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

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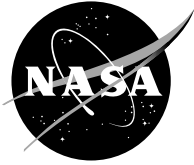
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Summary

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 long 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 and emissions; however, the life cycle cost was not part of the work scope.

At the system level, the overall integration of a fuel cell power unit, turbine engine and power subsystems for a long-range commercial transport was evaluated and the associated enabling technologies were identified. The baseline aircraft considered was the Boeing 777-200ER airframe with more electric subsystems, Ultra Efficient Engine Technology (UEET) engines, and an advanced APU with ceramics for increased efficiency. In addition to the baseline architecture, four architectures using an SOFC system to replace the conventional APU were investigated.

Architecture-A simply replaced the APU with a 450 kW 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. 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 let to improved overall system efficiency and hence reduced the mission fuel burn. Architecture-C employed greater integration of the SOFC with aircraft sub-systems and advanced aircraft technologies to improve the benefits and applications of the SOFC system. Architecture-C also utilized proprietary UTC technology to extend the fuel heat sink capability thus enabling recovery of the waste heat from the SOFC to pre-heat the fuel for the propulsion engines. This waste heat recovery further reduced the mission fuel burn. Architecture-D explored the potential for reducing parasitic power losses due to pressurization by running the Architecture-C SOFC system at one atmosphere pressure.

System integration is critical to maximize benefits from the SOFC APU for aircraft application. The mission fuel burn savings for Architecture-A, which had minimal system integration, was 0.16 percent. Architecture-B and Architecture-C employed greater system integration and obtained fuel burn benefits of 0.44 and 0.70 percent, respectively. Architecture-D had the highest level of integration and obtained a benefit of 0.77 percent. System integration will also minimize the technology development cost/time.

Recognizing that most of the benefits of the SOFC system were realized during ground operations, the potential benefits for a short-range mission were also explored. The preliminary short-range mission study showed that the SOFC system provided more benefits to short-range mission aircraft (about 3 percent mission fuel burn savings for the 500 NM B777-200ER aircraft mission) as compared to the long-range mission aircraft (0.7 percent mission fuel burn benefit).

The SOFC APU produced zero emissions, thus eliminating the emissions of the conventional APU during ground operations. The reduction in engine fuel burn (partly due to reduced extractions) also resulted in a reduction in emissions from the engines. For Architecture-C, the engine emissions in flight decreased by 0.23 percent for oxides of nitrogen (NO_X), 1.46 percent for carbon monoxide (CO) and 2.89 percent for unburned hydrocarbons (UHC). The ground emissions from the engines were reduced by 15.55 percent for NO_X, 3.35 percent for CO, and 4.82 percent for UHC.

The noise level of the baseline APU during ground operations was 90 dBA. A silencer was required to achieve the noise target of 80 dBA. The Architecture-C SOFC APU produced a noise level of 72 dBA, needing no silencer. However, the Architecture-D SOFC APU produced a noise level of only 51 dBA.

A paradigm shift is needed in the SOFC stack concepts to achieve the year 2015 goal metrics (weight, life, etc.). 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. Additional areas requiring further development are the fuel processing 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.

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 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. This present NASA study is intended to look into the potential benefits of tightly integrating the SOFC fuel cell with the aircraft subsystems using Integrated Total Aircraft Power Systems (ITAPS, United Technology Corporation) proprietary methodologies.

1.1 Objective

The objective of the 'Aircraft Propulsion and Subsystems Integration Evaluation' (NAS3–01138: Task Order 20) contract effort 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 aircraft, and define the technology gaps to enable such a system.

1.2 Scope

The project scope regarding the technologies, system evaluation methodologies, performance metrics and the baseline system used to benchmark the benefits is listed below.

- The technologies would be commensurate with the year 2015 Entry into Service (EIS)
- The Boeing 777-200ER mission requirements and the United Technology Corporation UTC Integrated Total Aircraft Power System (ITAPS) methodologies were used to evaluate technologies as elements of complete system concepts.
- The future SOFC systems were designed to meet at least the Department of Energy (DOE) program Solid-state Energy Conversion Alliance (SECA) goals.
- The system architectures were evaluated to a conceptual level of fidelity.
- *Metrics*: The technology benefits were captured as reductions of the mission fuel burn and emissions (NO_X, CO, and UHC). However, the life cycle cost (capital cost, installation cost and the maintenance cost) was not within project scope.
- *Baseline System*: Fixed B777-200ER airframe (Long Range Commercial Aircraft) with
  o More electric subsystems
  o Ultra Efficient Engine Technology (UEET) engines
  o Advanced APU (with ceramics)

1.3 Tasks

At the system level, the overall integration of a fuel cell power unit, turbine engine and power subsystems for a long-range commercial transport were evaluated and the associated enabling
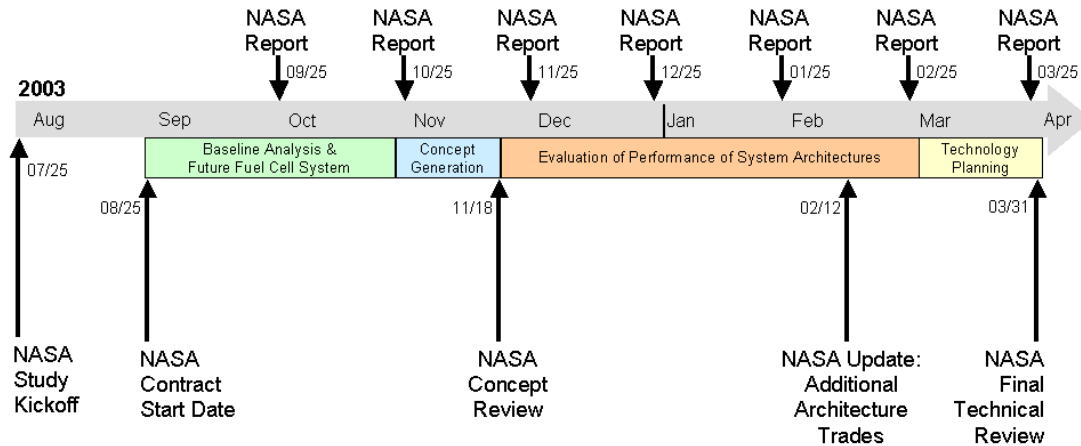
Figure 1.—Tasks and events.

technologies were identified. The work covered the following general areas of activity: analysis of a pre-established baseline (Task-1), estimation of future fuel cell performance (Task-2), generation of three fuel cell integration concepts (Task-3), evaluation of performance of the system architectures (Task-4), and identification of enabling technologies (Task-5). Figure 1 shows the key events and the tasks executed for this project.

1.4 Study Challenges

The technical challenges involved 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 0.4 percent aircraft mission fuel burn).
- The SOFC system operation during flight cruise condition requires input air stream and providing that air from the ambient (ram air) introduces ram-drag penalty. This ram-drag penalty increases the amount of fuel burned by the aircraft (equivalent of 0.3 percent aircraft mission fuel burn).
- The SOFC system (which is a hybrid system with the SOFC stack and the turbo-machinery) generates both ac and dc power. The dc power is from the stack and the ac power is from the turbine generator. The distribution of the power (ac and dc) generated by the SOFC system in the aircraft requires additional power electronics (power converters etc), which, in turn, increase the amount of fuel burned by the aircraft.
- The current technology of the SOFC system requires a longer time (more than 30 min) to startup the SOFC system. Therefore, frequent starting and stopping cycles for the SOFC system may not be a good option for the aircraft application.
- The processing of the Jet-A fuel with sulfur levels between 300 to 1000ppm requires a bulkier de-sulfurizer, which restricts the de-sulfurization options for the aircraft.
- 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 application, the system integration concepts for the SOFC system should provide substantial benefits to overcome penalties imposed by the technical challenges listed above.

1.5 Related Documents

A companion report, "Solid Oxide Fuel Cell APU Feasibility Study for a Long Range Commercial Aircraft Using UTC ITAPS Approach: 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.

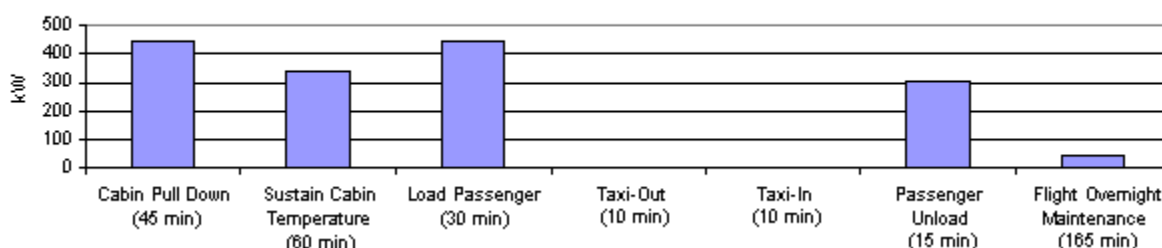**APU Electrical Loads: Ground Operation**

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

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, (iii) Architecture-B, and (iv) Architecture-C.

2.1 Baseline System

The baseline aircraft system is a UEET aircraft from an earlier Pratt & Whitney / NASA study. The baseline consists of B777-200ER mission with UEET engines, advanced APU (with ceramics material) and more-electric-aircraft (MEA) sub-systems (electric engine start, electric environmental control system, electric anti-ice and electric and hydraulic actuation).

The APU electric load requirements and the ground operation time are shown in figure 2. During regular flight operation, the APU remains operational until the "taxi-out". During the flight segment the APU will not be operated; however, for the emergency and anti-ice requirements, the APU may be operated during flight. The APU was sized at 450 kW to satisfy all of its requirements (ground operation, emergency operation and also to satisfy anti-ice loads).

TABLE I.—BASELINE : MISSION PROFILE

Mission Point	Description	Altitude (ft)	Mach	Elapsed Time (min)
1	Engine Start	0	0.00	0
2	End of Taxi	0	0.00	9
3	Take Off	0	0.23	9.5
4	Beginning of Climb	1500	0.39	10.98
5	Climb	10000	0.45	14.2
6	Cruise	35000	0.85	33.02
7	Climb for BCA	35000	0.85	438.5
8	Beginning of Final Cruise	39000	0.85	448.37
9	End of Cruise	39000	0.85	942.1
10	Cutback	39000	0.85	942.1
11	Descent 1	32159	0.85	944.44
12	Descent 2	1500	0.39	964.55

The baseline system analyzed is a 305 passenger, 7700 nautical miles (NM) long-range mission, EIS 2015 aircraft with a maximum cruising altitude 39000 ft at Mach number 0.85. Table I and figure 3 show the aircraft mission for the climb-cruise-descent segment. In table I, BCA refers to the Best Cruise Altitude. The flight segment represented by the mission points MP1 through MP3 corresponds to the taxi-out segment in figure 2. After the end of the descent segment, the taxi-in continues (as in fig. 2). The engine will be operational from the beginning of the taxi-out (engine start represented as MP1) to the end of taxi-in (engine stop). The APU will be operational during the taxi-out and taxi-in segment operating at zero loads.
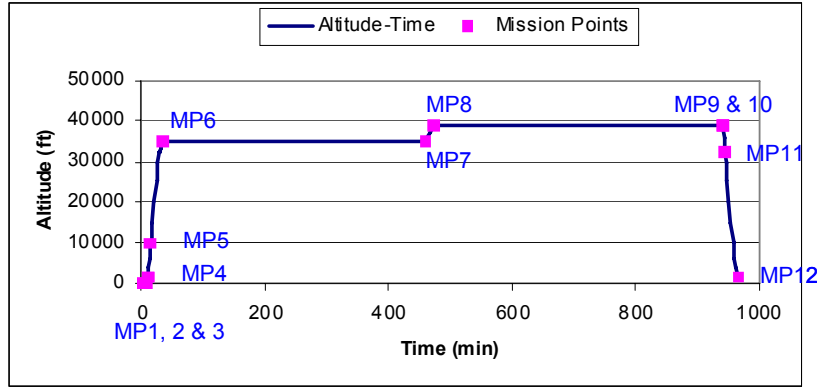
Figure 3.—Baseline : Mission profile.
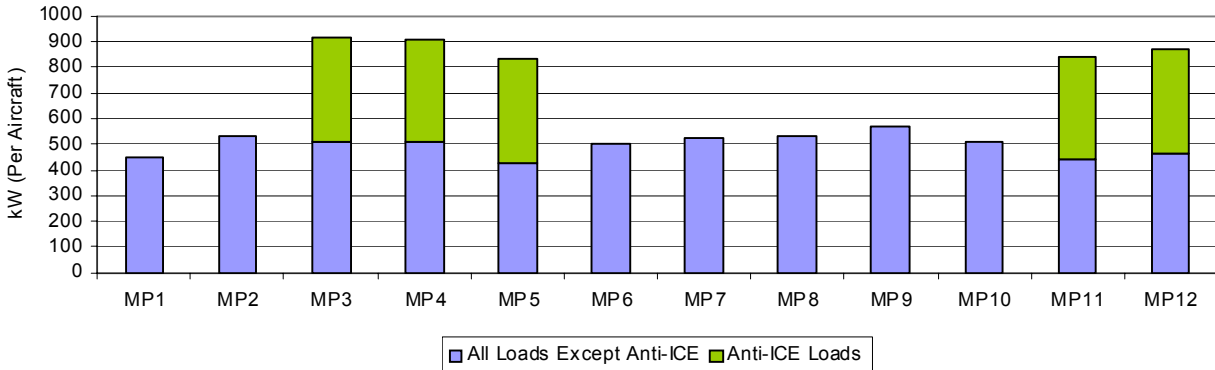
Electrical Loads: Climb/Cruise/Descent

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

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

The 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 450 kW were required. Using the UTC ITAPS tools the baseline system was evaluated. The mission fuel burned during the APU ground operation and that of the flight during the climb-cruise-descent segment were 1849 and 187400 lb, respectively. The Take Off Gross Weight (TOGW) of the baseline system was 571000 lb.

