NASA/TM-2004-212989

Evaluation of a Hydrogen Fuel Cell Powered Blended-Wing-Body Aircraft Concept for Reduced Noise and Emissions

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February 2004

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Acknowledgments

The authors gratefully acknowledge the blended-wing-body analytical modeling of Karl Geiselhart (NASA Langley Research Center) and the fuel cell system analytical modeling of the Electrochemistry Branch at NASA Glenn Research Center, both of which served as starting points for the analysis methods described in this report.

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Executive Summary

As the demand for air travel has grown over the years, so have the negative environmental impacts from aviation and the pressures to mitigate those impacts. Aircraft-produced noise and emissions are two of the most important environmental issues associated with air travel. Although technology advances have enabled each new generation of aircraft produced to be quieter and less polluting than the previous, the current rate of improvement is slower than the rate of growth in air travel. Revolutionary approaches to aircraft noise and emission reduction are needed to realize continued growth in air travel without a steady rise in the negative environmental impacts. An evaluation of such approaches was conducted in the "Quiet Green Transport" (QGT) study of the NASA Revolutionary Aerospace Systems Concepts program. The objectives of the QGT study were to develop and evaluate commercial transport aircraft concepts that significantly reduce or eliminate aircraft noise and emissions, and to identify technology advances necessary to make those concepts feasible. Modeling and evaluation of the second study concept, Concept B, is described in this report.

QGT Concept B is a blended-wing-body configuration with distributed, hydrogen fuel cell propulsion. Hydrogen fuel cells offer the potential to increase fuel efficiency and eliminate all emissions except H_2O (water). Distributing the propulsion system into several engines instead of a few large ones tends to increase the frequency of the engine noise, leading to greater atmospheric attenuation of the noise. The blended-wing-body is an aerodynamically efficient configuration which also provides a significant amount of noise shielding for top mounted engines. Evaluation of Concept B was impeded by the unconventional nature of the design. Adequate characterization of the fuel cell based propulsion system required the development of new models and analysis tools. Other aspects of the concept necessitated adaptation or modification of existing tools. Due to the limitations of the analysis tools used and the uncertainties in characteristics of revolutionary future technologies, the evaluation of Concept B was conducted at a somewhat high, conceptual level.

Revolutionary technology advances in a number of different areas are necessary to make Concept B feasible and to realize the full environmental benefits of the concept. Significant advances in fuel cell propulsion system technologies are necessary just to make a fuel cell powered transport aircraft possible. Even with 25-30 year projected fuel cell propulsion improvements, a fuel cell based system is much heavier than conventional aircraft propulsion and advances in airframe technology are needed to offset propulsion system weight penalties. Concept B's emission benefits rely on the use of liquid hydrogen (LH_2) fuel. In order for Concept B to be practical, large-scale, economical, environmentally friendly production of LH_2 is needed. The noise benefits of Concept B partially rely on successful development of continuous moldline technology flap systems and a relatively "quiet" means to generate drag or reverse thrust on approach. With advanced technology assumptions, projected benefits for Concept B relative to today's conventional aircraft include the complete elimination of all aircraft emissions except H_2O and the potential to eliminate the formation of persistent contrails, 8 to 22dB EPNL reduction in noise at the FAA noise certification points (43dB EPNL cumulative reduction), and a 10% reduction in the area exposed to noise levels of 55dBA and greater during takeoff and landing operations. The use of a fuel cell based propulsion system was found to have an indirect negative impact on the noise characteristics of Concept B. In order to minimize the propulsion system weight, the aircraft thrust-to-weight ratio was the minimum necessary to meet the mission requirements. The resulting low thrust-to-weight ratio negatively impacted the aircraft's ability to climb away from the airport and extended the aircraft noise over a large area. This outcome is one example of the potential for trade-offs between the levels of emission reduction and noise reduction that are achieved by a "Quiet Green Transport" concept.

