to overcome penalties imposed by these technical challenges. The current study uses some of the proprietary concepts for the SOFC stack and system design, desulfurization, and heat utilization to maximize the benefits of integration of an SOFC system as an APU for short-range more-electric aircraft.

1.5 Related Documents

A companion report, "Fuel cell Airframe Integration Study for Short-Range Aircraft: Volume II - Subsystem Details of Architectures Studied," documents the details of the subsystems involved in the study. The subsystem details report contains limited-rights data.

2. Power System Architectures: Synthesis and Benefits

This section presents the system evaluation results for the various power system architectures: (i) Baseline system, (ii) Architecture-A, and (iii) Architecture-B.

2.1 Baseline System

The baseline aircraft system is a UEET engine powered aircraft from an earlier Pratt & Whitney/NASA study. The baseline consists of a study airplane for short-range missions with UEET engines, an advanced more-electric APU and more-electric-aircraft (MEA) sub-systems (electric engine start, electric driven environmental control system, electric wing anti-ice and electric and hydraulic powered actuation).

All baseline APU power requirements are electrical, and the auxiliary generator is considered part of the APU. APU electric load requirements and the ground operation times are shown in figure 2. During regular operation, the APU remains operational until the "taxi-out". During the flight segment the APU 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). Ultimately, the size of the APU is determined by the peak electrical power demand on a hot day for ground conditions.

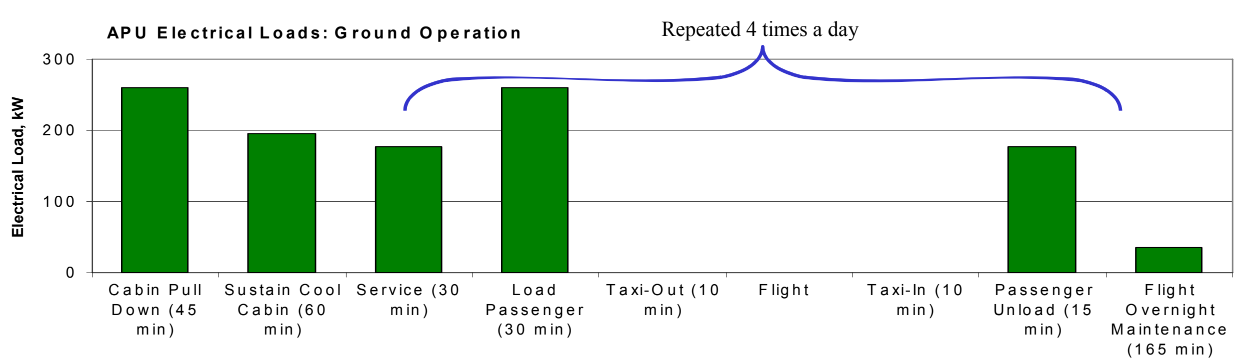


Figure 2.—Baseline: APU electrical loads for ground operation.

TABLE I.—BASELINE: MISSION PROFILE

Mission Points	Designation	Altitude (feet)	Mach Number	Elapsed Time (min)
MP1	Engine Start	0	0	0
MP2	Begin Taxi Out	0	0	1
MP3	End Taxi Out	0	0	9
MP4	Begin Take Off	0	0	9
MP5	Begin Initial Climb	0	0.198	9
MP6	End Initial Climb	1500	0.388	10
MP7	Begin Climb @ 250 KCAS	1500	0.388	10
MP8	Begin Accel @ 10000 ft	10000	0.4523	13
MP9	Begin Climb @ 280 KCAS	10000	0.5056	14
MP10	Begin Climb @ 0.80 Mach	33710	0.8	27
MP11	End Climb	39000	0.8	33
MP12	Begin Cruise	39000	0.8	33
MP13	End Cruise	39000	0.8	124
MP14	Begin Descent @ 0.80 Mach	39000	0.8	124
MP15	Begin Descent @ 280 KCAS	33710	0.8	126
MP16	Begin Decel @ 10000 ft	10000	0.5056	142
MP17	Begin Descent @ 250 KCAS	10000	0.4523	142
MP18	End Descent	1500	0.388	149
MP19	Begin Decel @ 1500 ft	1500	0.388	149
MP20	End Decel @ 1500 ft	1500	0.186	151
MP21	Begin Approach	1500	0.186	151
MP22	End Approach	0	0.181	153
MP23	End Rollout	0	0	154
MP24	Begin Taxi In	0	0	154
MP25	End Taxi In	0	0	159

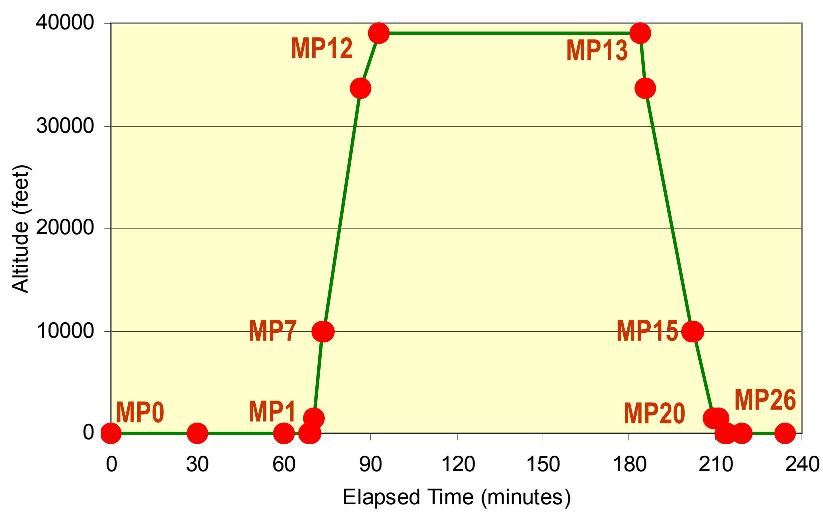


Figure 3.—Baseline: Mission profile.

The baseline aircraft performance analyzed is a 162 passenger, sized for a 3200 nmi mission at a cruise Mach number of 0.8. The mission analyzed for this study is a 1000 nmi mission for which the optimum cruise altitude was 39,000 ft. Table I and figure 3 show the aircraft mission for the climb-cruise-descent segment. In table I, KCAS refers to the Knots, Calibrated Air Speed. The flight segment represented by the mission points MP0 through MP1 corresponds to the ground segment in figure 2. After the end of the descent segment, the taxi-in continues (as in fig. 2). The engines are operational from the beginning of the taxi-out (engine start represented as MP1) to the end of taxi-in (engine stop). The APU is operational during the taxi-out and taxi-in segments, operating at zero loads.

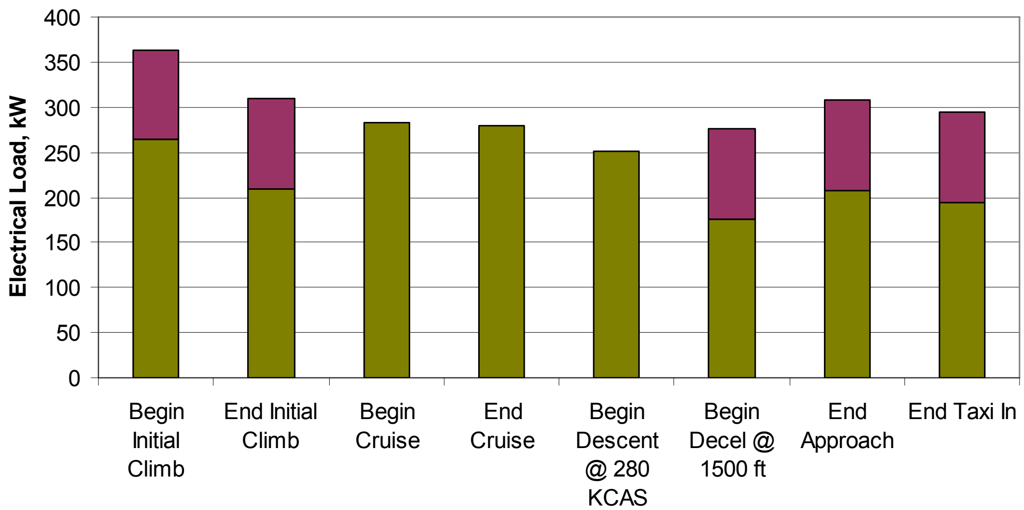


Figure 4.—Baseline: Electrical loads for climb/cruise/descent mission.

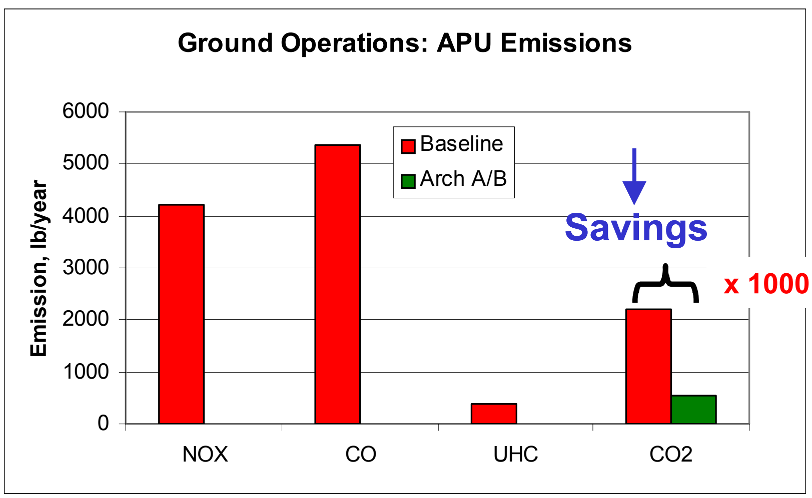


Figure 5.—Baseline: APU Emissions for Ground Operations

Figure 4 shows selected electrical load requirement for the aircraft for the climb-cruise-descent segment, which includes the aircraft electrical service load, ECS electrical load and the electrical portion of the actuation load.