The NO_x, UHC and CO emissions for the baseline APU and that of the engine (per engine numbers) are shown in figure 5 and table II. The ground operation time listed for the engine emissions include engine start, taxi-out, and taxi-in. Note that there is not a separate mission point in table I for taxi-in as the importance of including this part of the flight was recognized after running the simulations. This did not pose a problem because the taxi-in segment is essentially the same as the taxi-out segment, which was computed.

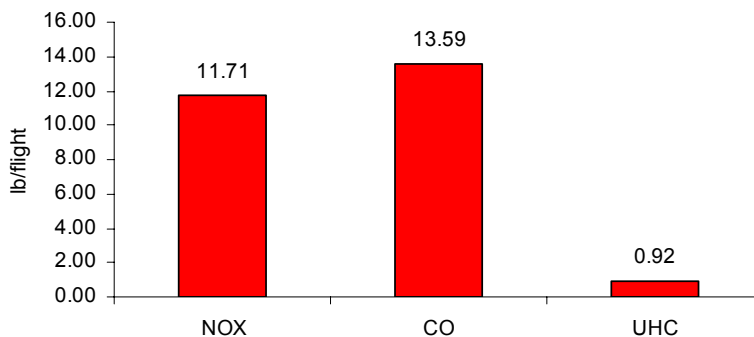**Baseline APU Ground Emission (lb/aircraft)**

Figure 5.—Baseline : APU emissions for ground operations.

TABLE II.—BASELINE: ENGINE EMISSIONS (PER ENGINE)
DURING CLIMB/CRUISE/DESCENT MISSION

MISSION SEGMENT DESCRIPTION	Baseline Actuals			
	Duration (hr)	W NOx (lbm)	W CO (lbm)	W UHC (lbm)
Ground Operations	0.317	0.91	3.46	0.22
Take Off and Climb	0.392	355.54	8.02	0.06
Cruise	15.150	3062.68	169.28	1.90
Descent	0.383	1.74	2.72	0.14
	totals	3420.87	183.49	2.32

2.2 Concept Generation

Rich sets of concepts were generated and down selected to form three architectures classified under the following theme areas: (I) High performance SOFC systems, (II) Integrated SOFC system—SOFC system integrated with aircraft sub-systems and (III) Highly integrated SOFC system—SOFC system integrated with aircraft sub-systems and advanced aircraft technologies to improve the benefits and applications of the SOFC system.

Figure 6 shows a conceptual diagram for the three architectures defined. To realize the same benefits (or values) the technology development dollars for the Architecture-A would be substantially more compared to that of the Architectures B and the development dollar for the Architecture-B would be more compared to that of the Architecture C.
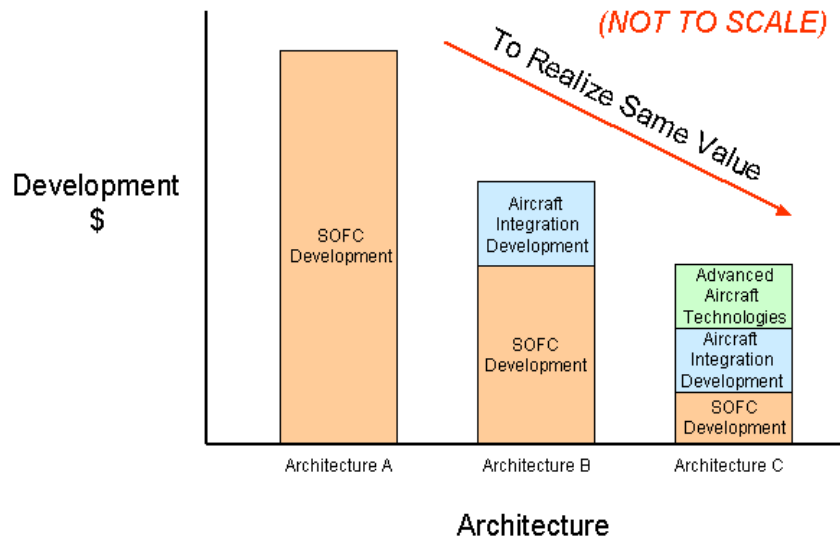
Figure 6.—Development costs for chosen architectures.

To illustrate this, consider the following example: Architecture-A with specific power of 0.5 kW/kg SOFC system requiring Z amount of development dollars to achieve Y fuel burn benefits. Compared to the current technology, about 7X improvement in specific power is needed to achieve the above goal. With integrated system concepts (such as that of Architectures B and C) the overall performance of the SOFC system can be increased with few advances to the aircraft sub-system thereby realizing the benefits (Y) of the Architecture-A with <0.5 kW/kg SOFC system. Therefore the development dollars needed to achieve <7X improvement in weight would be substantially less (<Z) compared to that of the less-integrated systems (Architecture-A). The major concept areas analyzed as a part of different architectures are shown in table III.

TABLE III.—CONCEPTS EMBODIED IN CHOSEN ARCHITECTURES
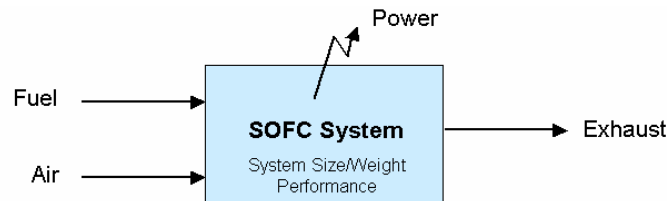
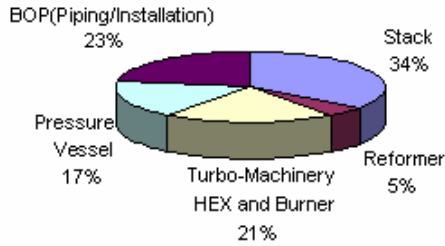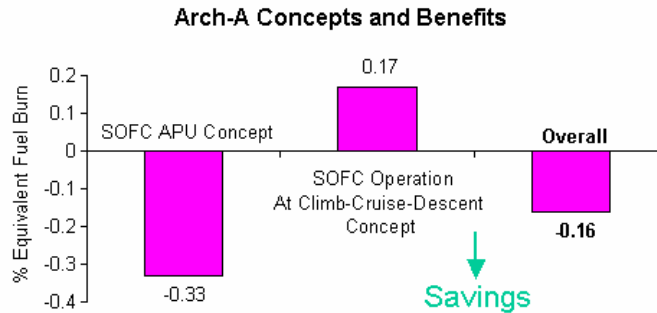| Concept Areas	Architecture A	Architecture B	Architecture C
SOFC Application: System Operation (Ground and Flight)	X	X	X
SOFC System Integration With Other Systems	X	X	X
SOFC System: Performance	X	X	X
Input Fuel Processing - Trade Options	X	Best of A	Best of A
Input Air - Trade Options		X	Best of B
Power Distribution - Trade Options		X	Best of B
Electrical Load Reduction		X	X
Electrical Power Source: Reduced Redundancy		X	X
System Weight Reduction		X	X
Exhaust: Water Recovery		X	X
Exhaust: Gas Usage		X	X
Exhaust: Heat Recovery			X
Advanced Aircraft Technologies Impacting SOFC System			X

Figure 7.—2015 SOFC system weight goals.

Figure 8.—Architecture-A: benefits of included concepts.
Architecture-A achieves overall 0.16 percent savings on fuel burn.

2.3 Architecture-A

Architecture A includes the features of the baseline system and two additional architecture concepts: (i) SOFC system serving as an APU in place of the gas turbine APU and (ii) SOFC system operating during the flight climb-cruise-descent segment thereby reducing the engine shaft extractions substantially.

The SOFC system APU is a 450 kW system with efficiency of 53.2 percent at cruise conditions (at full load operation) and 48.4 percent at ground conditions (at full load operation). The SOFC system uses de-sulfurized fuel (de-sulfurization performed on-ground) and weighs 2372 lb. Figure 7 shows the weight distribution for the SOFC system. The weight is based on the following assumptions: (i) 1 kW/kg stack and (ii) 0.5 kW/kg system (without pressure vessel) consistent with other earlier studies. The pressure vessel weight is based on an integral shell design at ground temperature; it should be considered as a lower bound estimate.

For Architecture-A, the APU electric load during the ground operation, the total electrical load requirement for the aircraft for the climb-cruise-descent and the flight climb-cruise-descent operation mission remain the same as that of the baseline system. However, the engine-mounted generators provide the electrical power for the anti-ice loads.

Using the UTC ITAPS tools the Architecture-A system was evaluated. Figure 8 shows the benefits or the penalties of the Architecture-A 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 1980 lb (0.43 percent mission fuel burn penalty), drag increased by 32 lb (0.27 percent mission fuel burn penalty), fuel consumption at climb-cruise-descent decreased (equivalent of 0.1 percent mission fuel) and the ground fuel usage decreased (equivalent of 0.76 percent mission fuel burn). The overall mission fuel burn savings for the Architecture-A system is 0.16 percent (as shown in fig. 9). The overall benefit is the sum of the individual contributions.
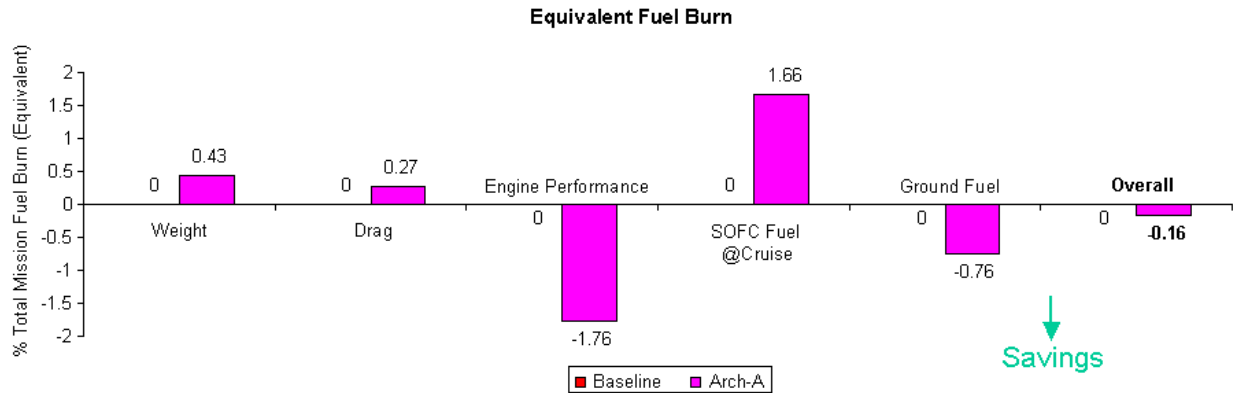
Equivalent Fuel Burn

Figure 9.—Architecture-A : Equivalent fuel burn relative to baseline, showing 0.16 percent fuel burn savings overall.
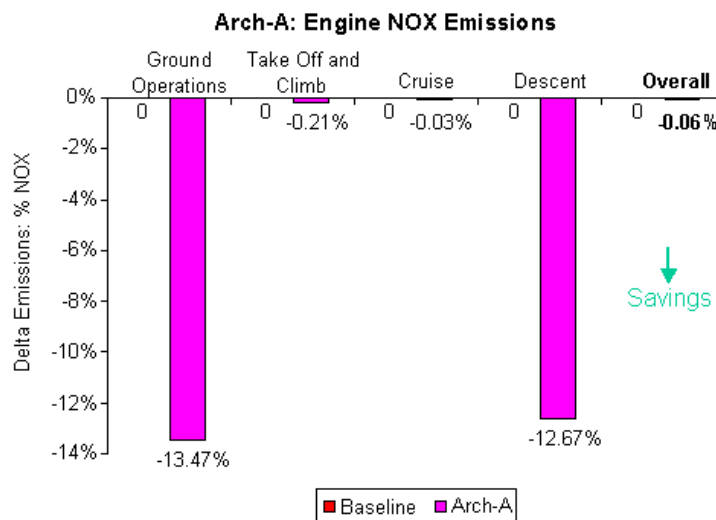
Arch-A: Engine NOX Emissions

Figure 10.—Architecture-A : NO$_x$ emissions relative to baseline.