Contents

1. Introduction

Protecting the environment is becoming an important factor in many decisions made by the public, industry, and government. The growing attention to environmental issues is likely due to an increased understanding of how both today's quality of life and the future public health and welfare can be adversely impacted by human activities. The current desire to protect our environment is not only reflected in more stringent government regulations but also in demands from the general public. Aviation is not immune to these regulatory and popular pressures. The growing attention to aviation related environmental issues is demonstrated by numerous reports on the topic (e.g., refs. 1, 2, 3, 4, 5). The aviation industry faces a particularly difficult environmental challenge due to projected rapid growth of the industry (faster than Gross Domestic Product and most other industries). The events of September 11, 2001 resulted in a significant drop in the demand for air travel. Nevertheless, it is anticipated that over the long term as the global economy and population grow so will the demand for air travel (ref. 6). Although individual aircraft are becoming more environmentally friendly as the result of technology advances, the rate of improvement is slower than the rate of growth in air travel and the total environmental impact from aviation is on the rise. One possible response to this increasing environmental impact is to constrain growth. The National Research Council concluded in their report, *For Greener Skies – Reducing Environmental Impacts of Aviation* (ref. 5), "Environmental concerns will increasingly limit the growth of air transportation in the 21st century unless vigorous action is taken to augment current research and technology related to the environmental impacts of aviation." While restricting growth alleviates environmental problems, there are clearly negative economic consequences from this approach. A sustainable air transportation system which is able to meet society's demand for minimal environmental impact will be an important factor in future economic growth.

The environmental impact of aviation is a broad topic involving many aspects, including aircraft, airports, ground support equipment, and operational procedures. A complete assessment of just the aircraft related aspects would have to include a number of factors such as the manufacturing process and the ability to recycle aircraft materials, in addition to the traditional concerns of aircraft noise and emissions. Although there are numerous facets to the environmental impacts of aviation, aircraft-produced noise and emissions are at the forefront. Over the past fifty years aircraft and engine manufactures have made great progress in reducing noise and emissions (though usually not motivated strictly by concern for the environment). However, the rate of aircraft noise and emission reductions from evolutionary technology improvements is slowing. For example, figure 1 from reference 4 shows the reduction in specific fuel consumption that has occurred since the introduction of jet transports. The rate of improvement in fuel efficiency has slowed drastically in the past two decades. A similar trend exists for aircraft noise levels. Revolutionary approaches to aircraft noise and emission reduction are needed to enable continued growth in air travel without a steady rise in negative environmental impacts. The NASA Revolutionary Aerospace Systems Concepts (RASC) Program was initiated in 2000 to develop and analyze revolutionary (25-50 year time horizon) aerospace concepts that address strategic objectives of the NASA Enterprises, and to identify advanced technologies required to enable those concepts. One of the initial studies undertaken in the RASC program was the "Quiet Green Transport" (QGT) study, which addressed NASA's objective to "Protect local and global environmental quality by reducing aircraft noise and emissions" (ref. 7).

The ultimate vision for a "Quiet Green Transport" would be the ability to move people (and goods) by air without harming the Earth or degrading the quality of life of its residents. For the purpose of the RASC QGT study the vision of a "Quiet Green Transport" was decomposed into two goals: "objectionable" aircraft noise (defined as >55dB DNL) is contained within the airport boundary; and the aircraft does not emit any substance where it has a significant environmental impact. The objectives of the study were to define revolutionary aircraft concepts aimed toward achieving the goals and to identify the technology advances necessary to make those concepts feasible. A set of concepts for evaluation was derived by "brainstorming" options to eliminate aircraft noise and emission sources (or significantly reduce their impacts). Evaluation of the first concept derived, "Concept A," is described in reference 8. Concept A is a relatively near-term concept which, although fundamentally different in design from current aircraft, does not require revolutionary technology advances to be built. Concept A features two "ultra-high" bypass ratio, hydrogen (H_2) fueled turbofan engines with scarf inlets placed above a strut-braced wing. As detailed in reference 8, significant reductions in aircraft environmental impacts could be achieved with this concept, including complete elimination of all aircraft emissions except NO_X and water vapor and a 53% reduction, relative to today's equivalent aircraft, in the area exposed to noise levels of 55dB and greater during takeoff and landing operations. NO_X emitted by the aircraft during takeoff and landing operations is also reduced by 18%. While these benefits are significant, Concept A does not fully achieve the noise and emission goals set for the Quiet Green Transport study. Fully achieving the QGT goals requires more radical approaches to noise and emission reduction/elimination such as those implemented in the second QGT concept, "Concept B." The evaluation of Concept B is the focus of this report.

2. Study Overview

Some general information on the RASC QGT study is presented in this section. Additional information is also presented in reference 8.