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 icing condition. To satisfy the overall electrical load two engine-mounted generators of 250 kW were required. Using the UTC ITAPS tools the baseline system was evaluated. The fuel burned during APU ground and flight operation, during the climb-cruise-descent segments, was 1996 lb/day and 41,216 lb/day, respectively. The fuel usage is based on four cycles (or flight segments) a day. The Take Off Gross Weight (TOGW) of the baseline system was 153,471 lb.

The NO_X, UHC and CO emissions for the baseline APU and that of the engine (in total emissions per day) are shown in figure 5 and table II. The landing and take off time listed for the engine emissions includes engine start, taxi-out, take off, climb to 3000 ft, decent below 300 ft, approach and taxi-in.

TABLE II.—BASELINE: ENGINE EMISSIONS DURING LANDING TAKE OFF CYCLE AND CRUISE MISSION

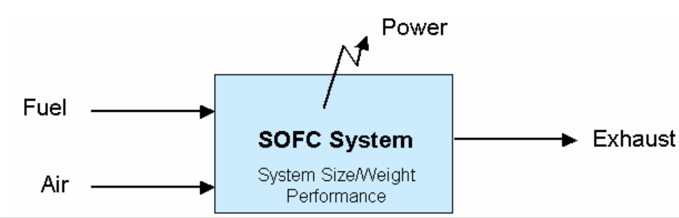
Mission Segment Description	Baseline Actuals per day Duration (hrs)	NOX (lbm)	CO (lbm)	UHC (lbm)
LTO	1.62	140.24	17.17	1.29
Cruise	6.08	582.65	48.25	0.67

3.2 Concept Generation

Rich sets of integration concepts were generated, in addition to those from the previous study (NASA Raser study conducted under NAS3-01138, Task Order 20), and down selected to form two architectures. The first architecture (Architecture A) includes the best concepts from the previous study, with few changes highlighted in the architecture section. The second architecture (Architecture B) includes changes to the SOFC system design as well as aircraft integration. Realizing that the benefits from SOFC integration arise from higher efficiency and minimal weight, the integration concepts were selected to achieve higher performance.

The major concept areas analyzed as a part of different architectures are shown in table III. Also indicated in the same table are the risks associated with some of the concepts. This can be best explained with two examples. In the SOFC system concepts of Architecture A, realistic assumptions based on available experimental data and projected performance of the fuel processing, desired performance of an SOFC system, and 2015 projected performance of turbo-machinery are assumed. In Architecture B several trades were carried out to suggest fuel reformer and stack operating conditions that are thermodynamically achievable. However, these might encounter challenges on durability due to low steam fraction and oxygen fraction that could lead to coking. Similarly, with the concept of partial integration of SOFC and ECS, the turbo-machines are downsized due to this integration. However, the practicality of such integration is not known and potential for co-dependent failure of ECS and SOFC sections is high. Breakthrough technologies may be needed to ensure efficient operation of the equipment over a range of speeds and varying pressure ratios. Some of the risks and technological breakthroughs required in Architecture B are discussed in the later sections of this volume and also in the subsystem details in volume 2.

TABLE III.—CONCEPTS EMBODIED IN CHOSEN ARCHITECTURES



Concept Areas	Architecture A	Architecture B
SOFC Application: System Operation (Ground and Flight)	X	X
SOFC System Integration with other Aircraft Systems	X	X
SOFC System Performance	X	X
SOFC Stack Operating Conditions	X	X
Input Fuel Processing	X	X
Fuel Processing Efficiency	X	X
SOFC DC Electrical Power Reduction		X
System Weight Reduction		X
Exhaust Heat Recovery	X	X
Advanced Integration of SOFC and ECS		X

X	In line with Current Projections
X	Needs a Breakthrough
X	Not Critical

3.3 Architecture-A

Architecture A includes the features of the baseline system and the best features from Arch C of the previous study: (i) Twin SOFC system serving as an APU in place of the gas turbine APU (ii) SOFC system operating during the flight climb-cruise-descent segment thereby reducing the engine shaft extractions substantially (iii) Waste heat from the SOFC system added to the fuel, and (iv) using the overboard flow from ECS as air supply to SOFC. An additional concept of using the SOFC exhaust, after cooling, as tank inerting gas is evaluated separately, discussed in detail in the concepts section is not included in this architecture due to the possibility of formation of carbonic acid, affecting the fuel tank life.

The SOFC APU is a 300 kW system with efficiencies of 64.3 percent at cruise conditions and 44.8 percent at ground conditions (each at full load operation). The APU is sized to serve ground electrical service loads, and to provide ground electrical power required by the electric ECS for cabin cooling on a hot day.

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

(i) proprietary light weight, high specific power stack design,
(ii) proprietary desulfurizer design based on regenerative concepts,
(iii) pressure vessel design with minimum weight (based on an integral shell design at ground temperature; it should be considered as a lower bound estimate) and minimum tolerance to withstand the pressure differentials across it,
(iv) power conditioning for SOFC dc power regulation only (ac power is regulated with EPS equipment weighing 120 lb).

The weight projections are based on the best guess in some cases and these weights should be considered as the minimum weight of the equipment to meet the performance requirements.

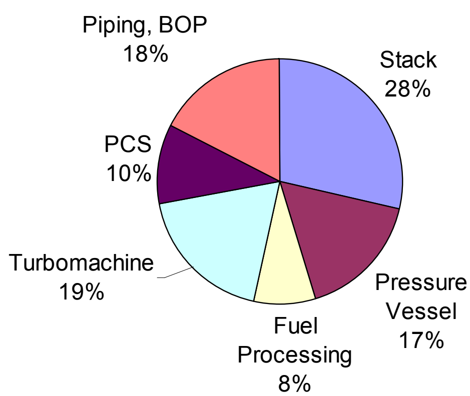


Figure 6.—2015 SOFC system weight goals.

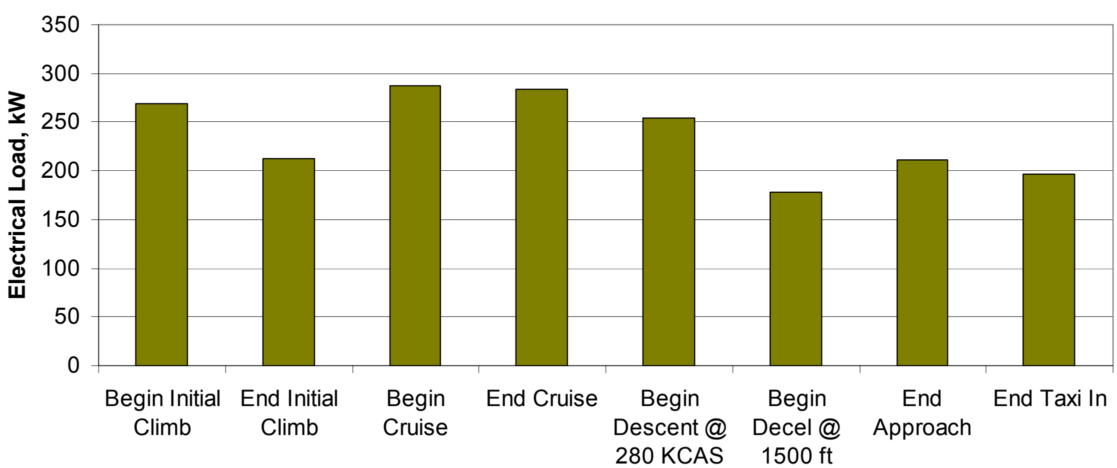


Figure 7.—Architecture-A: Electrical loads on the SOFC for varied mission points, without anti-ice loads.

Aircraft electrical loading powered by the SOFC APU for various mission points is shown in figure 7. The loads on the SOFC are widely varying for different mission points, which challenges the transient operability of the SOFC. Transient response of the SOFC system to the load changes is discussed further in Volume 2, and strategies to mitigate voltage fluctuations on the electric system bus are also discussed. Using the UTC ITAPS tools, the Architecture-A system was evaluated. For the Architecture-A, the NO_X, UHC and CO emissions for the engines are shown in figures 8, 9, and 10, respectively, and of the APU relative to that of the baseline system in figure 11. The SOFC system operates at zero-emissions, (total, or 100 percent improvement relative to baseline) and the engine emissions also improve by 0.2 percent for NO_X, 4.9 percent for CO and 9.2 percent for UHC (figs. 8, 9, and 10, respectively). The overall benefit over the entire mission is not simply the sum of the benefits for each segment of the mission. It is effectively a weighted sum where the weighting is dependent on the duration (or total fuel burned) during each segment of the mission.

The large percentage reduction in the NO_X emissions (fig. 8) for ground operations results from the fact that the engine is operating near idle in those mission segments. The reduction in horsepower extracted from the engines' high spools for architecture A represents a sizable fraction of the total energy consumption of the engine and hence a reduction in fuel flow. Associated with that reduction in fuel flow is a reduction in the combustor inlet temperature that decreases the emissions index for NO_X. Combined with the reduced fuel flow, the lower emissions index (g of emission per kg of fuel) gives a substantial reduction in the net production of NO_X. The NO_X emissions during climb segment are higher than baseline, reflecting the penalty for carrying the additional weight. The reduced combustor temperature leads to a lower combustor efficiency that increases the emissions indices for CO and unburned hydrocarbons. However, the reduced fuel consumption and zero emissions from the fuel cell for its portion of the fuel consumption results in lower emissions for most of the sections.