For the Architecture-A, the NO$_X$, UHC and CO emissions for the engine and that of the APU relative to that of the baseline system are shown in figures 10 to 13, respectively. The SOFC system operates at zero-emissions, (100 percent improvement relative to baseline) and the engine emissions also reduce by 0.06 percent for NO$_X$, 1.22 percent for CO and 2.48 percent for UHC (figs. 11 to 13, 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. 10) for ground operations and for descent results from the fact that the engine is operating near idle in those mission segments. The reduction in horsepower extracted from the high spool 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 reduced combustor temperature leads to a lower combustor efficiency which increases the emissions indices for CO and unburned hydrocarbons. Combined with the reduced fuel flow, there is a small reduction in CO for ground operations and a modest increase in the descent segments (fig. 11).
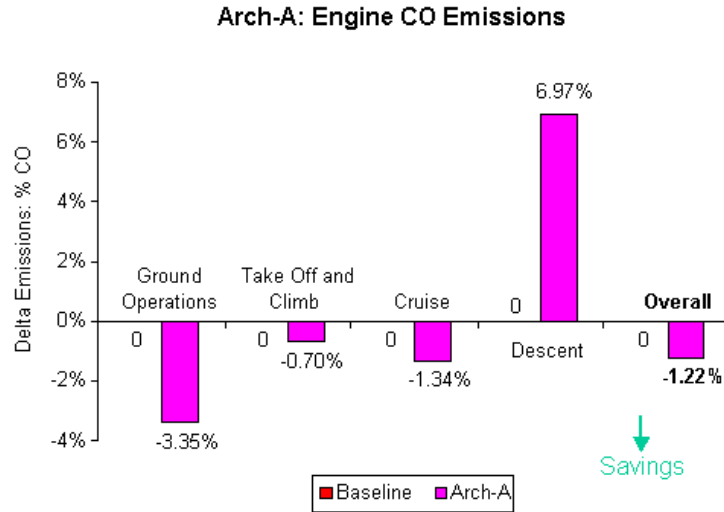
Arch-A: Engine CO Emissions

Figure 11.—Architecture-A : CO emissions relative to baseline.
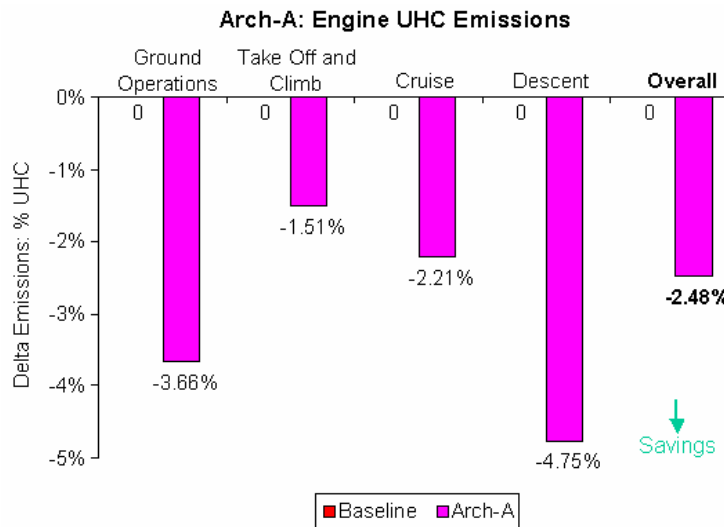
Arch-A: Engine UHC Emissions

Figure 12.—Architecture-A : UHC emissions relative to baseline.

Figure 12 shows that the net impact on UHC emissions is a modest decrease for both ground operations and descent. The percentages shown in figures 10 to 12 should be placed into perspective. For NO_X ground operations account for 0.01 percent of the total NO_X emissions and the descent segments account for 0.05 percent. Similarly, ground operations account for 0.95 percent of CO emissions and the descent segments account for 1.50 percent. Finally, ground operations account for 5.03 percent of the total UHC emissions and the descent segments for 6.14 percent. For a shorter mission, the ground, climb, and descent phases will be of relatively greater importance, but for the long-range mission studied here, the cruise segments dominate the emissions picture.
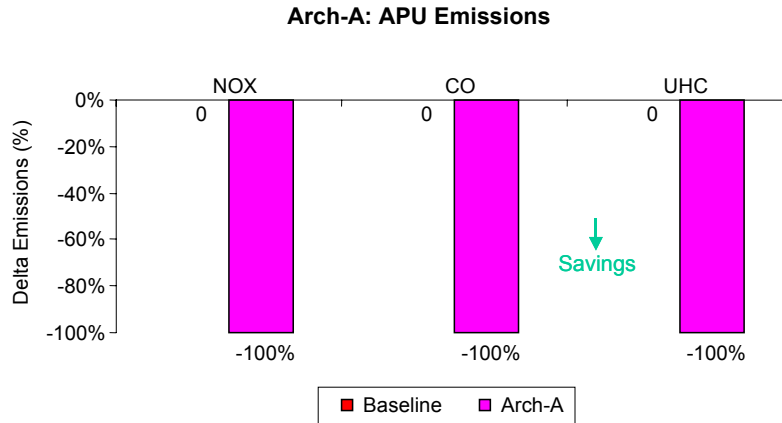
Arch-A: APU Emissions

Figure 13.—Architecture-A : APU emissions relative to baseline; SOFC APU achieves 100 percent reduction in emissions.
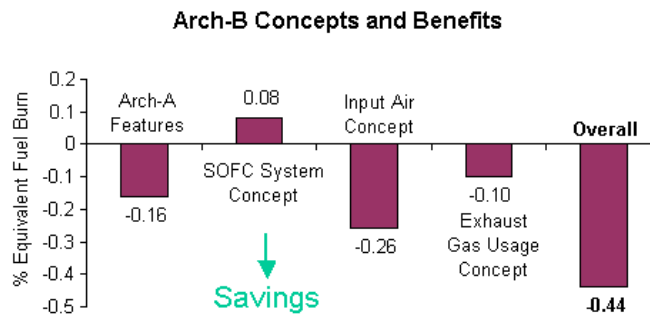
Arch-B Concepts and Benefits

Figure 14.—Architecture B : Benefits of included concepts achieve 0.44 percent overall fuel burn savings.

2.4 Architecture-B

Architecture-B achieves greater integration between the SOFC and aircraft sub-systems. It includes the features of the Architecture-A system and three additional architecture concepts: (i) SOFC system configuration concept and (ii) SOFC input air concept and (iii) SOFC exhaust gas usage concept. The first concept improves the mission reliability, the second one improves the SOFC system operating efficiency and the third concept improves the mission fuel burn. The SOFC efficiency goes up to 65.4 percent at cruise conditions (at full load operation) and 51.8 percent at ground conditions (at full load operation). For Architecture-B, the APU electric load during the ground operation and the flight climb-cruise-descent operation mission remains the same as that of the baseline system. However, due to the elimination of the inert gas generation system, the total electrical load requirement for the aircraft for the climb-cruise-descent goes down by 4 to 20 kW for different mission points. 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 14 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 2134 lb (0.46 percent mission fuel burn penalty), drag increased by 43 lb (0.37 percent mission fuel burn penalty), fuel consumption at climb-cruise-descent decreased (equivalent of 0.49 percent mission fuel) and the ground fuel usage decreased (equivalent of 0.77 percent mission fuel). The overall mission fuel burn savings for the Architecture-B system is 0.44 percent (as shown in fig. 15).

For the Architecture-B, the NO_X, UHC, and CO emissions for the engine and that of the APU relative to that of the baseline system are shown in figures 16 to 19, respectively. The SOFC system operates at zero-emissions (100 percent improvement) and the engine emissions increase by 0.06 percent for NO_X and decrease by 1.22 percent for CO and 2.56 percent for UHC.
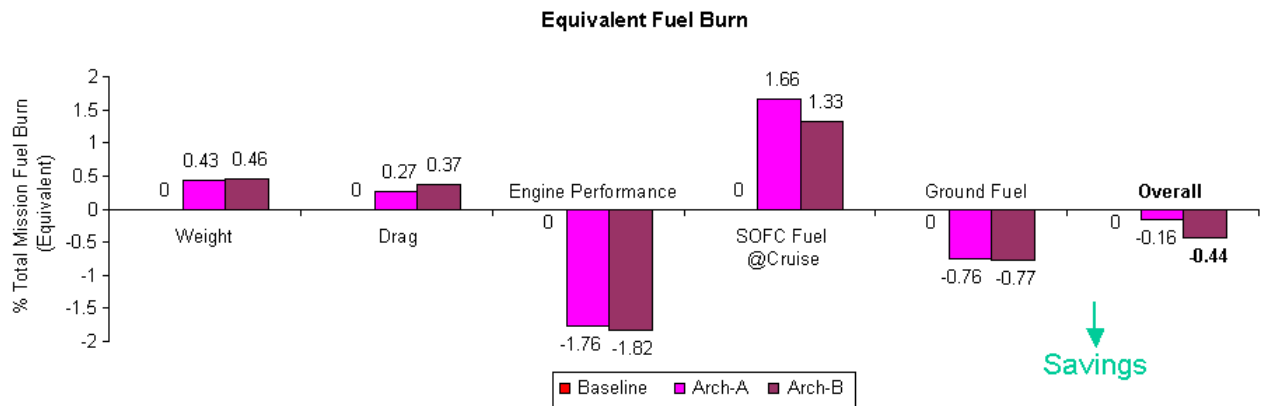
Equivalent Fuel Burn

Figure 15.—Architecture B : equivalent fuel burn relative to baseline and Architecture A. Architecture-B achieves 0.44 percent fuel burn savings and nearly 3X improvement over Architecture-A.
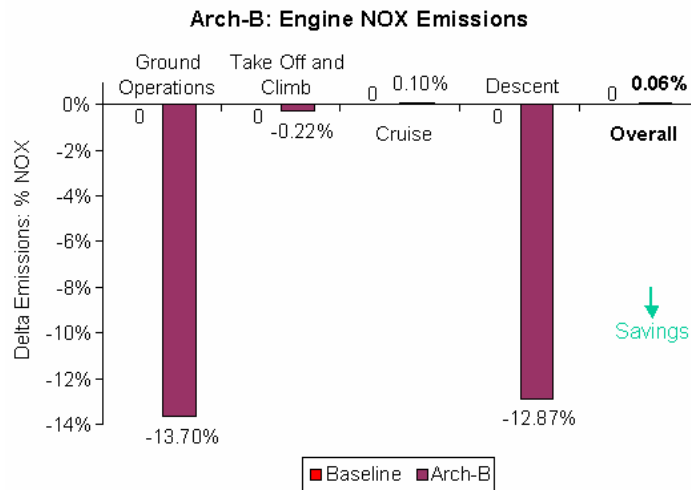
Arch-B: Engine NOX Emissions

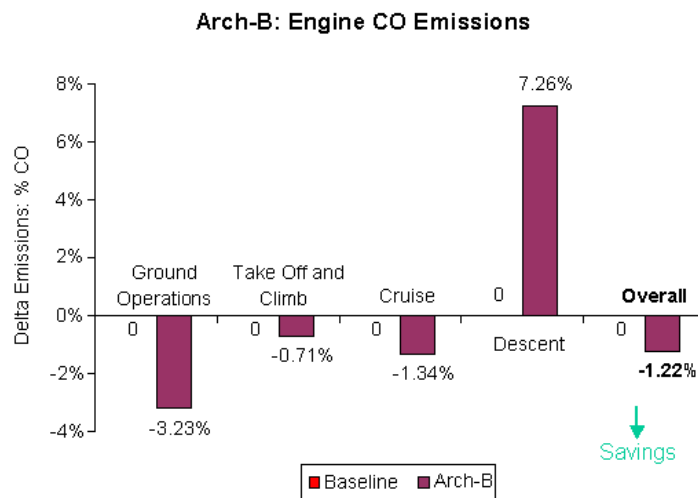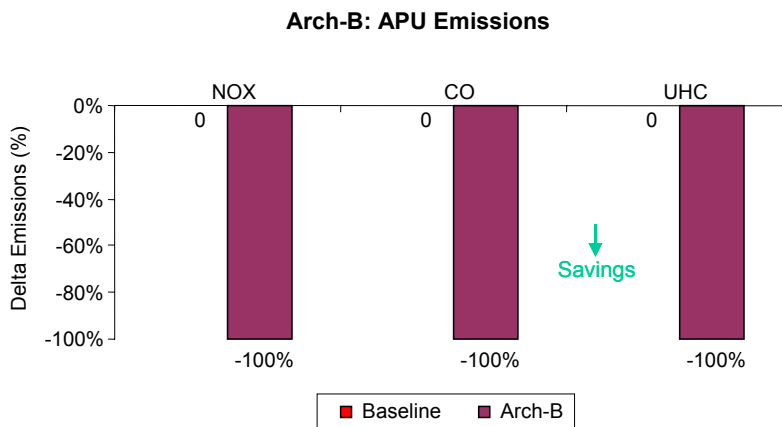Figure 16.—Architecture-B : NO$_x$ emissions relative to baseline.