2.1 Supporting Studies

The Quiet Green Transport study evolved from a number of recent NASA studies investigating advanced concepts for reducing noise and emissions. Past studies were generally focused on either reducing noise or emissions, and did not combine both into one aircraft configuration as done in the QGT study. However, many of the ideas, concepts, assumptions, and knowledge from these previous studies were used as initial input for the QGT study. In addition, related studies being performed concurrently with the QGT study were used as a continuing source of input. In 1998-1999 a series of high-level studies exploring aircraft with unconventional propulsion systems for the reduction or elimination of aircraft emissions was performed jointly by NASA Langley Research Center (LaRC) and NASA Glenn Research Center (GRC). The propulsion systems studied included methane fueled gas turbine propulsion, hydrogen fueled gas turbine propulsion, hydrogen fuel cell electric propulsion, lithium-air fuel cell electric propulsion, and nuclear propulsion. Hydrogen fueled gas turbine based propulsion was investigated further in concept studies conducted during 2000 as part of the GRC Zero CO_2 Emissions Technology (ZCET) project. Since 1999, MSE Technology Applications, Inc. has been performing a study funded by NASA LaRC to investigate the future possibilities for a totally "emissionless" transport aircraft (ref. 9). This study has covered a broad range of possible technologies, including breakthrough concepts which challenge traditional views of propulsion and energy systems. Aircraft noise reduction concepts have been investigated in a number of recent NASA studies as part of the former Advanced Subsonic Transport (AST) Noise Reduction program and the current Quiet Aircraft Technology program. Several concepts with significant noise reduction potential have been identified in these studies. In addition to addressing airframe and engine source noise, recent noise reduction studies have also included various means to reduce the impact of the noise generated, such as shielding and modified approach and climb profiles. The available knowledge base for noise and emission reduction concepts is much broader than the recent studies mentioned above and includes numerous past reports. Where appropriate, information from these reports was also used as a resource.

2.2 Future Scenario Assumptions

When developing and evaluating advanced aircraft concepts, which could enter the market decades in the future, it is not sufficient to only consider the current market environment. The possible future environments that will dictate the desired design attributes must also be considered. Many factors will dictate what characteristics of a transport aircraft are important in the future. The fact that "quiet green" aircraft concepts are being studied implicitly assumes a future scenario in which these things are important. But it is not known to what extent these aspects will dominate others such as cost, maintainability, etc. The QGT concepts are not intended, nor expected, to be capable of competing with conventional aircraft in today's market environment. Rather, it is assumed that an increased emphasis on environmental issues will result in sufficient economic incentives for reducing aircraft noise and emissions to make the concepts viable.

If "green" is important for aviation in the future, it will be for other industries as well. Substantial research efforts are in place today to develop the technologies needed to move towards an economy based on "greener" energy sources and fuels. A transition to alternate fuels is not something the aviation industry would likely do alone, but as part of a shift towards these fuels by many industries. The incentive for using alternate fuels is currently much stronger in other sectors than in aviation, as evidenced by the large investment in hydrogen fuel technologies for ground vehicles. For this reason, and because of the greater challenges faced in aircraft design, it is anticipated that aviation will follow behind other sectors in making any fuel transition. Based on the current direction of research in the U.S. Department of Energy (DOE), hydrogen appears to be a likely alternate fuel candidate. The DOE has outlined a vision and roadmap for transition to a "hydrogen economy" (refs. 10 and 11) and there are numerous DOE supported research efforts currently underway in the areas of H_2 production, delivery, and storage (ref. 12).

2.3 Concept Evaluation Metrics

What is ultimately important is not the level of noise or pounds of emissions generated by an aircraft, but the impact of these on the environment. However, the connection between aircraft noise and emissions to high-level issues such as quality of life and local and global environmental health cannot be easily defined. There are numerous physical, and in the case of noise psychological, processes involved, leading to a complex interaction among various factors. Since it is not possible to directly evaluate reductions in environmental impact associated with advanced aircraft concepts, other metrics based on the aircraft characteristics have to be employed. The QGT noise goal is related to noise around the airport. Therefore, noise benefits were only assessed in terms of landing and takeoff operations. Estimates were made of both the certification noise (i.e., noise measurements at discrete points based on Federal Aviation Regulations (FAR) Part 36) and the noise level contours surrounding the runway during takeoff and landing. The QGT emissions goal is related to emissions throughout the flight. Since the issues for aircraft emissions in the local airport area and cruise flight differ, however, emission characteristics were assessed in terms of both the total emissions throughout the flight and airport area emissions.