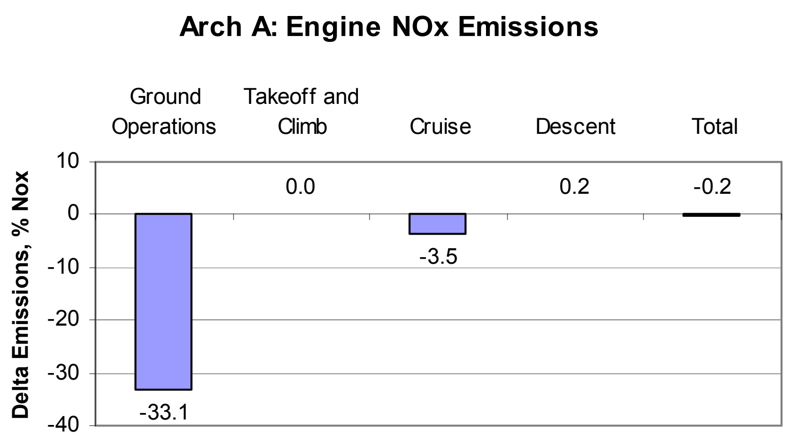


Figure 8.—Architecture-A : NO_x emissions relative to baseline.

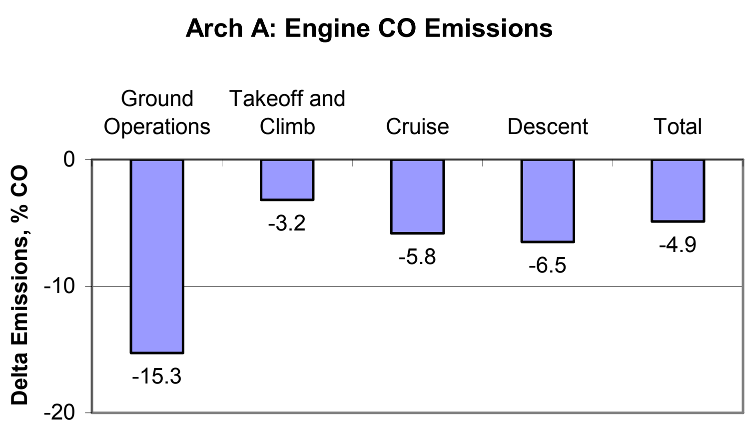


Figure 9.—Architecture-A : Carbon monoxide emissions relative to baseline.

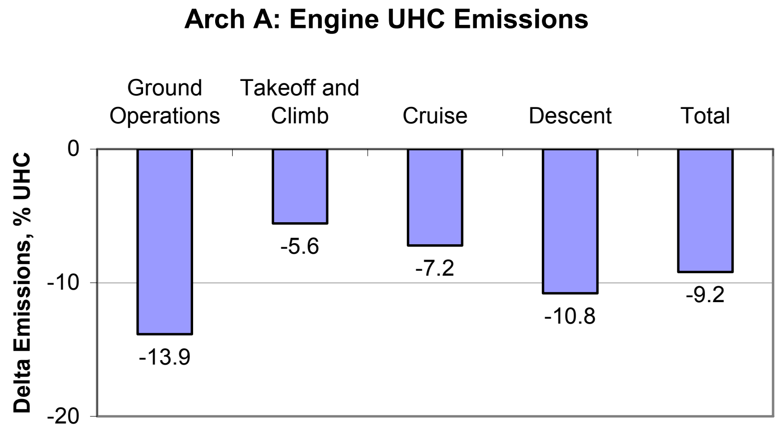


Figure 10.—Architecture-A : Unburned hydrocarbons emissions relative to baseline.

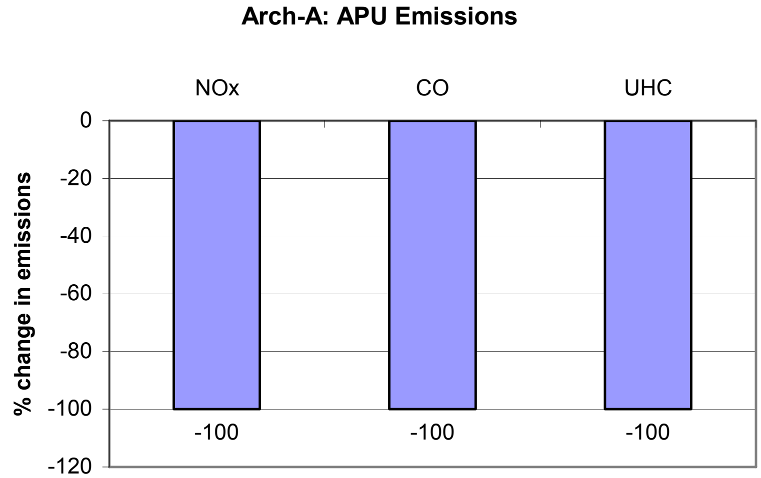


Figure 11.—Architecture-A : APU emissions relative to baseline; SOFC APU achieves 100 percent reduction in emissions.

The percentages shown in figures 8, 9, and 10 should be placed into perspective. For NO_X ground operations account for 0.2 percent of the total NO_X emissions, climb for 50 percent, cruise for 47 percent and the descent segments account for 1.9 percent. Similarly, ground operations account for 9.95 percent of CO emissions and the descent segments account for 15.8 percent. Finally, ground operations account for 33 percent of the total unburned hydrocarbons emissions and the descent segments for 32 percent. It is important to note that, for a shorter mission in this study, the ground, climb, and descent phases are of relatively greater importance. For the long-range mission in previous study, the cruise segments dominate the emissions picture.

3.4 Architecture-B

Architecture-B achieves greater integration between the SOFC and aircraft sub-systems with smart sizing of the components. It includes the features of the Architecture-A system and three additional architecture concepts:

(i) SOFC and ECS turbo-charger on the same shaft,
(ii) SOFC sized for a ground operations on a normal day, and
(iii) 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. The SOFC efficiency goes up to 70 percent at cruise conditions (at full load operation) and 53 percent at ground conditions (at full load operation). However, for Architecture-B, the APU electric load during the ground operation remains the same as baseline and architecture A due to the sizing of the components the flight climb-cruise-descent operation mission changes as shown in figure 12. In addition, the engine-mounted generators provide the electrical power for the anti-ice loads, similar to that of the Architecture-A.

Using the UTC ITAPS tools the Architecture-B system was evaluated. Figure 13 shows the benefits or the penalties of the Architecture-B concepts relative to the baseline system in terms of the percentage equivalent mission fuel burn.

Relative to the baseline, the overall system weight increased by 1,235 lb (1 percent mission fuel burn penalty from baseline and 0.4 percent improvement from Arch A). Relative to Architecture A, the drag decreased by 4 lb (negligible fuel burn savings), fuel consumption at climb-cruise-descent decreased 1.3 percent due to more efficient electricity production at climb, cruise, descent operation, 0.2 percent due to down sized stack arising from sizing for typical day ground operations, 0.3 percent due to weight reduction obtained from SOFC and ECS turbomachinery integration, and 0.2 percent from ground operations due to efficient fuel cell system. Together, an additional 2 percent point efficiency benefits can be achieved with Architecture B relative to A (as shown in fig. 13) and 6.7 percent fuel burn savings relative to baseline.

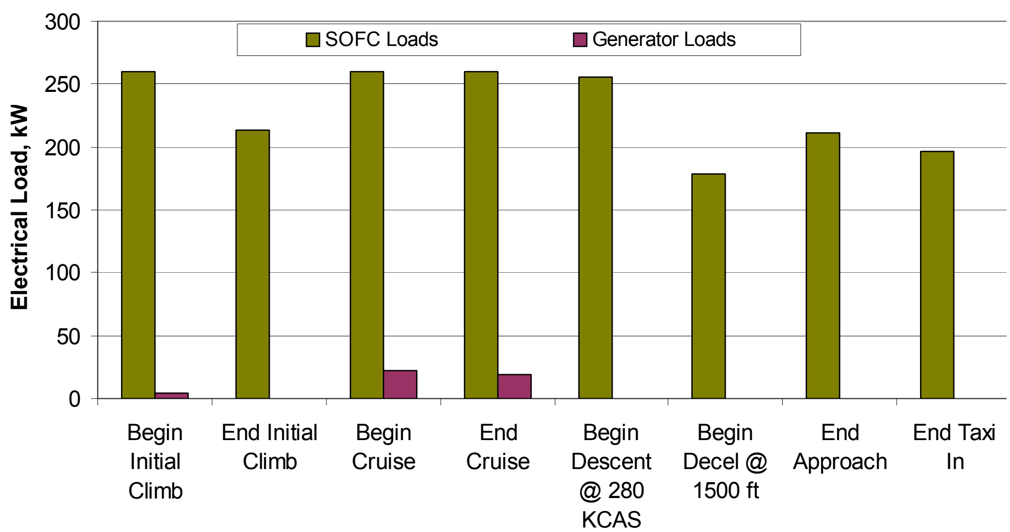


Figure 12.—Architecture-B: Electrical loads on the SOFC for varied mission points, without the anti-ice loads.

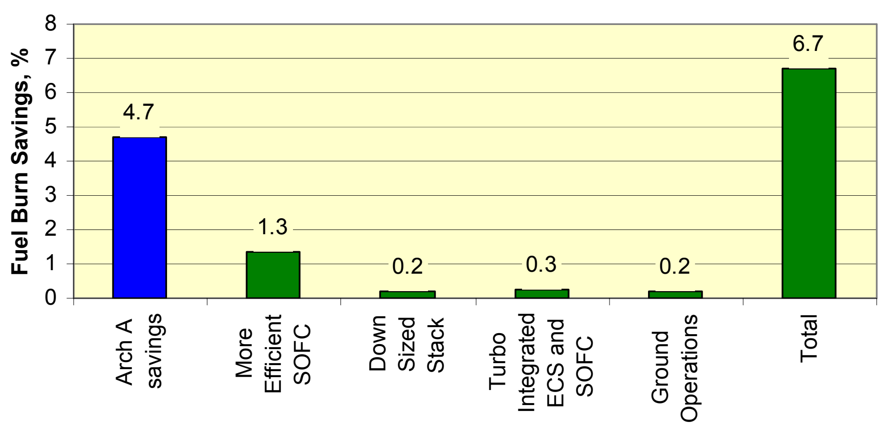


Figure 13.—Architecture B : Benefits of included concepts achieve 6.7 percent overall fuel burn savings.