Arch-B: Engine CO Emissions

Figure 17.—Architecture-B : CO emissions relative to baseline
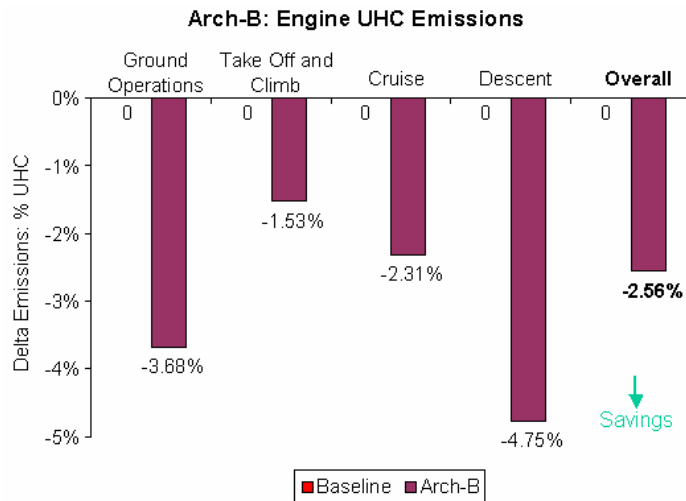
Figure 18.—Architecture-B : UHC emissions relative to baseline.

Figure 19.—Architecture-B : APU emissions relative to baseline;
SOFC APU achieves 100 percent reduction in emissions.

2.5 Architecture-C

Architecture C achieves higher integration between the SOFC and aircraft sub-systems. It includes the features of the Architecture-B system and the SOFC waste heat recovery architecture concept. A UTC proprietary technology is utilized to extend the fuel heat sink capability thus enabling recovery of the waste heat from the SOFC to pre-heat the main-engine fuel. This waste heat recovery further reduces the fuel burn and increased savings.

For Architecture-C, the APU electric load during the ground operation, the total electrical load requirement for the flight climb-cruise-descent operation mission remains the same as that of the Architecture-B system. Moreover, the engine-mounted generators provide the electrical power for the anti-ice loads, similar to that of Architecture-B.

Using the UTC ITAPS tools the Architecture-C system was evaluated. Figure 20 shows the benefits of the Architecture-C 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 2311 lb (0.5 percent mission fuel burn penalty), drag increased by 43 lb (0.37 percent mission fuel burn penalty), fuel consumption at climb-cruise-descent decreased (equivalent of 0.79 percent mission fuel) and the ground fuel usage decreased (equivalent of 0.77 percent mission fuel burn).

The overall mission fuel burn savings for Architecture-C system is 0.70 percent (as shown in fig. 21). For Architecture-C, the NO_X, UHC, and CO emissions for the engine and that of the APU relative to that of the baseline system are shown in figures 22 to 25, respectively. The SOFC system operates at zero-emissions (100 percent improvement) and the engine emissions decrease by 0.23 percent for NO_X, 1.46 percent for CO and 2.89 percent for UHC.
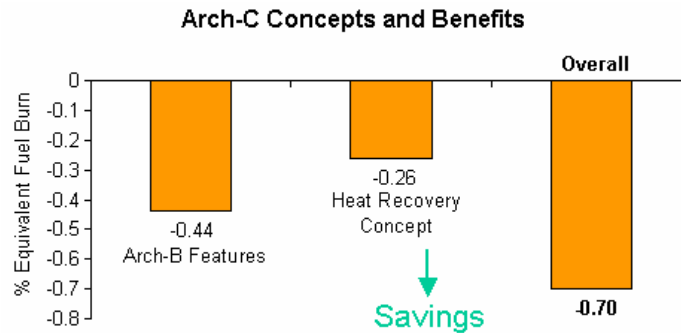

Figure 20.—Architecture-C : Benefit of included concepts.
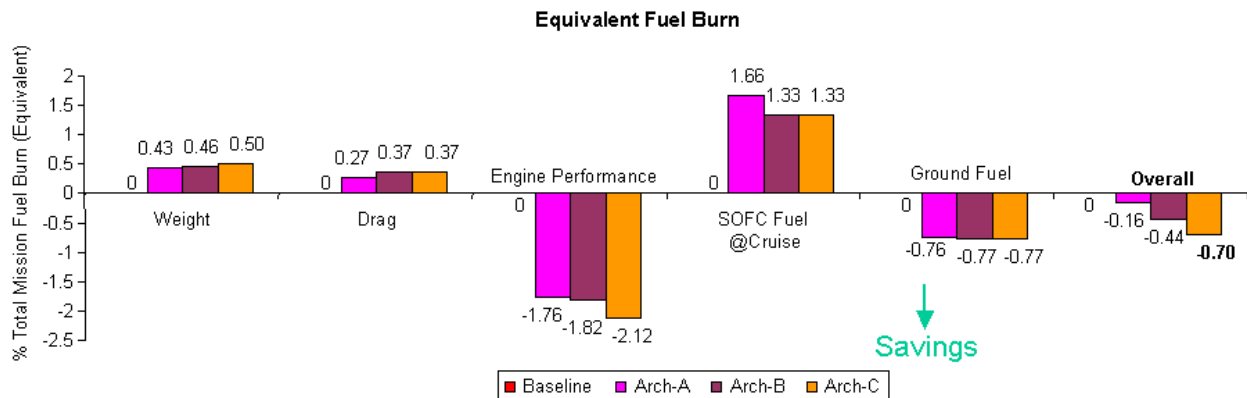Architecture-C achieves overall 0.70 percent savings on fuel burn.

Figure 21.—Architecture-C : Equivalent fuel burn relative to baseline and Architectures A and B.
Architecture-C achieves 0.7 percent fuel burn savings and nearly 5X improvement over Architecture-A.
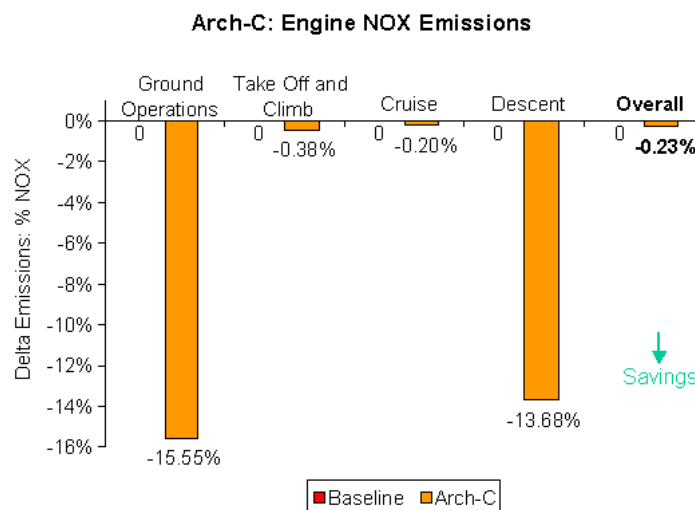

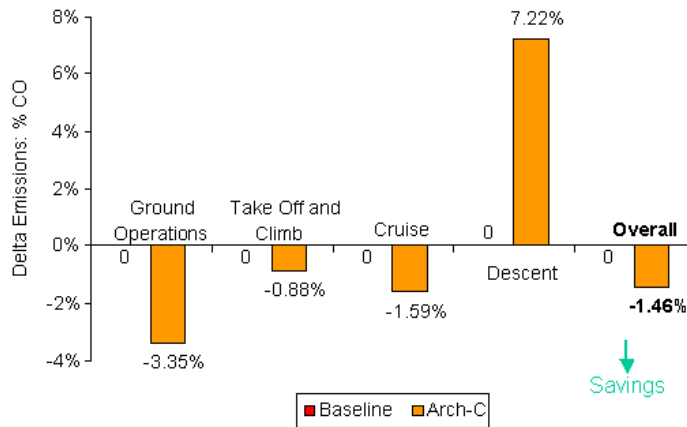Figure 22.—Architecture-C : NO_x emissions relative to baseline.
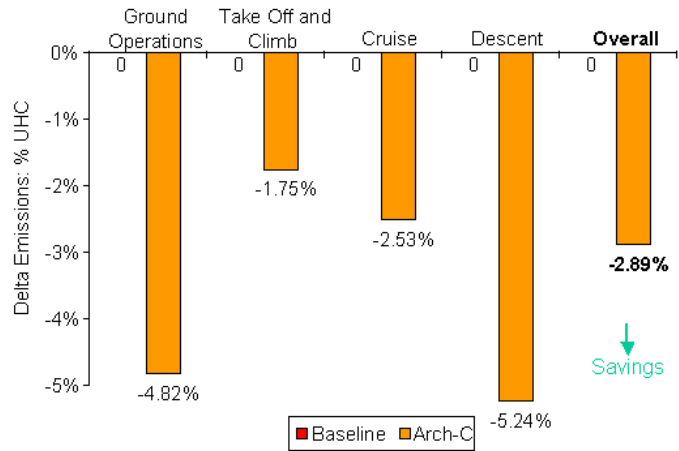
Figure 23.—Architecture-C : CO emissions relative to baseline.

Figure 24.—Architecture-C : Unburned hydrocarbons
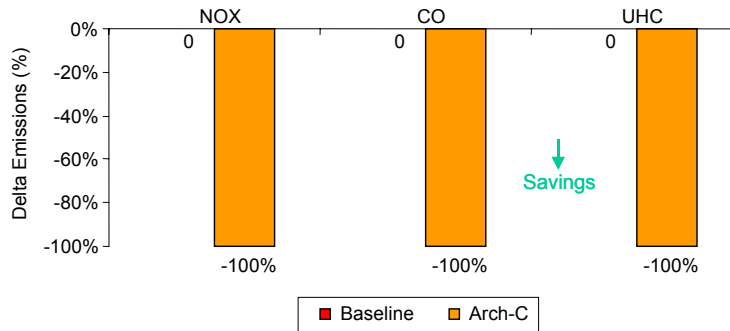emissions relative to baseline.

Figure 25.—Architecture-C : APU emissions relative to baseline;
SOFC APU achieves 100 percent reduction in emissions.

3. Additional Architecture Trades

The ITAPS evaluation results for the baseline architecture and three fuel cell powered architectures (Architectures A, B and C), estimated the benefits of a pressurized SOFC system for a long-range commercial aircraft. As an extension, two additional architecture trades have been performed to estimate the benefits of the fuel cell system for one atmosphere pressure operation and also that for a short-range aircraft mission.

3.1 Architecture-D Trades

Architecture-D explored the potential for reducing parasitic power losses due to pressurization by running the Architecture-C SOFC system at one-atmosphere pressure conditions. The SOFC system efficiency decreases during both the cruise and ground operations due to ambient pressure operation. However, the waste heat recovery concept improves the overall aircraft system efficiency and reduces the mission fuel burn. The comparison of the SOFC system efficiency for various architectures is shown in figure 26.

For Architecture-D, the APU electric load during the ground operation, the total electrical load requirement during the flight climb-cruise-descent operation mission remains the same as that of the Architecture-C system. Moreover, the engine-mounted generators provide the electrical power for the anti-ice loads, similar to that of Architecture-B. For Architecture-D trade analysis, it is assumed that the engine shaft extraction and the engine fan bleed are the same as that of Architecture-C. The SOFC system performance and weight due to ambient pressure operation, the thermal management system performance and weight due to the waste heat recovery concept and their impact on the engine and aircraft performance were evaluated using the UTC ITAPS tools.

Figure 27 shows the benefits of the Architecture-D concepts relative to the baseline system in terms of the percentage equivalent fuel burn. Relative to the baseline, the overall system weight increased by 1891 lb (0.41 percent mission fuel burn penalty), drag increased by 41 lb (0.35 percent mission fuel burn penalty), fuel consumption at climb-cruise-descent decreased (equivalent of 0.84 percent mission fuel) and the ground fuel usage decreased (equivalent of 0.70 percent mission fuel). The overall mission fuel burn savings for the Architecture-D system is about 0.77 percent. For the Architecture-D, the NO_X, UHC and CO emissions for the APU and that of the engine relative to that of the baseline system are shown in figures 28 to 31, respectively. The SOFC system operates at zero-emissions (100 percent improvement) and the engine emissions decrease by 0.71 percent for NO_X, 1.92 percent for CO and 3.19 percent for UHC.
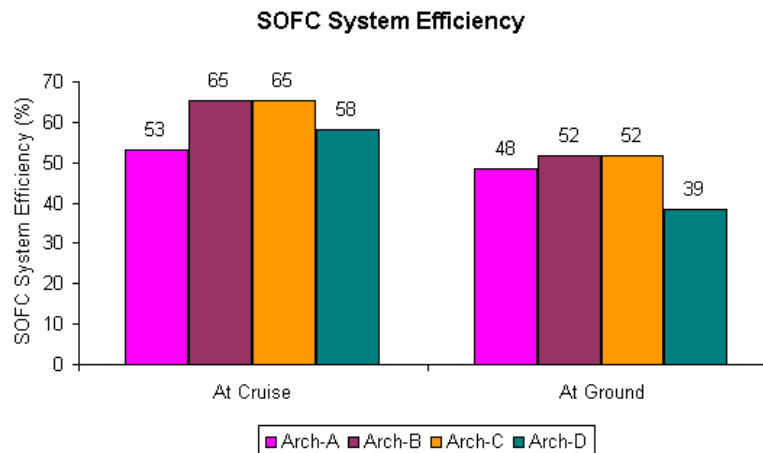
SOFC System Efficiency

Figure 26.—SOFC system efficiency for architectures examined.