One of the primary objectives of the QGT study is to determine the technology advances necessary to make the concepts investigated "feasible." Concept feasibility is a somewhat vague notion that can have a number of interpretations. One definition of feasibility is simply whether or not it would be possible to build the aircraft and fly the mission. The idea of concept feasibility in the broadest sense relates to the market for the concept; i.e., the desire of airlines to own that type of aircraft. Assessing feasibility in this broad sense was well beyond the scope of the QGT study. For the purpose of the QGT study "feasibility" was defined based on weight. A QGT concept was considered to be feasible if the predicted gross weight was comparable to that of a "state-of-the-art" conventional aircraft with the same range and payload capabilities.

2.4 Concept Design Mission

The basic design mission requirements used for the study were a payload capability of 225 passengers (in a 3-class seating arrangement) plus baggage and a range capability of 3500 nmi with full payload. The design mission profile is illustrated in figure 2. In addition to the payload and range requirements, the concept must satisfy constraints on landing and takeoff field length, approach speed, takeoff and missed approach climb gradients, and rate-of-climb capability at top of climb. The same mission requirements were applied to all the QGT concepts. For comparison purposes a current technology conventional aircraft was also designed to these mission requirements. A 225 passenger vehicle class was chosen based on the projected future fleet mix shown in figure 3. Small aircraft tend to have a large number of operations but fly relatively few seat-miles. Large aircraft tend to have relatively few operations, but represent the majority of the seat-miles flown. Airport noise and local air quality issues are related primarily to the number of operations, while global atmospheric issues are related primarily to the total number of seat-miles flown. A fleet of quiet, green aircraft of various sizes would obviously be needed to significantly reduce aviation's environmental impacts. However, since the scope of the current study was limited to one vehicle class, a "mid-size" class was selected which represents a significant portion of both projected airport operations and projected seat-miles flown. The chosen passenger capacity is roughly equivalent to a Boeing 767-300 class aircraft while the range capability is lower. The maximum range of a Boeing 767-300ER is slightly over 6000 nmi, but the majority of routes flown by aircraft in the 225 passenger class do not require this range capability. In fact, in 1999 the average route distance flown by 767-300s was only 1424 nmi (ref. 13). Previous studies of "green" aircraft indicated that the feasibility of some concepts is very sensitive to the design range. With a 6000 nmi range requirement these concepts would be penalized by a range capability which is not often needed or used. A range capability of 3500 nmi was deemed suitable to complete the majority of flights typical for this class of aircraft.

3. General Concept Description

The general arrangement of Quiet Green Transport Concept B is presented in figure 4. As with QGT Concept A, hydrogen fuel is used to eliminate all carbon and hydrocarbon emissions, as well as SO_X emissions. In Concept B the energy in the hydrogen fuel is released electrochemically by fuel cells instead of by combustion in gas turbine engines. This approach eliminates NO_X emissions, which result from the high temperatures and pressures experienced by the air stream in a gas turbine engine. It also eliminates some of the noise sources in the propulsion system. The electric power generated by the fuel cells is used to run electric motors which turn ducted fans to generate thrust. Multiple, lower thrust fuel cell propulsion units provide the required thrust instead of a few large units. Distributing the propulsion system in this manner can shift the propulsion system noise to higher frequencies, which results in greater atmospheric attenuation of the noise. Liquid hydrogen (LH_2) fuel is stored inside the airframe in insulated tanks. A blended-wing-body (BWB) airframe was selected for its increased aerodynamic efficiency and the noise shielding it provides for the top mounted ducted fans. The gaps and edges of a flap system are a significant source of airframe noise. Concept B employs a "continuous moldline technology" flap system to eliminate these important noise sources. Concept B also includes two operational approaches to reducing the impact of the noise and emissions generated. To reduce approach noise, the approach angle is increased from today's 3° standard approach to 12°. At a given distance from the runway, this increases the aircraft altitude and reduces the noise propagated to the ground. The second operational measure is providing a reduced altitude, "contrail avoidance" cruise capability. The optimum cruise altitude for subsonic jet aircraft is usually in the upper troposphere. The ambient conditions at this altitude are often conducive to the formation of persistent contrails, which are triggered by aircraft H_2O emissions and are believed to have a significant environmental impact (ref. 4). It is presently unclear exactly how contrails for a H_2 fuel cell aircraft would differ from current aircraft contrails. However, by providing cruise capability at lower altitudes where contrail formation is unlikely, it should be possible to fly Concept B on a cruise profile that avoids the formation of persistent contrails.