For the Architecture-B, the NO_X, UHC and CO emissions for the engine relative to that of the baseline system are shown in figures 14, 15, and 16, respectively, and that of the APU in figure 17. The SOFC system operates at zero-emissions (100 percent improvement) and the engine emissions decrease by 6 percent for NO_X and decrease by 9.7 percent for CO and 14.4 percent for UHC.

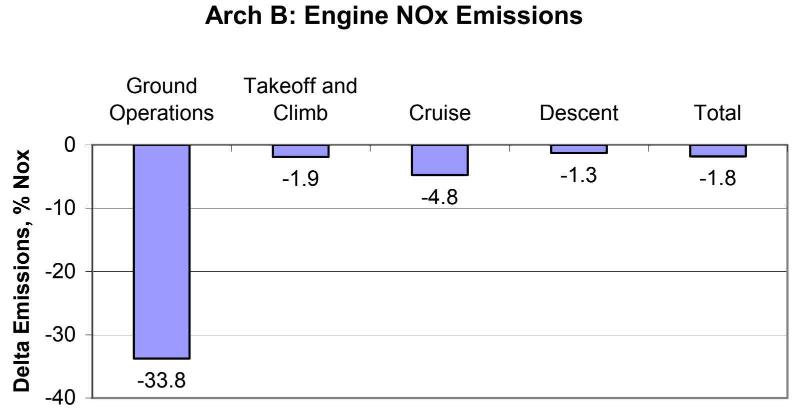


Figure 14.—Architecture-B : NO_x emissions relative to baseline.

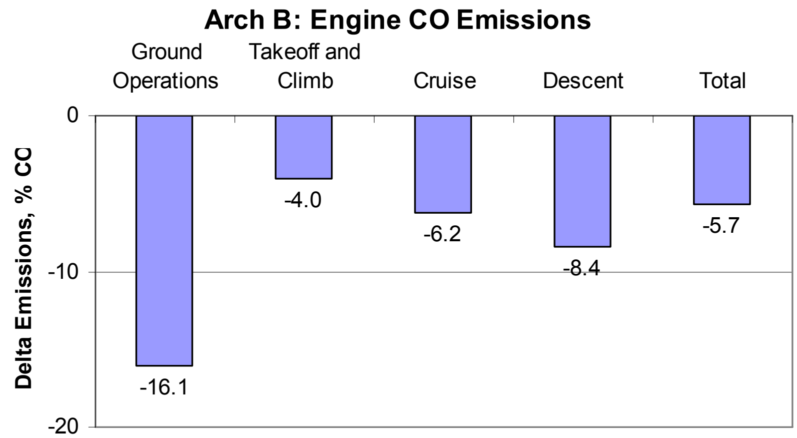


Figure 15.—Architecture-B : Carbon monoxide emissions relative to baseline.

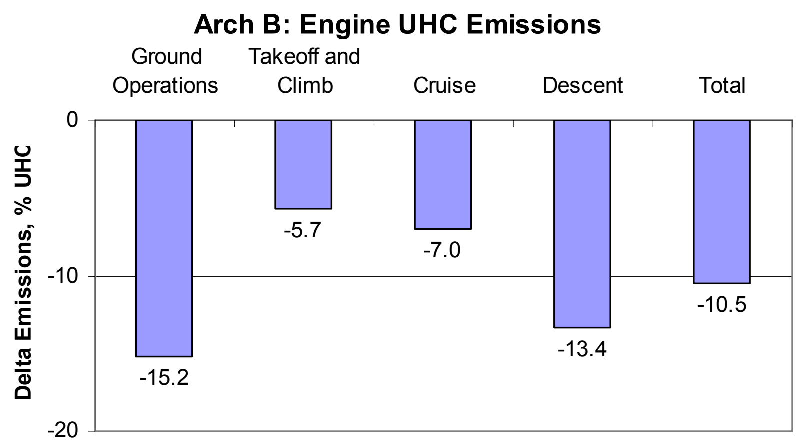


Figure 16.—Architecture-B : Unburned hydrocarbons emissions relative to baseline.

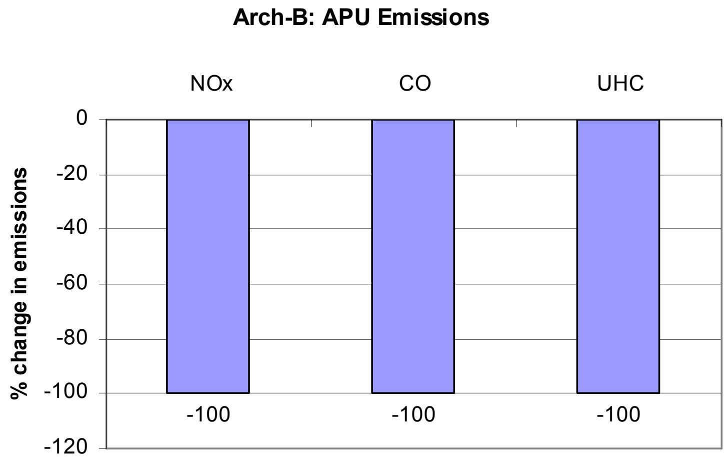


Figure 17.—Architecture-B : APU emissions relative to baseline; SOFC APU achieves 100 percent reduction in emissions.

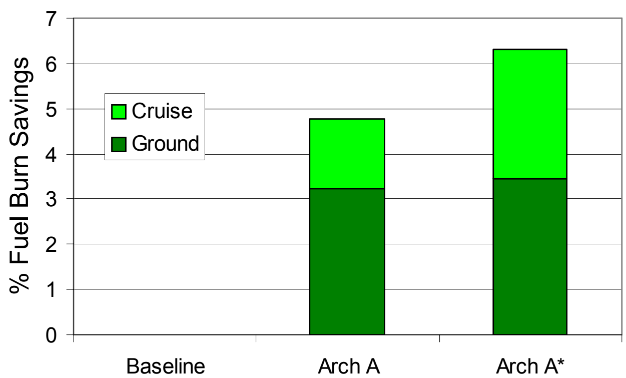


Figure 18.—Benefits of higher performance SOFC system on overall fuel burn savings.

3. Additional Architecture Trades

The ITAPS evaluation results for the baseline architecture and two fuel cell powered architectures (Architectures A and B), estimated the benefits of higher efficiency SOFC system and integration of an SOFC system with other aircraft systems, for a short-range commercial aircraft. While some of the benefits in Architecture B are coming from more efficient operation of the SOFC and some from better integration, an intermediate Architecture that decoupled the two factors was evaluated to understand the relative importance of each contribution. This gave rise to Architecture A*, which is identical to Architecture A in aircraft integration, but included a more efficient SOFC system used in Architecture B.

3.1 Architecture A*

Architecture-A* explored the potential for setting aggressive technical targets for SOFC system performance targets. The benefits of increasing the SOFC efficiency from 44.8 to 53 percent at ground and 64.3 to 70 percent at cruise provided significant fuel burn savings (1.3 percent) at cruise arising from both lower weight of the efficient SOFC system and lower intake of fuel to provide the same electrical power. 0.2 percent fuel burn savings are obtained from more efficient electric power production during APU ground operation.

4. Technology Planning

The key technology development areas for the SOFC system application for the long-range commercial aircraft are presented in this section. The areas for development were identified based on comparison of the current status of the key components and sub-systems technologies with that of the Entry Into Service (EIS) 2015 goals/requirements.

4.1 Summary of Key Technologies

The key components/sub-systems for development and its requirements can be categorized into four sections (as listed below):

- SOFC System
  - Develop high specific power SOFC Stack (>40K hr life, 0.01 percent/T.C., to enable 0.45 kW/kg system)
  - Develop Jet-A Fuel De-Sulfurizer (fuel intake composition of 300 to 1000 ppm sulfur, outlet fuel composition of <1 ppm sulfur)
  - Develop Jet-A Fuel Reformer (with >95 percent fuel conversion and size <25 kg/25L)
  - Develop light weight, high efficiency, compact BOP components
- Aircraft Integration (being addressed by the existing technology plans)
  - Resolve aircraft electric system issues for electrical power generation and distribution related to More Electric Aircraft (Federal Aviation Regulation FAR Chapter-25).
- Advanced Aircraft Technologies
  - Extend fuel heat sink capability up to 600 °F (from 325 °F)
- Electrical System Integration
  - Evaluate bus voltage regulation strategies for compliance with MIL-STD-704F (12 Mar 2004)
  - Develop optimal electric system architecture

The technology development areas listed under the “Aircraft Integration” section are already being addressed by the existing technology plans (such as the power-by-wire programs). Regarding the area listed under the “advanced aircraft technology”, UTC proprietary technologies and technology roadmaps exist. The following sub-sections detail the technology planning for the SOFC system components and electrical system integration that will meet aircraft power requirements.

4.2 SOFC De-Sulfurizer

The current technology for the de-sulfurizer is at Technology Readiness Level (TRL) 2. The EIS 2015 requirements, technology gaps and the roadmap for the de-sulfurizer are presented below.

4.2.1 EIS 2015 Requirements/Goals

The EIS 2015 requirements/goals for the SOFC de-sulfurizer are listed below for regenerative on-board de-sulfurization system.