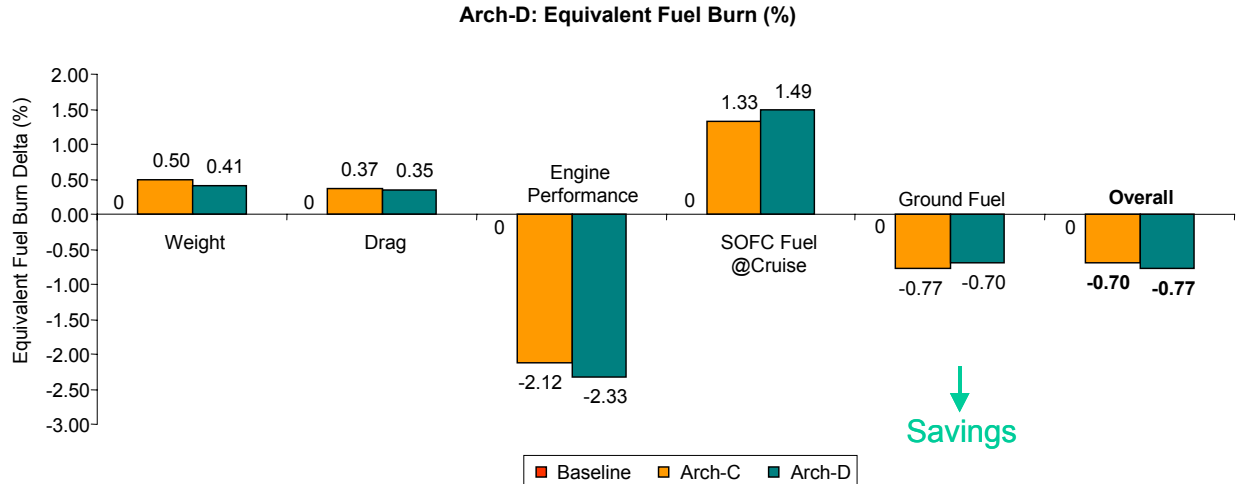**Arch-D: Equivalent Fuel Burn (%)**

Figure 27.—Architecture-D : equivalent fuel burn compared to baseline and Architecture-C; showing 0.77 percent fuel burn savings overall and 10 percent improvement over Architecture-C.
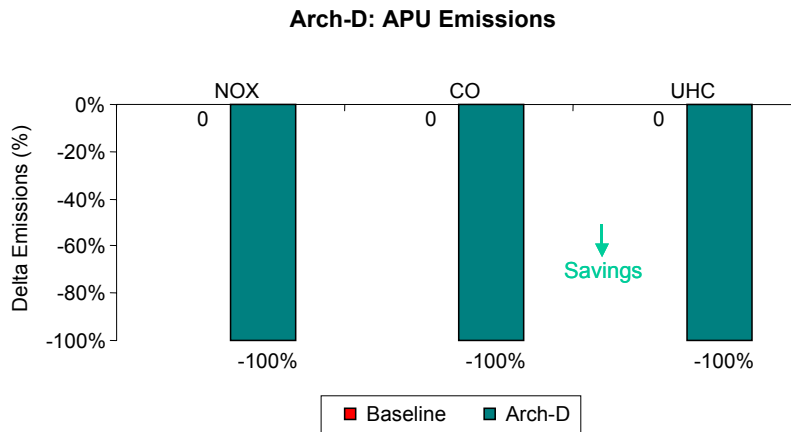
Arch-D: APU Emissions

Figure 28.—Architecture-D : Total emissions relative to baseline; SOFC APU achieves 100 percent reduction in emissions.

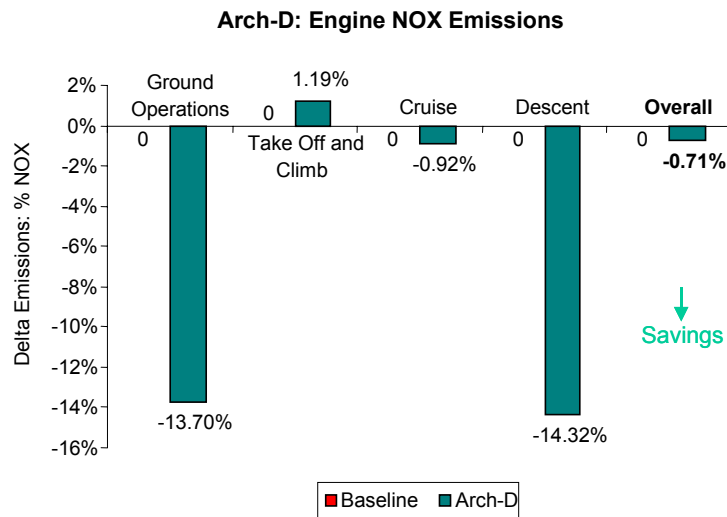**Arch-D: Engine NOX Emissions**

Figure 29.—Architecture-D : NO_x emissions relative to baseline. The Architecture-D is the best system for emission reduction.
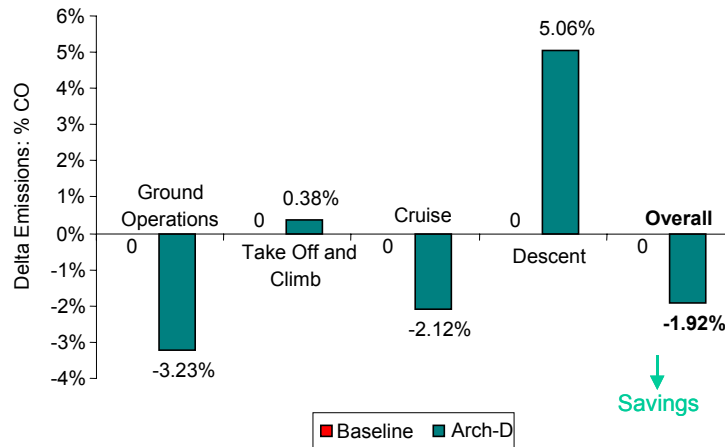
Arch-D: Engine CO Emissions

Figure 30.—Architecture-D : CO emissions relative to baseline. The Architecture-D is the best system for emission reduction.
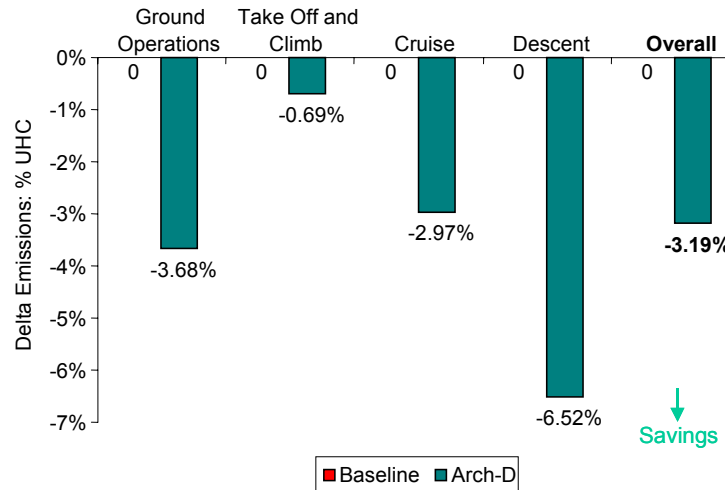
Arch-D: Engine UHC Emissions

Figure 31.—Architecture-D : UHC emissions relative to baseline. The Architecture-D is the best system for emission reduction.

3.2 Short Range Mission Trades

Recognizing that most of the benefits of the SOFC system were realized during ground operations, the potential benefits for a short-range mission were also explored. Two short-range missions (500 and 1000 NM) ranges were analyzed for both Architecture-C and Architecture-D. The ground mission and also that for the climb-cruise-descent mission points for both 1000 NM and that for the 500 NM are shown in tables IV to VI, respectively.

For short-range mission trade analysis (for Architecture-C and Architecture-D), it is assumed that the electrical loads, thermal loads, engine shaft extraction, the engine fan bleed and the heat added to the fuel are the same as that of the corresponding long-range mission system (Architecture-C and Architecture-D, respectively). The engine and aircraft performance were evaluated using the UTC ITAPS tools. Only the fuel burn savings were estimated, and the emission savings were not computed as part of the trades.

TABLE IV.—SHORT RANGE MISSION WITH MULTIPLE FLIGHTS PER DAY

Description	Load (kW)	Time (min)
Cabin Pull Down (45 min)	450	45
Sustain Cool Cabin (60 min)	338	60
Load Passenger (30 min)	450	30
Taxi Out (10 min)	0	10
Flight		
Taxi-In (10 min)	0	10
Passenger Unload (15 min)	306	15
Service (30 min)	306	30
Load Passenger (30 min)	450	30
Taxi-Out (10 min)	0	10
Flight		
Taxi-In (10 min)	0	10
Passenger Unload (15 min)	306	15
Flight Overnight Maintenance (165 min)	45	165

Repeated 3 times/day for 1000NM mission and 5 times/day for 500NM mission

TABLE V.—1000 NM RANGE MISSION FOR THE FLIGHT CLIMB-CRUISE-DESCENT SEGMENT

Mission Points	Description	Altitude	Mach Number	Elapsed Time (min)
MP1	Engine Start	0	0.00	0.0
MP2	End of Taxi	0	0.00	9.0
MP3	Take Off	0	0.26	9.5
MP4	Beginning of Climb	1500	0.39	10.3
MP5	Climb-2	10000	0.45	12.3
MP6	Beginning of Cruise	39000	0.85	25.6
MP7	Cruise-2	39000	0.85	118.0
MP8	Cruise-3	39000	0.85	118.0
MP9	End of Cruise	39000	0.85	118.0
MP10	Cut Back	39000	0.85	118.0
MP11	Descent 1	32159	0.85	120.4
MP12	Descent 2	1500	0.39	140.3

TABLE VI.—500 NM RANGE MISSION FOR THE FLIGHT CLIMB-CRUISE-DESCENT SEGMENT

Mission Points	Description	Altitude	Mach Number	Elapsed Time (min)
MP1	Engine Start	0	0.00	0.0
MP2	End of Taxi	0	0.00	9.0
MP3	Take Off	0	0.26	9.5
MP4	Beginning of Climb	1500	0.39	10.2
MP5	Climb-2	10000	0.45	12.1
MP6	Beginning of Cruise	39000	0.85	24.9
MP7	Cruise-2	39000	0.85	56.4
MP8	Cruise-3	39000	0.85	56.4
MP9	End of Cruise	39000	0.85	56.4
MP10	Cut Back	39000	0.85	56.4
MP11	Descent 1	32159	0.85	58.7
MP12	Descent 2	1500	0.39	78.6

Figures 32 and 33 show the benefits of the short-range mission for that of the Architecture-C and Architecture-D, respectively relative to the baseline system in terms of the percentage equivalent fuel burn. For short-range B777-200ER aircraft mission, the overall mission fuel burn savings for the Architecture-C is about 3.57 percent for 500 NM and 2.55 percent for 1000 NM (as shown in fig. 32). Similarly, for the Architecture-D system, the overall mission fuel burn savings is about 3 percent for 500 NM and 2.23 percent for 1000 NM (as shown in fig. 33).
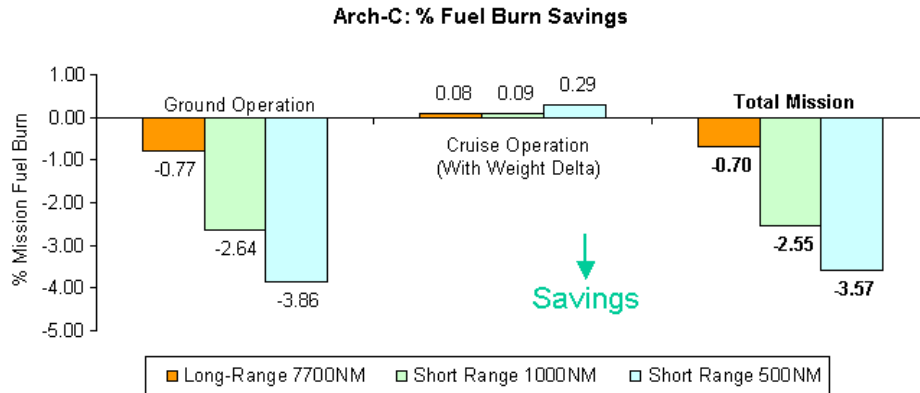
Arch-C: % Fuel Burn Savings