- Lifetime: Equipment (40,000 hr); Sorbent to be replaced every 10,000 hr.
- Fuel: Reformate (Jet-A fuel)
- Fuel composition: 300 to 3000 ppm sulfur
- Outlet fuel composition: ≤1 ppm sulfur
- Size (for 300 kW system): 30 kg/35 L
- Cost: $10,000

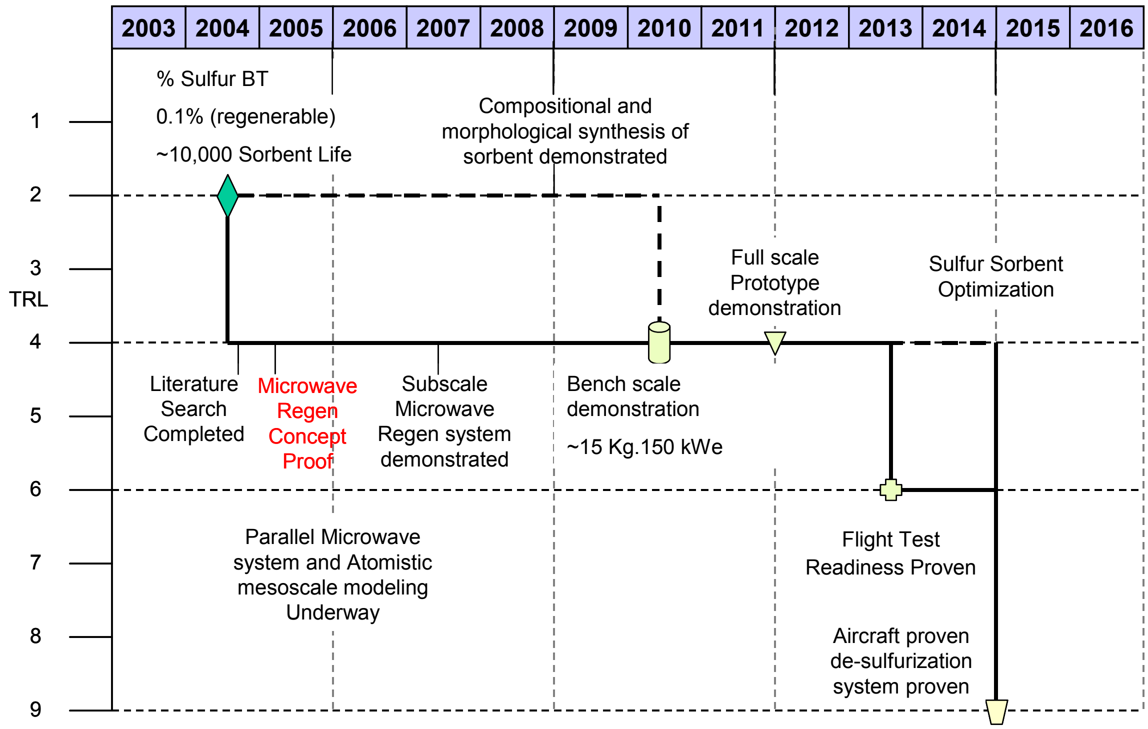


Figure 19.—Roadmap for de-sulfurizer technology development.

4.2.2 Technology Gaps

The compact regenerative desulfurization concept assumed for the present study needs to be demonstrated for feasibility. The technology gaps for the de-sulfurizer system comparing the current best practices/technology with that of the EIS 2015 goals/requirements are listed below.

- Feasibility demonstration of the regenerative concept.
- Decrease sorbent weight by a factor of 2.
- Resolve aircraft Integration issues.

4.2.3 Roadmap

The key recommendations for the de-sulfurizer development are (i) To consider development of on-board de-sulfurization techniques in parallel with that of the on-ground de-sulfurization. (ii) The environmental factors should be evaluated in selecting the material for the de-sulfurizer. Figure 19 shows the top-level roadmap for the de-sulfurizer development. In this roadmap, BT refers to the sulfur breakthrough. The key accomplishments in terms of the EIS and TRL milestones to be reached for the de-sulfurizer are shown.

4.3 SOFC Reformer

The current technology for the SOFC fuel reformer is in Technology Readiness Level (TRL) 2. The EIS 2015 requirements, technology gaps and the roadmap for the reformer are presented below.

4.3.1 EIS 2015 Requirements/Goals

The EIS 2015 requirements/goals for the SOFC reformer are listed below.

- Lifetime: 10,000 hr
- Performance: ≥95 percent fuel conversion
- Size: ≤20 kg/7L (per 300 kW system)

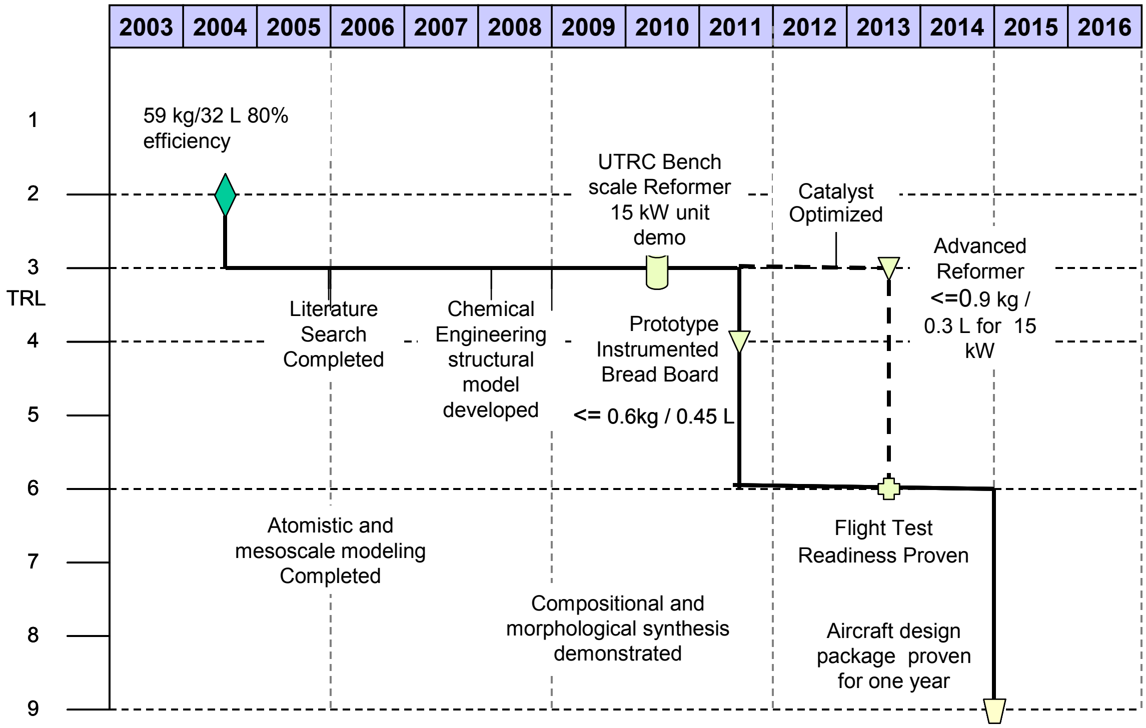


Figure 20.—Roadmap for reformer technology development.

4.3.2 Technology Gaps

The technology gaps for the reformer system comparing the current best practices/technology with that of the EIS 2015 goals/requirements are listed below.

- Highly active and stable catalyst development.
- Fuel reformer size decrease by factor of 2

4.3.3 Roadmap

The key recommendations for the reformer development are: To develop new catalyst materials and supports that prevent coking under the operating conditions of low O_2 to C and steam to C (refer Volume II for conditions). Figure 20 shows the top-level roadmap for the reformer technology development. The key accomplishments in terms of the EIS and TRL milestones to be reached for the reformer are shown.

4.4 SOFC Stack

The current technology for the SOFC stack is in Technology Readiness Level (TRL) 2, with cell technology at 3-4, and that for the SOFC system is in TRL-2. The EIS 2015 requirements, technology gaps and the roadmap are presented below. The high-level roadmap presented includes all the other key sub-systems as well.

4.4.1 EIS 2015 Requirements/Goals

The EIS 2015 requirements/goals for the SOFC stack and the system are listed below.

- Lifetime: 40,000 hr
- Robustness to thermal cycling (TC): 0.01 percent/T.C.
- Fuel: Reformate
- Fuel utilization: 85 percent
- Stack specific power: >1 kW/kg
- System specific power: 0.45 kW/kg

4.4.2 Technology Gaps

The technology gaps for the SOFC stack and the system comparing the current best practices/technology with that of the EIS 2015 goals/requirements are listed below.

- Current technology does not meet lifetime and thermal cycling durability.
- Stack specific power is off by 4X in best case.
- System specific power is off by 7X for the best case.
- Start-up time is off by several hours.
- Cost targets $400/kW (SECA) and $1300/kW (current study)

4.4.3 Roadmap

The key recommendations for the SOFC stack and system development are: (i) Design a high specific power, low to mid range temperature operational stack and system concepts and (ii) Substantial new investment in stack development. The above two recommendations are based on the fact that the current SECA technologies will limit the maximum specific power (kW/kg) that can be reached for the stack and achieving 0.45 kW/kg system is not a reality. High specific power concepts will achieve the 2015 goals. Figure 21 shows the top-level roadmap for the SOFC system technology development. The key accomplishments in terms of the EIS and TRL milestones reached for the SOFC system and other key technologies are also shown.

4.5 High Voltage Power Distribution

The SOFC APU is central to the electric generating system. For these new architectures, it provides primary and auxiliary power in flight. The SOFC APU has very distinct electrical response characteristics in comparison to conventional engine mounted generators, which could drive many changes to current practices. Electrical integration of various power sources in the aircraft will require adaptation of the SOFC, the remainder of the electric system, aircraft loads, regulatory and industry requirements, or any or all of the above to ensure compatibility and safe performance with economical operation.