Figure 32.—Architecture-C : Fuel burn savings for all missions. SOFC system leads to higher fuel burn savings in short-range missions

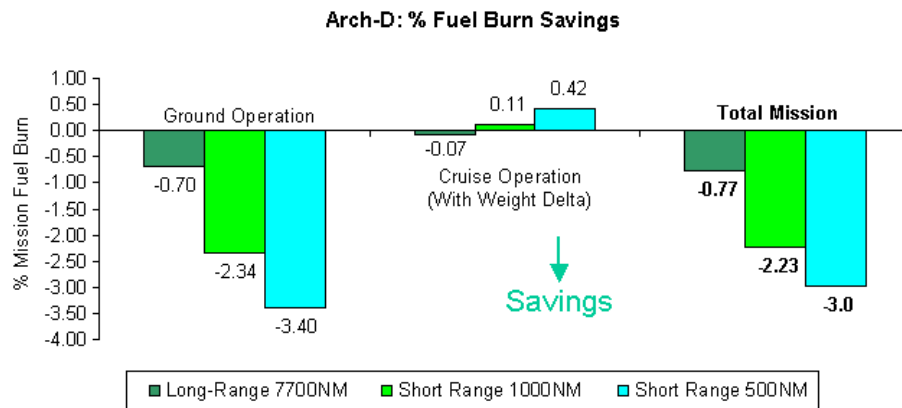**Arch-D: % Fuel Burn Savings**

Figure 33.—Architecture-D : Fuel burn savings for all missions. SOFC system leads to higher fuel burn savings in short-range missions.

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 comparing the current status of the key components and sub-systems technologies with that of the year 2015 goals/requirements.

4.1 Summary of Key Technologies

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

- SOFC System
  - o Develop SOFC Stack (for 1 kW/kg stack, >40 K hr life, 0.01 percent/T.C., 0.5 kW/kg system)
  - o Develop Jet-A Fuel De-Sulfurizer (fuel intake composition of 300 to 1000ppm sulfur, outlet fuel composition of <1ppm sulfur)
  - o Develop Jet-A Fuel Reformer (with >95 percent fuel conversion and size <25 kg/25 L)
- Aircraft Integration (being addressed by the existing technology plans)

- o Develop desiccant system to ensure dry air (–65 °F dew point) for inerting (exhaust gas usage concept).
  - o Resolve aircraft power quality issues for generator and electrical power distribution related to More Electric Aircraft (Federal Aviation Regulation FAR Chapter-25).
- Advanced Aircraft Technologies
  - o Extend fuel heat sink to 800 °F (from 325 °F)

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", a UTC proprietary technology and roadmap exists. The following sub-sections detail the technology planning for the SOFC system components.

4.2 SOFC De-Sulfurizer

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

4.2.1 Year 2015 Requirements/Goals

The year 2015 requirements/goals for the SOFC de-sulfurizer are listed below for both on-ground de-sulfurization system and also that for the non-regenerative on-board de-sulfurization system.

- Lifetime: 1 year (on-ground system) and 1 day (on-board system)
- Fuel: Reformate (Jet-A fuel)
- Fuel composition: 300 to 1000 ppm sulfur
- Outlet fuel composition: <=1 ppm sulfur
- Percent sulfur at breakthrough: 0.22 percent (on-ground) and 1.5 percent (on-board)
- Size (for 225 kW system): 400 kg (on-ground) and 60 kg (on-board)

4.2.2 Technology Gaps

The technology gaps for the de-sulfurizer system comparing the current best practices/technology with that of the year 2015 goals/requirements are listed below.

- Percent sulfur breakthrough increase by factor of 1.5
- Sorbent weight decrease by factor of 2

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 34 shows the top-level roadmap for the de-sulfurizer development. In this roadmap, BT refers to the sulfur breakthrough. The key milestone accomplishments in terms of the year and the TRL reached for the de-sulfurizer are shown.
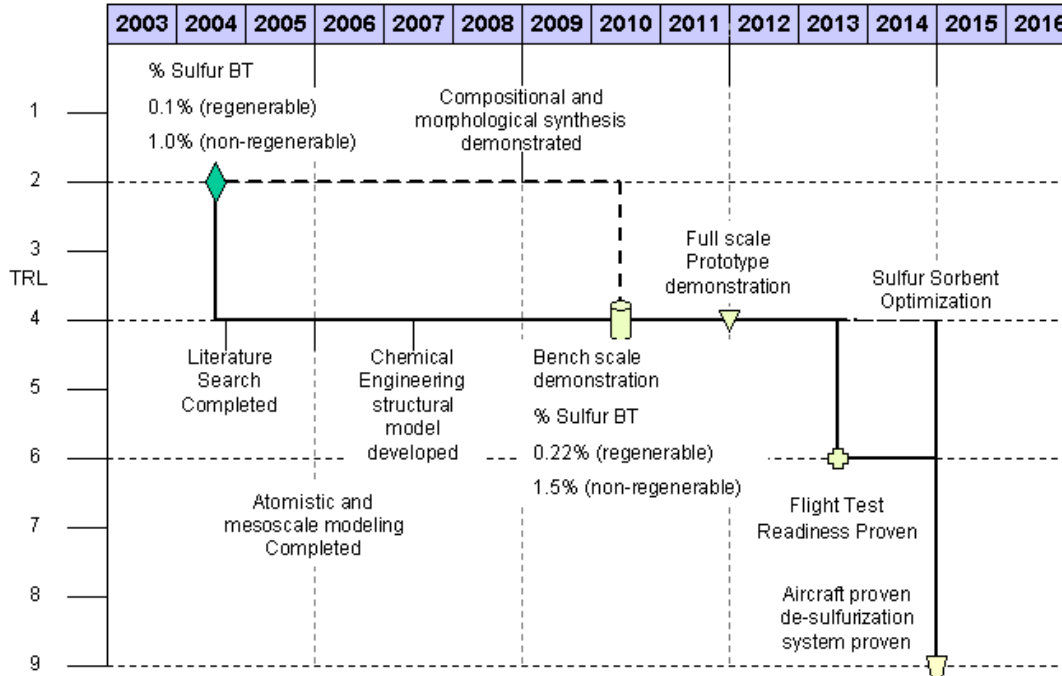
Figure 34.—Roadmap for de-sulfurizer technology development.

4.3 SOFC Reformer

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

4.3.1 Year 2015 Requirements/Goals

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

- Lifetime: 10000 hr
- Performance: >=95 percent fuel conversion
- Size: <=25 kg/25L (per 225 kW system)

4.3.2 Technology Gaps

The technology gaps for the reformer system comparing the current best practices/technology with that of the year 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: (i) To develop new catalyst materials and supports and (II) Consider modified Auto Thermal Reformer (ATR) type designs. Figure 35 shows the top-level roadmap for the reformer technology development. The key milestone accomplishments in terms of the year and the TRL reached for the reformer are shown.
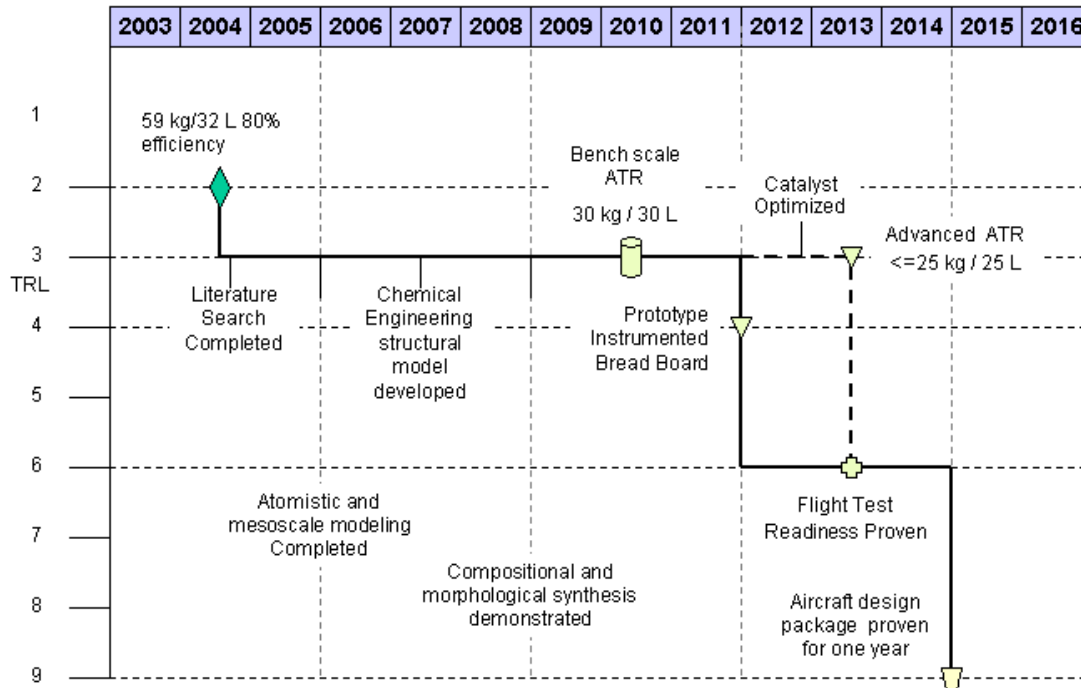
Figure 35.—Roadmap for reformer technology development.

4.4 SOFC Stack

The current technology for the SOFC stack is in Technology Readiness Level (TRL) 3-4 and that for the SOFC system is in TRL-2. The year 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 Year 2015 Requirements/Goals

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

- Lifetime: 40000 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: 0.5 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 year 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.
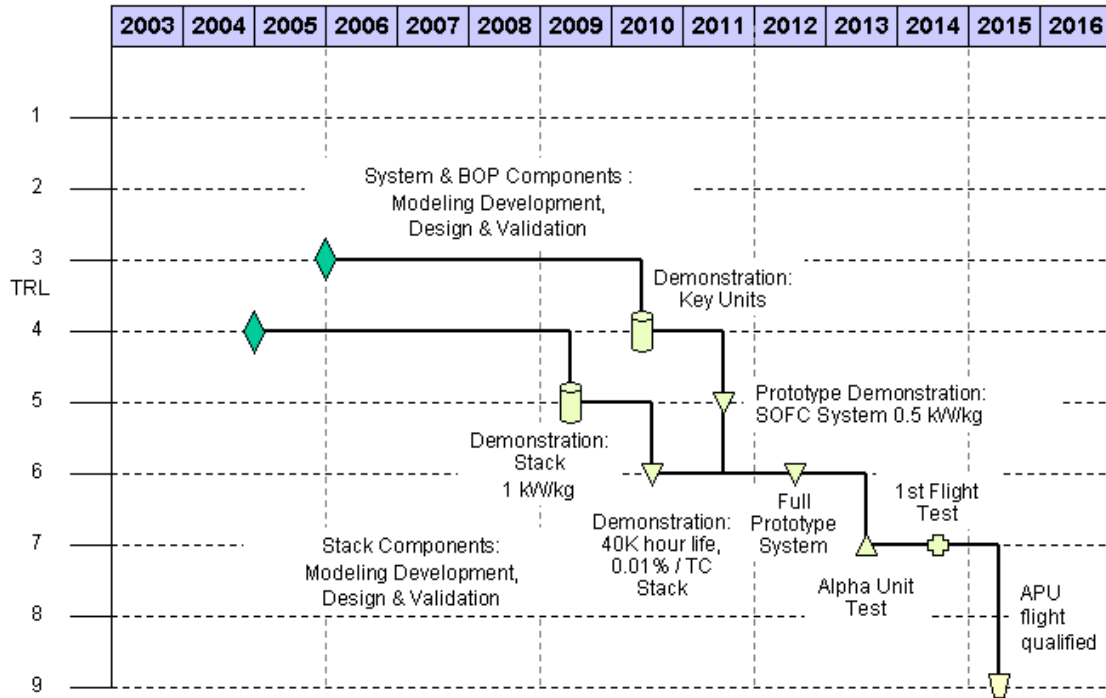- Start-up time is off by several hours.
- Cost targets $400/kW.

Figure 36.—Roadmap for SOFC system technology development.

4.4.3 Roadmap

The key recommendations for the SOFC stack and system development are: (I) Need paradigm shift in 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 0.5 kW/kg system is not a reality. High specific power concepts (such as the UTC proprietary concept presented during the contract final review) will achieve the 2015 goals. Figure 36 shows the top-level roadmap for the SOFC system technology development. The key milestone accomplishments in terms of the year and the TRL reached for the SOFC system and other key technologies are also shown.