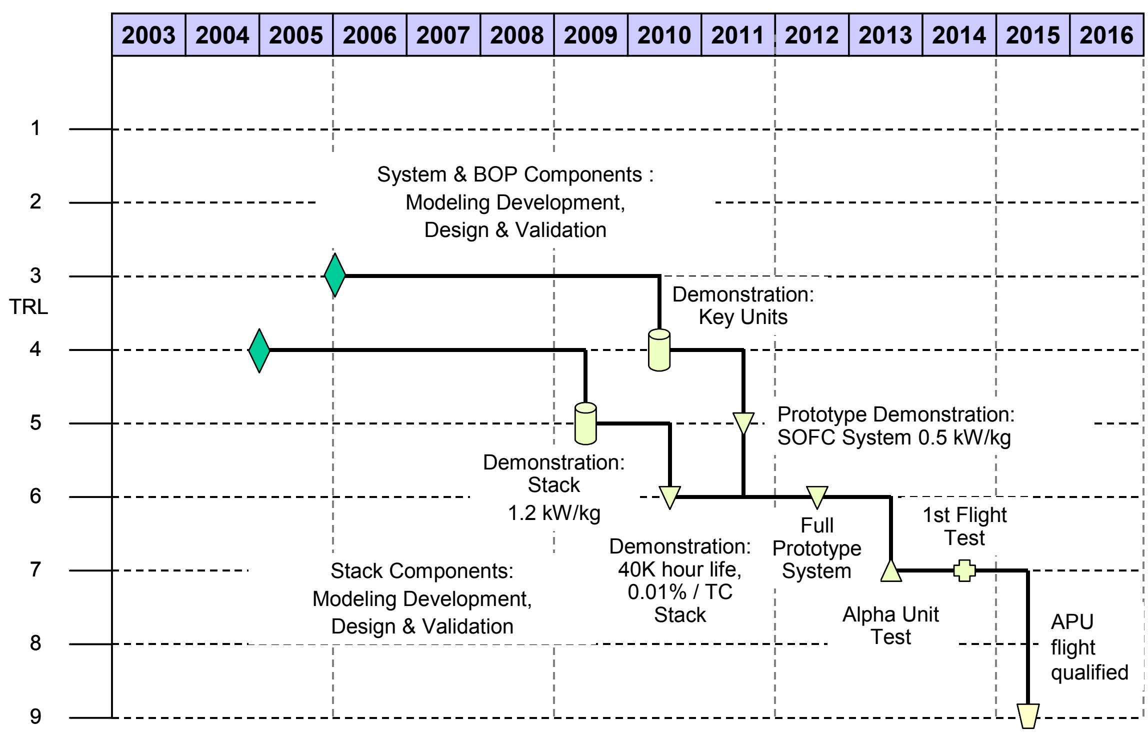


Figure 21.—Roadmap for SOFC system technology development.

4.5.1 EIS 2015 Requirements/Goals

Power Quality: Based on Mil-Std-704F

<u>Summarized Mil-Std-704 270Vdc Bus Voltage Requirements:</u>

Min/Max Steady State:	250/280 Vdc rms
Min/Max Transient:	200/330 Vdc rms
Max Recovery Time to SS Limits:	0.040 s
Max Distortion Factor:	0.015
Max Voltage Ripple Amplitude:	6.0 V peak

Certification: Title 14 CFR Part 25 Airworthiness Standards: Transport Category Aircraft

4.5.2 Technology Gaps

The response time of the SOFC alone is of the order of seconds, while the bus voltage regulation needs to recover within tens of milliseconds. This transient power mismatch needs to be well understood, and optimal strategies to perform bus voltage regulation and efficient and safe electrical integration need to be identified. Further discussion on this is included in volume II.

4.5.3 Roadmap

The key recommendations for electric system integration are: (i) to perform detailed load analyses of the aircraft electrical loads and various power sources with their respective power conversion equipment and (ii) identify optimal power regulation strategies that are specific to the particular aircraft. Figure 22 shows the top-level roadmap for the electric system integration. The key accomplishments in terms of the EIS and TRL milestones to be reached for the electric system integration are shown.

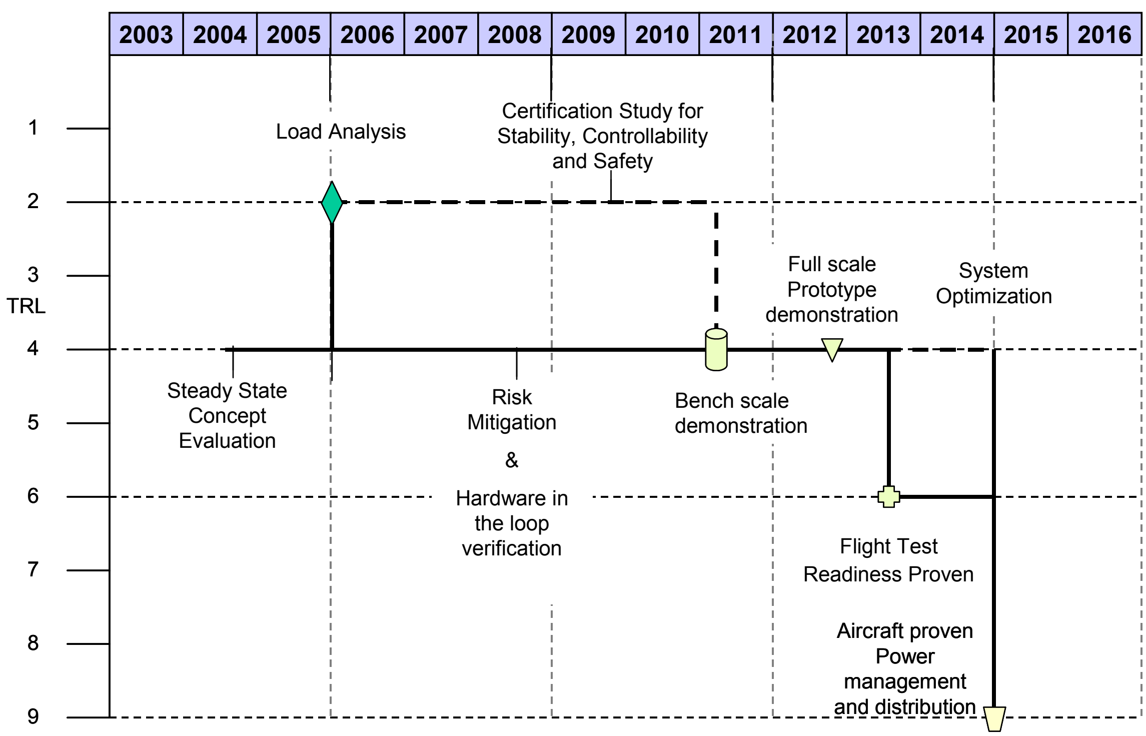


Figure 22.—Roadmap for electric system integration.

5. Discussion of Results

5.1 Fuel Burn Benefits

The impacts of the changes embodied in the two architectures studied are shown in figure 23. Replacing the conventional gas turbine APU with an SOFC system resulted in a weight increase (1868 lb for Architecture A and 1235 lb for Architecture B).

The benefits from SOFC integration can be broadly classified in APU ground operations and 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, like drag incurred for taking air to operate SOFC and increased fuel burn due to additional weight for 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 ram drag incurred due to uptake of air, and the loss in cabin air thrust recovery for Architectures A and B resulted in increased mission fuel burn, which is shown in the “drag” group.

The net fuel burn benefit due to all of these individual factors is the main contributing factor for operational savings. Figure 23 illustrates the financial benefits of these architectures, per aircraft. The assumption for this estimate is the price of aviation fuel at $0.9/gal and 365 days a year of operation. It is obvious that the greater consideration of integration of the SOFC system into the aircraft systems is beneficial. The net fuel burn savings is 2034 lb per day for Architecture A and 2900 lb per day for Architecture B.

5.2 Life Cycle Cost

Fuel burn savings obtained from integration of an SOFC in an aircraft is encouraging. However, the initial capital cost incurred on the SOFC system is higher than a gas turbine APU. Therefore, life cycle cost estimates are needed to assess if SOFC replacing a gas turbine APU is an economical proposition. The assumptions that went into the analysis and the cost information captured are described next.

5.2.1 Definition and Evaluation

The life cycle cost is the overall estimated cost of replacing a gas turbine APU with an SOFC based power plant, over 10 years for a 120 unit fleet of 162 PAX, deployed on short-range aircraft. In this analysis direct and indirect initial costs plus periodic or continuing costs for operation and maintenance are included. The current analysis did not include any benefits for reductions in emissions or noise achievable through the clean fuel cell technology. Additionally, for some of the newer technologies identified the development costs are not included.

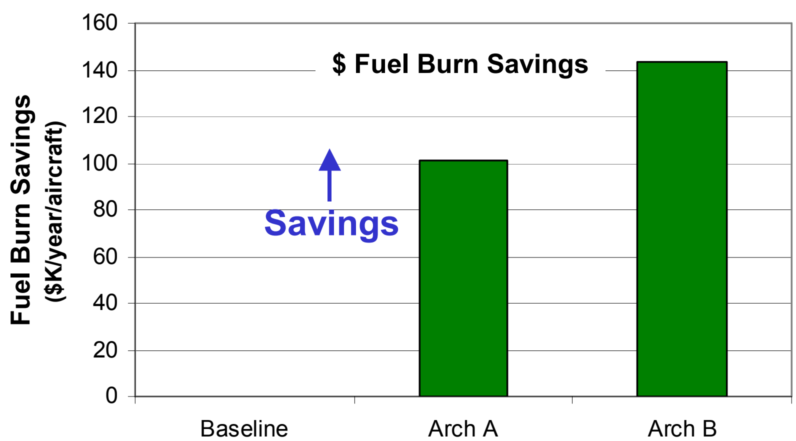


Figure 23.—Financial impact of fuel burn savings of all architectures investigated.