5. Discussion of Results

5.1 Fuel Burn Benefits

The impact of the changes embodied in the four architectures studied is shown in figure 37. Replacing the conventional APU with an SOFC system resulted in a weight increase (1980 lb for Architecture A). This weight increase consistently led to an increase in mission fuel burn, with the differences in the SOFC weights for the different architectures accounting for the different fuel burn penalties shown in the "weight" group below. Architecture-A is the most basic SOFC system. Architectures B and C required additional hardware to achieve greater integration with the aircraft systems. In Architecture-D the weight was lower than for the other architectures because the stack was run at ambient pressure and did not require a pressure vessel.

All SOFC system architectures required an air source during flight when a conventional APU would be shut down. The ram drag required to obtain this air, and the loss in cabin air thrust recovery for Architectures B, C, and D resulted in increased mission fuel burn, which is shown in the "drag" group.

The use of the SOFC system reduced the extractions required from the engine (shaft power and bleed air) and thus resulted in a decrease in the mission fuel burn shown in the "engine performance"

group. For Architectures C and D, waste heat is being returned to the fuel, resulting in additional reductions in the mission fuel burn.

The "SOFC fuel" group represents the fuel actually consumed by the SOFC system plus the fuel required by the engines to carry that additional weight. Architectures B and C represent the highest efficiencies for the SOFC system because of tighter integration with the ECS cabin air system, and hence yield the lowest fuel burn penalties of the architectures studied. Architecture D loses some efficiency because of the one-atmosphere pressure operation.

The ground fuel burn ("ground fuel" group) is consistently lower for all SOFC systems because all SOFC systems investigated are more efficient than the conventional APU. Differences in the efficiencies of the various architectures (see above) result in the variations in the benefit obtained.

The "overall" group represents the net fuel burn benefit due to all of these individual factors. It is obvious that the greater degree of integration of the SOFC system into the aircraft systems is benefit. Figure 38 illustrates the financial benefits of these architectures.
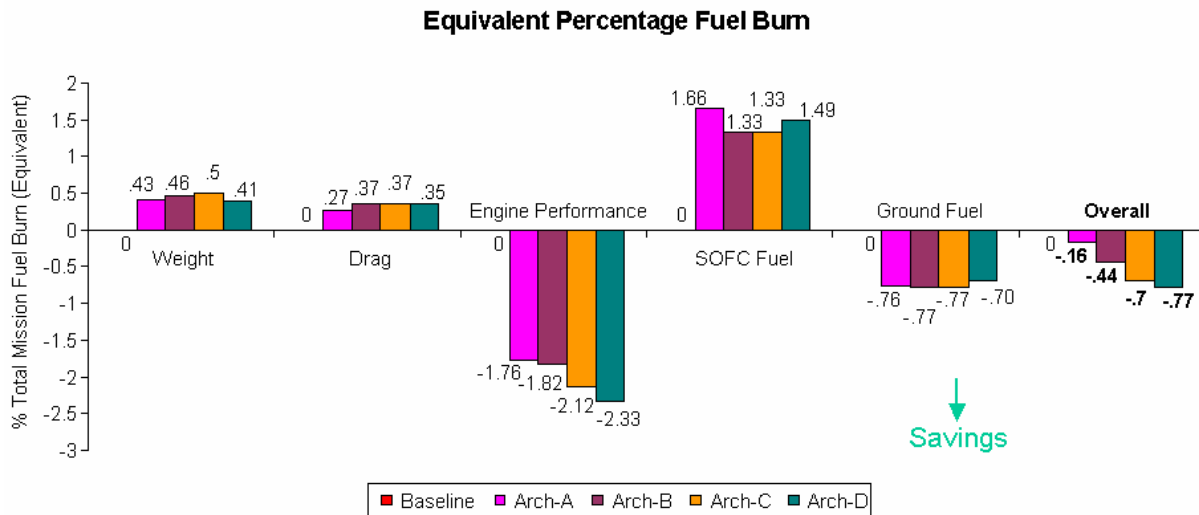

Figure 37.—Equivalent fuel burn savings for all the architectures. Architectures C and D are the best performing systems.
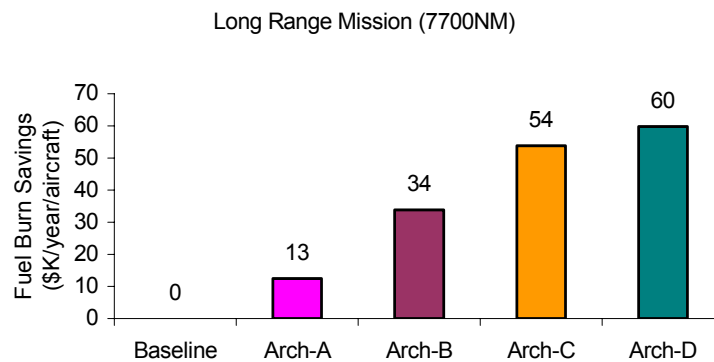

Figure 38.—Financial impact of fuel burn savings of all architectures investigated. Architectures C and D are the best performing systems.

5.2 Emissions

None of the SOFC systems studied produce any NO_x, CO, or UHC. 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 5.1. 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. The engine and aircraft emissions for the four architectures relative to the baseline are shown in figures 39 and 40.

5.3 APU Noise

While prediction of the noise levels of the SOFC APU was not part of the contract, a preliminary estimate was made of the noise levels for ground operations. The noise level at 20 m is shown in figure 41 for the baseline APU and for the SOFC APU of Architectures C and D. Without a silencer, the conventional APU exceeds the 80 dBA noise requirement, but with the addition of a silencer, the requirement is met. The Architecture C SOFC APU is significantly under the requirement at 72 dBA with the main noise contribution coming from the combustion noise of the turbo-machinery necessary to pressurize the stack for ground operations. The Architecture-D APU is operated at ambient pressure and does not need that turbo-machinery. The resulting noise level is only 51 dBA.
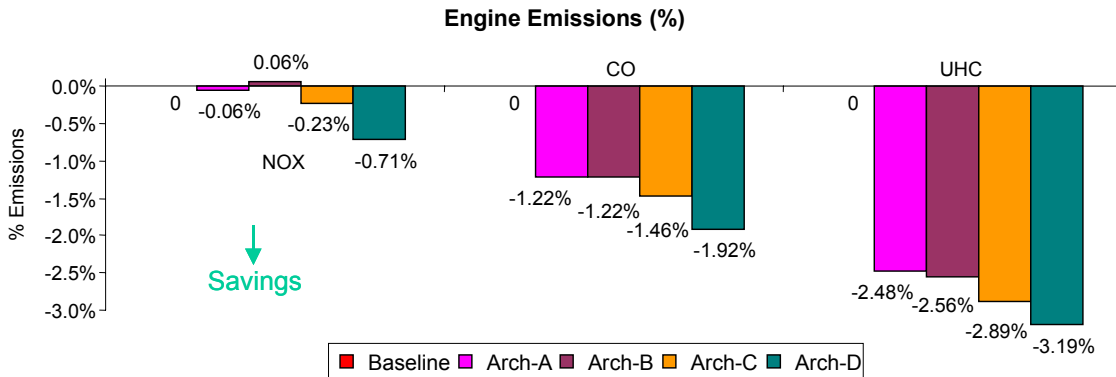

Figure 39.—Engine emissions for complete mission relative to baseline.
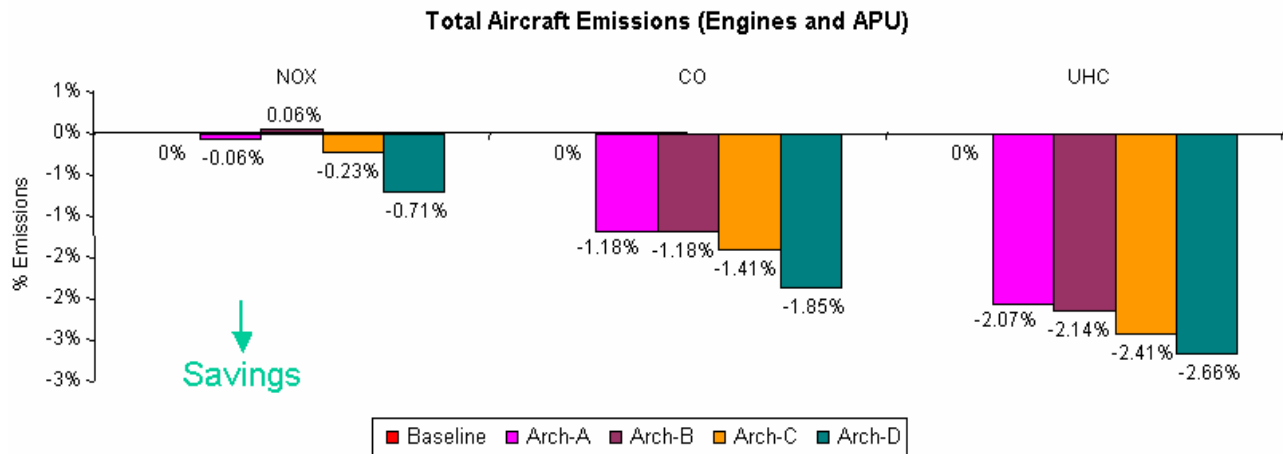The Architecture-D is the best system for emission reduction.

Figure 40.—Aircraft emissions for complete mission relative to baseline.
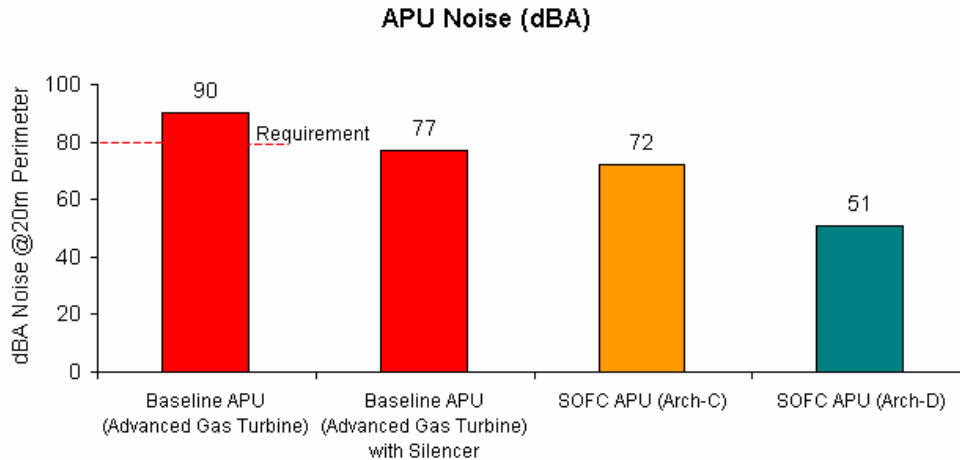The Architecture-D is the best system for emission reduction.

APU Noise (dBA)

Figure 41.—APU noise at 20 m (dBA). The Architecture-D is the best system for noise reduction.
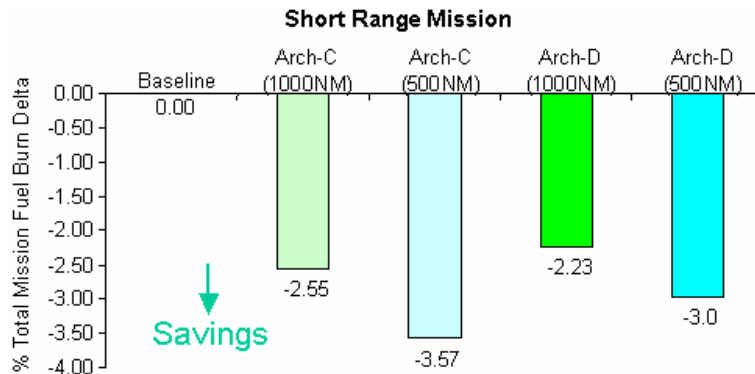

Short Range Mission

Figure 42.—Equivalent fuel burn savings for the Architectures C and D on short-range missions. SOFC system leads to higher fuel burn savings in short-range missions.

5.4 Short-Range Missions

As the study results were being analyzed, it became apparent that the greatest benefit of the SOFC system was in the ground operations. The overall mission benefit of the ground operations will be emphasized in shorter missions; consequently, it was decided to evaluate the two best architectures (C and D) for two short-range missions (1000 and 500 NM). The results of this exercise are shown in figures 42 and 43.