The life cycle cost is estimated based on the net present value analysis. The economic, fleet and system data are processed to identify the costs for investment, operations and maintenance. The payback year is defined as the year when the delta net present value becomes positive. The net present value is presented as the delta between the Architecture in review and baseline net present values.

5.2.2 Assumptions

The assumptions on economic, fleet and system data used for evaluating the delta life cycle cost of different architectures are shown in table IV.

As seen in figure 24, the investment cost in fuel cells is higher than the baseline system. However, substantial benefits can be achieved in operations and maintenance. Architecture B has higher operational savings and lower investment costs due to greater integration with other systems, given the assumptions indicated in table IV. The cumulative delta net present value for different years is provided in figure 25. While Architecture A benefits result in a 5 year payback, Arch B savings could result in a 2 year payback. This scenario would improve in favor of SOFC integration with increasing fuel prices.

TABLE IV.—ASSUMPTIONS ON ECONOMIC, FLEET AND SYSTEM DATA USED FOR EVALUATING THE DELTA LIFE CYCLE COST OF DIFFERENT ARCHITECTURES.

Economic Data	
Discount Rate (%)	12
Non-Fuel Inflation Rate (%)	3.5
Fuel Inflation Rate (%)	3.5
Burdened Line Labor Rate ($/hr)	85
Fuel Price ($/gal)	0.9

System Data	
Warranty Period (years)	3
Warranty Acceptance Rate	1
Fuel Use Due to Power System (lb/hr)	100

Fleet Data	
Life (20 years max)	20
Fleet Size	120
Yearly Aircraft Operating Hours	5000
Number of Departures Per Year	1400
Cost of a Delay Per Hour	5000
Cost of a Cancellation	8000
Cost of a Diversion	10000
Holding Factor	0.1
Spare LRU Protection Level (%)	98

Delivery Schedule										
year	1	2	3	4	5	6	7	8	9	10
number	12	12	12	12	12	12	12	12	12	12

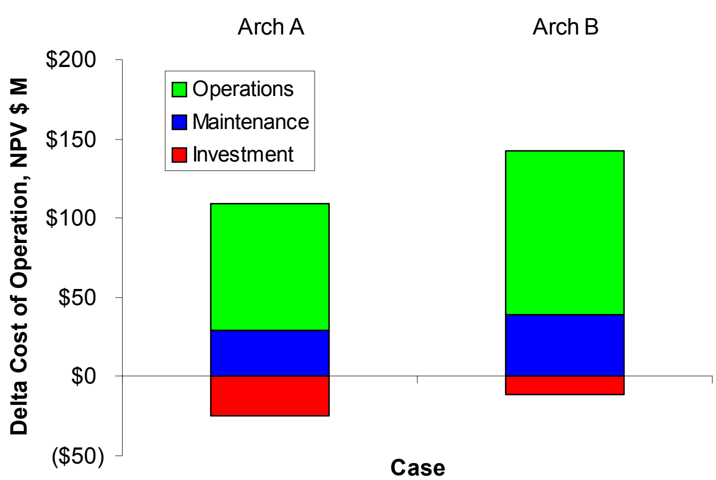


Figure 24.—Delta net present value for each of the 20 years, for the two architectures is shown with the split in operations, maintenance, and investment.

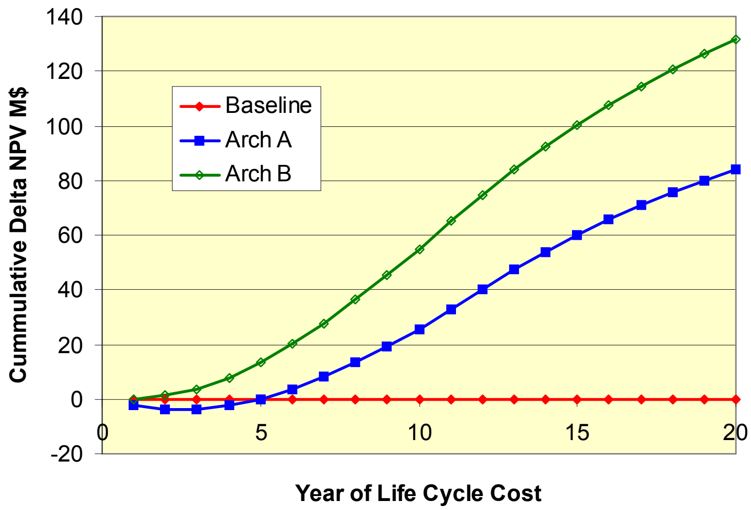


Figure 25.—Cumulative delta net present value (NPV) over 20 years.

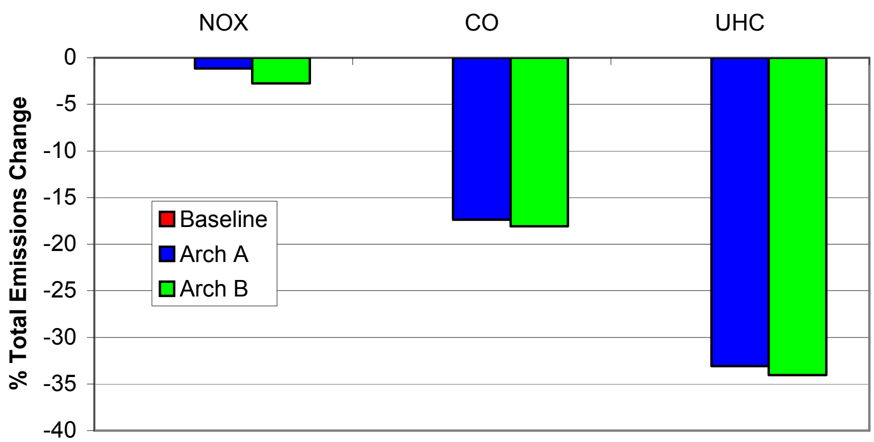


Figure 26.—Total aircraft emissions for entire mission relative to baseline. The Architecture-B is better for emission reduction.

5.3 Emissions

None of the SOFC systems studied produce any oxides of nitrogen, carbon monoxide, or unburned hydrocarbons. The use of an 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 change in fuel burn as discussed in Section 6.1. 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. The total aircraft emissions for the two architectures relative to the baseline are shown in figure 26 during engine operation and in figure 27 during the landing and take-off cycles (below 3000 ft altitude).

Ground emissions and LTO emissions are of interest at airports, where the requirement for air quality is hard to meet. Figure 27 shows the emission reduction during the LTO cycle. Substantial reduction in CO and UHC is achieved by operating the fuel cell during the LTO cycle.

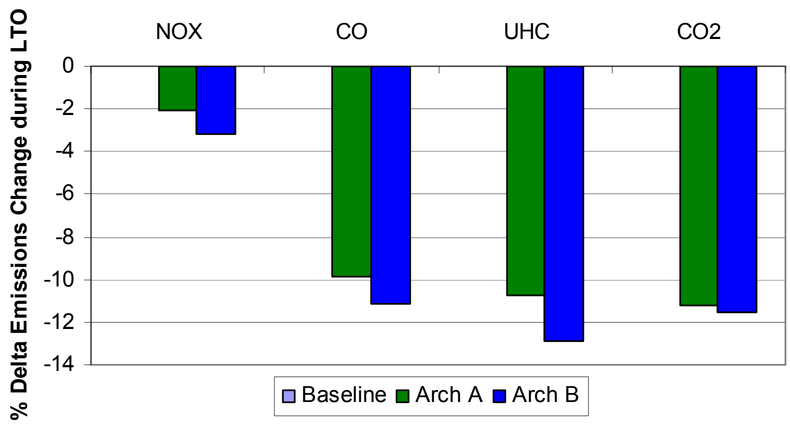


Figure 27.—Total aircraft emissions for LTO cycles relative to baseline.

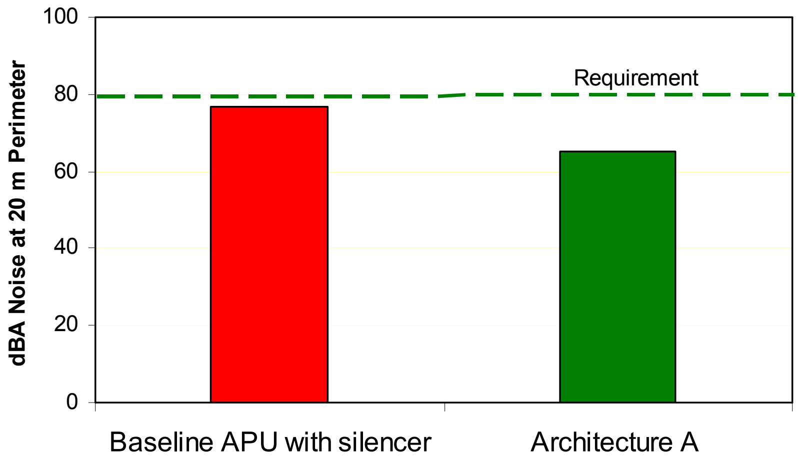


Figure 28.—APU noise (dBA) at 20 m. Architectures A and B have similar noise signatures.

5.4 APU Noise

The noise level at 20m is shown in figure 28 for the baseline gas turbine APU and for the SOFC APU of Architecture A. Since SOFC turbomachinery are sized similarly for Architectures A and B, noise level is evaluated for only one of the architectures. However, the noise level for Architecture B would be relatively higher. It is assumed that, a 2015 baseline APU with a silencer, meets the 80 dBA requirement at 77 dBA. The Architecture A SOFC APU is assessed to be significantly under that requirement at 65 dBA with the main noise contribution coming from the compressor noise of the turbo-machinery necessary to pressurize the stack for ground operations.