As might be expected, the benefit is greater for the 500 NM mission where the ground fuel burn represents a greater fraction of the total mission fuel burn. Architecture D is slightly less efficient than Architecture C because the SOFC stack is operated at one-atmosphere pressure. On the shorter missions, the reduction in weight and improved engine efficiency from waste heat recovery do not counteract this loss in efficiency on the ground. It must be noted that the aircraft used in the short-range mission analysis was still the Boeing 777-200ER and the results may be different if an aircraft more appropriate to a short-range mission were used.
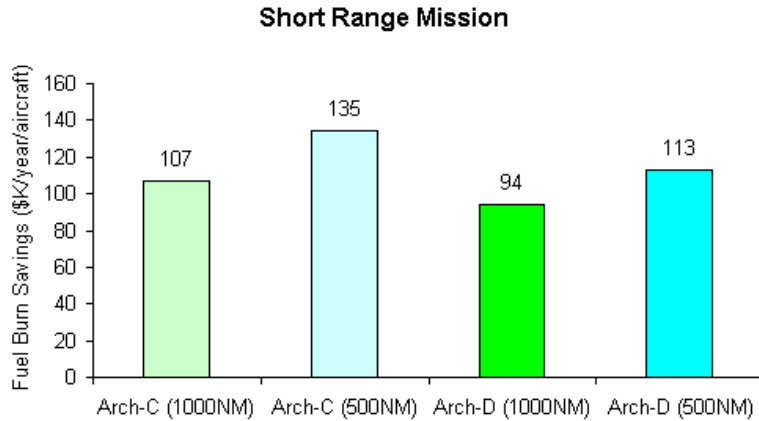
Short Range Mission

Figure 43.—Financial impact of fuel burn savings for short range missions.
SOFC system leads to higher fuel burn savings in short-range missions.
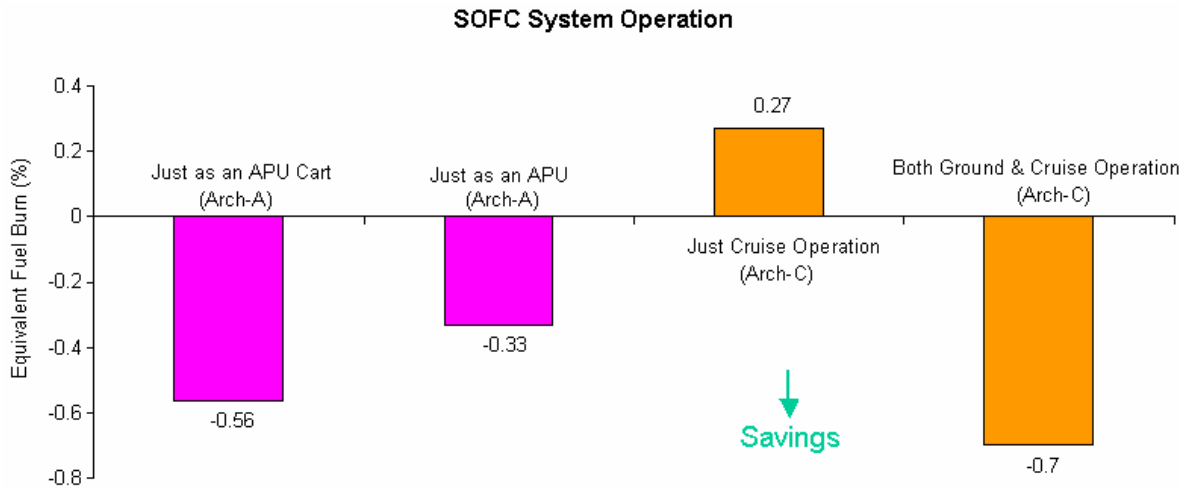
SOFC System Operation

Figure 44.—Benefits of various modes of operation for SOFC APU. Best benefit is achieved
for SOFC system operating at both ground and climb-cruise-descent operation.

5.5 SOFC System Trades

Figure 44 presents the benefits and penalties of various ways in which an SOFC system might be used. First, it is possible to use the SOFC system as a ground cart with a conventional gas turbine APU on board for emergency power. This application provides benefit during ground operations because the SOFC is more efficient than a conventional gas turbine APU.

The benefit comes without the penalty of increased weight because the SOFC unit stays on the ground. The second option explored was to simply replace the gas turbine APU with an SOFC equivalent, which is only used during ground operations. This approach yields less benefit because the aircraft has to carry the increased weight of the SOFC APU. A third option would be to use an SOFC system as a secondary power source during the climb, cruise, and descent portions of the mission instead of extracting the power from the engines. While this strategy unloads the engines, there is a net penalty because of the weight and drag associated with the SOFC system. The final option considered is to replace the conventional APU with an SOFC system, which is used both for ground operations and as a secondary power source during the flight. This option yields the greatest benefits.
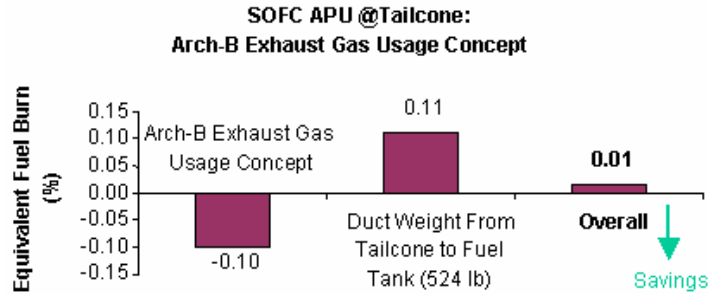
Figure 45.—Benefits of Architecture B exhaust
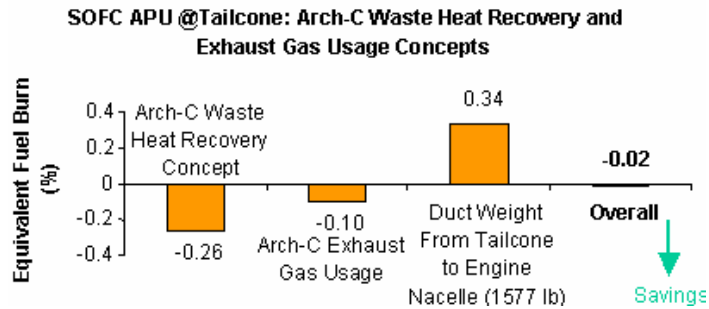gas usage concept with SOFC in tailcone.

Figure 46.—Benefits of Architecture C waste heat recovery
and exhaust gas usage concepts with SOFC in tailcone.

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. Preliminary results shown in figures 45 and 46 indicate that the weight penalty of the ducting necessary to accomplish waste heat recovery into the fuel and the use the SOFC exhaust effectively negate the expected benefits of the waste heat recovery and exhaust gas usage concepts. Location of the SOFC APU in the wing root region appears more attractive.

5.6 Impact of SOFC System Weight

The study was done with certain goals for SOFC system weights in the year 2015. The basic power density used in this study was 0.5 kW/kg for the SOFC system. This assumption is consistent with other similar studies. The weight of the pressure vessel and any additional equipment was assumed to be in addition to the weight calculated from this power density figure. The impact of additional SOFC system weight increase relative to this goal was estimated and is presented in figure 47. The better architectures can accommodate significant weight gains and still match the fuel burn of the baseline system. For example, Architecture D can accommodate an additional 3600 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.

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 48.

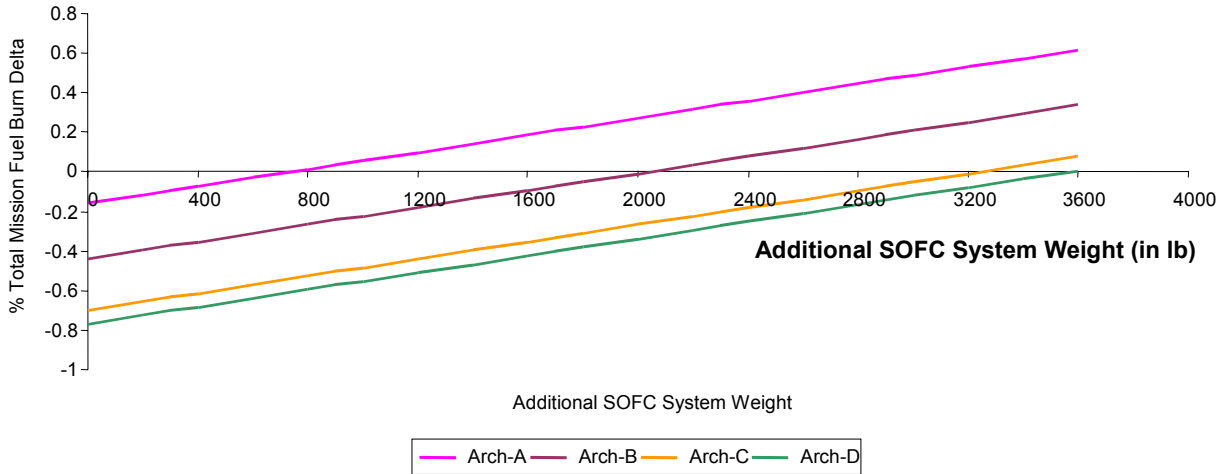**Effect of Additional SOFC System Weight On Benefits System**

Figure 47.—Effect of additional SOFC system weight on the fuel burn benefits.

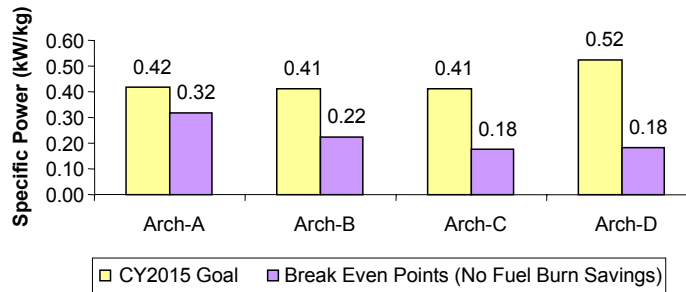**2015 SOFC System Weight Goals and Break-Even-Points (No Fuel Burn Savings)**

Figure 48.—Year 2015 SOFC system weight goals and the break even points (no fuel burn savings).

6. Conclusions

This study selected a more-aggressive year 2015 aircraft baseline system (UEET engines, advanced APU with ceramics 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 long-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 minimize the technology development cost/time. The mission fuel burn savings for Architecture-A, which has minimal system integration, is 0.16 percent. Architecture-B and Architecture-C employ greater system integration and obtain fuel burn benefits of 0.44 and 0.70 percent, respectively. Architecture-D represents the highest level of integration and obtains a benefit of 0.77 percent.

To realize any fuel burn benefit from an SOFC system for a long-range commercial aircraft, the SOFC system specific power should be >0.18 kW/kg (best case SOFC system—Architecture C/D). 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.

A paradigm shift is needed in the SOFC stack concepts to achieve the year 2015 goal metrics (weight, life, etc.). 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. The SECA-funded programs will not achieve the required specific power metrics. This is due to the limitation imposed by the ceramic technology for the anode-supported-cells, which restricts the SOFC system weight reduction to 0.5 kW/kg. NASA should fund the development of stack concepts (such as the UTC proprietary concepts presented during the contract final review) that increase the specific power of the SOFC system (kW/kg) for aircraft applications.

NASA should fund the development of on-ground de-sulfurization and non-regenerable on-board de-sulfurization for the processing of jet-A fuel (with sulfur levels of 300 to 1000 ppm). NASA should fund the development of advanced technologies (such as the UTC proprietary concept presented during the contract final review) to extend fuel heat sink capability above the current 325 °F limit.

The SOFC system provides more benefits to short-range mission aircraft. Preliminary analysis of the short-range mission (500 NM) for the B777-200ER aircraft shows about 3 percent mission fuel burn benefits compared to about 0.7 percent mission fuel burn benefit for the long-range mission (7700 NM). It is recommended that NASA fund a future study on SOFC system applications for short-range mission aircraft.

The SOFC system location should be closer to wing roots (or engine) to maximize system integration benefits. The benefits due to the waste heat recovery and the exhaust gas utilization concepts will not be realized if the SOFC APU is in the tail cone. Therefore, a future study should be performed to determine the optimal location of the SOFC-APU system in the aircraft.

Any future system study on the SOFC system application for the aircraft should also evaluate the cost goals of the SOFC system for the year 2015.

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Appendix—Symbols

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

Acronym	Meaning
APU	Auxiliary Power Unit
ATR	Auto Thermal Reformer
BCA	Best Cruising Altitude
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
MEA	More Electric Aircraft
NM	Nautical Mile
NOx	Oxides of Nitrogen
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 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 long 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 and emissions. The baseline aircraft considered was the Boeing 777-200ER airframe with more electric subsystems, Ultra Efficient Engine Technology (UEET) engines, and an advanced APU with ceramics for increased efficiency. In addition to the baseline architecture, four architectures using an SOFC system to replace the conventional APU were investigated. The mission fuel burn savings for Architecture-A, which has minimal system integration, is 0.16 percent. Architecture-B and Architecture-C employ greater system integration and obtain fuel burn benefits of 0.44 and 0.70 percent, respectively. Architecture-D represents the highest level of integration and obtains a benefit of 0.77 percent.

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