5.5 Technological Risks

Some of the concepts selected for Architecture B involve technology integration that involves risks in certain areas relative to Architecture A, as shown in table V.

TABLE V.—THE CONCEPTS USED IN EVALUATION OF ARCHITECTURE B HAVE HIGHER TECHNOLOGICAL RISKS, IN SEVERAL AREAS INDICATED

Issues		Arch B
Integration of ECS and SOFC tubomachines.		
	Lower Efficiency/Performance	*
	Failure of both systems due to interdependencies	
	Fire safety due to co-location of critical components	
	Isolation of Turbomachinery exhaust air and fresh air	
	Keep the air ducting away from the exhaust	
Fuel Reforming Technology		
	Durability; coke formation; Slip of C3s and higher HC	
Stack Technology		
	Thermal Cycling	
	Stack temperature gradient	

	Same as Arch A
	High Risk relative to Arch A
	Low Risk relative to Arch A
* In practice, some mission points may not be operated due to lower efficiency	

5.6 Location of SOFC

TABLE VI.—ISSUES TO BE CONSIDERED FOR POSSIBLE LOCATION OF SOFC IN THE AIRCRAFT

Issues	Tail Cone	Wing Root
• Fire Zone		
– Suppression		
– Containment		
– Resistance		
– Proximity to passenger area		
– Proximity to fuel tank		
– Electric Arcing		
• Failure Modes and Mitigations		
– Explosion proofing -primary		
– Explosion proofing -secondary		
– Mechanical Rupture/ Containment		
– Fuel Rupture/Containment		
– Electric Fault Protection		
– Performance with limited failure		
• Weight and Envelope		
– Center of Gravity		
– Weight		
– Volume		
• Maintainability		
– Accessibility		
• Noise		
• Integration for Fuel Burn Benefits		
– ECS Overboard flow for SOFC air inlet		
– SOFC exhaust for additional heat into fuel		
– SOFC exhaust injection into engine		
– ECS & SOFC turbo machines on the same shaft		

Level of concern (Safety, Fit or Functionality)	
	low
	moderate
	medium (baseline)
	significant
	serious
	severe

Determining the optimal location of the SOFC APU was not within the scope of the contract; however, the impact of locating the SOFC APU in the tail cone as is common with a conventional APU was considered. While the quantitative impact of the location of SOFC needs detailed calculations, some high level contributions are discussed. Apart from the issues identified, several other factors need to be considered while deciding the location of the SOFC. Based on the ITAPS evaluation of the different architectures, the benefits offered by integrating the SOFC into an aircraft do provide sufficient margin for additional weight associated with some of the issues. However, volume of the SOFC is a potential concern. Based on integration capability and potential for achieving the fuel burn benefits identified, location of the SOFC APU at the wing root region appears more attractive.

5.7 Impact of SOFC System Weight

The study was done with certain goals for SOFC system weights for EIS 2015. The basic power density used in this study was 0.44 kW/kg for the Architecture A SOFC system. This assumption is consistent with other similar studies. The impact of additional SOFC system weight increase relative to this goal was estimated and is presented in figure 29. The better architectures can accommodate significant weight gains and still match the fuel burn of the baseline system. For example, Architecture B can accommodate an additional 8200 lb of weight and still break even on fuel burn. The full benefit in ground emissions savings would still be realized. In flight, the increased system weight will negate some of the emissions benefits and the net present value for the proposition would be negative, due to higher investment costs.

The net power density for each architecture and the power density corresponding to zero fuel burn benefit (i.e., the break even points) is shown in figure 30.

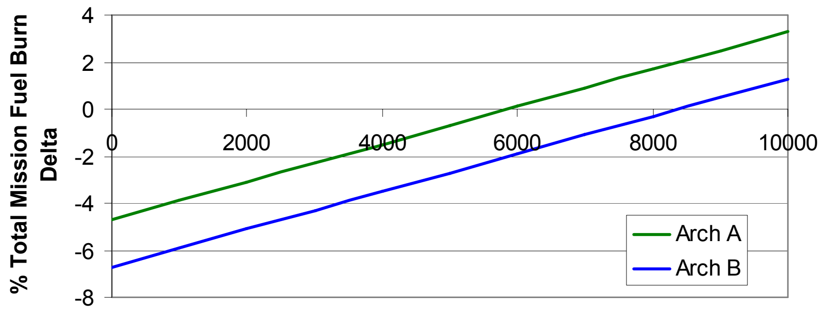


Figure 29.—Effect of additional SOFC system weight on the fuel burn benefits.

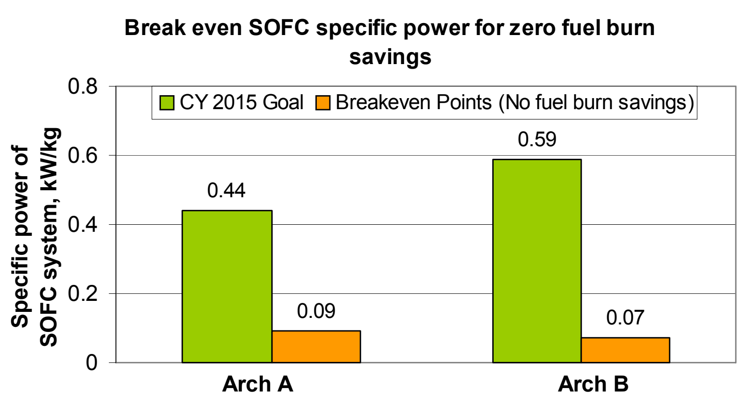


Figure 30.—Year 2015 EIS SOFC system weight goals and the break even points (no fuel burn savings).

6.0 Conclusions

This study selected an aggressive, year 2015 EIS aircraft for baseline systems (UEET engines, advanced more-electric APU and more-electric aircraft sub-system concepts). The potential benefits (emissions, noise and fuel burn) of the SOFC system application were quantified relative to this short-range commercial aircraft baseline system. The key technology development areas and potential future study areas were also presented.

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 percent. Architecture-B, with a higher degree of system integration and higher risk technologies, delivered fuel burn benefits of 6.7 percent.

To realize any fuel burn benefit from an 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 increased fuel burn for increases in the SOFC system weight. Furthermore, the value proposition for the fuel cell system results in many years to achieve payback. 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, for the assumptions of the study. At a system specific power of 0.59 kW/kg the payback is achieved in 2 years.

To achieve the EIS 2015 goal metrics (weight, life, etc.) required for aerospace applications, a paradigm shift is needed in the SOFC stack concepts. This is based on the 4X improvement needed for the stack weight and 7X improvement needed for the SOFC system weight, based on the current state of the art technologies. Furthermore, de-sulfurization of Jet A fuel is critical for operation of the SOFC system. A low maintenance and compact regenerative scheme for sulfur removal is desirable for aerospace applications. Funding should be prioritized to the development of advanced stack and de-sulfurization concepts (such as the UTC proprietary concepts presented during the contract final review) that have the potential to realize the benefits identified in this study.

Arguably, the SOFC APU location should be closer to wing roots (or engines) rather than the customary tail cone 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. Therefore, a future study should be performed to determine the optimal location of the SOFC-APU system in the aircraft and to assess the consequences.

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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Appendix—Symbols

Symbol	Description	Units
M	Mass Flow	kilograms/sec
P	Pressure	atmospheres
T	Temperature	degrees Fahrenheit

Acronyms

APU	Auxiliary Power Unit
ATR	Auto Thermal Reformer
BCA	Best Cruising Altitude
BOP	Balance of Plant
CO	Carbon Monoxide
DOE	Department of Energy
ECS	Environmental Control System
EPS	Electrical Power System
EIS	Entry Into Service
ITAPS	Integrated Total Aircraft Power Systems (United Technology Corporation)
kW	kiloWatts
LTO	Landing and Take-Off
MEA	More Electric Aircraft
nmi	nautical mile
NO_x	Nitrogen Oxides
ppm	parts per million
SECA	Solid-state Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell
TMS	Thermal Management System
TRL	Technology Readiness Level
UEET	Ultra Efficient Engine Technology
UHC	Unburned HydroCarbons

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13. ABSTRACT ***(Maximum 200 words)***

The objective of this study is to define the functionality and evaluate the propulsion and power system benefits derived from a Solid Oxide Fuel Cell (SOFC) based Auxiliary Power Unit (APU) for a future short range commercial aircraft, and to define the technology gaps to enable such a system. United Technologies Corporation (UTC) Integrated Total Aircraft Power System (ITAPS) methodologies were used to evaluate a baseline aircraft and several SOFC architectures. The technology benefits were captured as reductions of the mission fuel burn, life cycle cost, noise and emissions. As a result of the study, it was recognized that system integration is critical to maximize benefits from the SOFC APU for aircraft application. The mission fuel burn savings for the two SOFC architectures ranged from 4.7 percent for a system with high integration to 6.7 percent for a highly integrated system with certain technological risks. The SOFC APU itself produced zero emissions. The reduction in engine fuel burn achieved with the SOFC systems also resulted in reduced emissions from the engines for both ground operations and in flight. The noise level of the baseline APU with a silencer is 78 dBA, while the SOFC APU produced a lower noise level. It is concluded that a high specific power SOFC system is needed to achieve the benefits identified in this study. Additional areas requiring further development are the processing of the fuel to remove sulfur, either on board or on the ground, and extending the heat sink capability of the fuel to allow greater waste heat recovery, resolve the transient electrical system integration issues, and identification of the impact of the location of the SOFC and its size on the aircraft.

14. SUBJECT TERMS

Auxiliary power unit; Auxiliary power system; Fuel cells; Hybrid fuel cell; Solid oxide fuel cell

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