4. Hydrogen Fuel Cells

A fuel cell is an electrochemical device that converts the chemical energy of a reaction directly to electricity. In this respect it is similar to a battery. However, its performance does not decline like a battery because reactants are supplied from an external source. A fuel cell can theoretically continue to supply electricity as long as it is supplied reactants. The reactant flow for a typical H_2 fuel cell is depicted in figure 5. At the anode, H_2 flows past a catalyst which splits the H_2 into hydrogen ions and electrons. The electrons are conducted through the anode to an external circuit and the positive charged ions travel through the electrolyte to the cathode. At the cathode, electrons from the external circuit combine with the positive ions and O_2 to form H_2O. Although H_2 is the fuel cell reactant, in some systems it is supplied by reforming a more readily available fuel such as natural gas, or even gasoline. The O_2 needed for the reaction is usually supplied by air.

Using a propulsion system based on H_2 fuel cells has two primary potential advantages over burning H_2 in gas turbine engines as explored for QGT Concept A. Because the fuel cell process is at a much lower temperature than combustion with air, NO_X emissions can be eliminated. When using pure hydrogen as the fuel, H_2O is the only emission from a fuel cell propulsion system. The second benefit is the potential for increased fuel efficiency. Conventional aircraft propulsion systems are heat engines. The chemical energy of a reaction is released as heat and the heat is then converted to mechanical work. The operating temperature of a heat engine limits the maximum efficiency that can be achieved. A fuel cell is not a heat engine and is not subject to this fundamental efficiency limit, giving the potential for higher efficiency. In the case of aircraft propulsion, however, the electricity output of the fuel cell has to be converted to thrust. One way this can be accomplished is by powering an electric motor which turns a propeller or ducted fan. These necessary electricity-to-thrust conversion steps negatively impact the overall efficiency of the propulsion system and can offset the high efficiency of the fuel cell.

Different types of fuel cells are generally categorized by the electrolyte used. Five common types of H_2 fuel cells are presented in table 1: alkali, molten carbonate, phosphoric acid, proton exchange membrane, and solid oxide. The alkali fuel cell has found application in space transportation, but the need for a pure source of O_2 makes it less attractive for terrestrial applications since air cannot be used as the O_2 source. The complexity of the molten carbonate fuel cell makes it better suited for large stationary power plants than transportation applications. The phosphoric acid fuel cell has been commercially available for some time and is used in many places throughout the world as a small stationary power source. These commercial units typically include an external reformer which produces H_2 from readily available natural gas. Size and weight of the phosphoric acid fuel cell is an issue for transportation applications. In recent years a significant amount of research has focused on the proton exchange membrane (PEM) fuel cell and its potential application to automobiles. The PEM fuel cell is favored for automotive application because of its high power density and its short start-up time. PEM fuel cells have been used by a variety of car manufactures in a number of prototype vehicles, and a few plan to offer PEM fuel cell powered cars on a limited commercial basis in the near future. Interest in the solid oxide fuel cell (SOFC) has been increasing recently. The focus of SOFC applications has generally been large stationary power plants, but recent advances have increased interest in use as a mobile power source, including aircraft auxiliary power units (APUs).

In addition to electrolyte type, another distinction among fuel cells is operating temperature. High temperature fuel cell systems have the potential for increased system efficiency through cogeneration (generating useful heat in addition to electricity) or a bottoming cycle (waste heat used to generate additional electricity). High temperature fuel cells are also generally able to handle more impurities in the reactants and in some cases are capable of internal reforming (i.e., the high temperature causes the fuel to reform to H_2 inside the fuel cell). The issues with high temperature fuel cells include warm-up time and the need for exotic, high-temperature materials.

A propulsion system based on the PEM fuel cell was used for Concept B because of the current emphasis on the development of this type of fuel cell for automotive applications. Although not investigated in this study, an aircraft propulsion system based on a high temperature fuel cell such as the SOFC may be an attractive alternative to the PEM fuel cell system. The additional warm-up time and expensive high-temperature materials associated with a solid oxide fuel cell could be less of an issue for aircraft propulsion than it is for automobiles. In addition, the ability to use fuels other than hydrogen, as mentioned above, may enable simpler and more compact liquid fuel storage. A drawback to SOFCs is that they are typically heavier than PEM fuel cells, though this may be partially explained by their past research focus. SOFC research has focused on industrial applications where weight and volume are unrestricted while PEM fuel cell research has focused on transportation applications, which require low weight and volume.

5. Modeling and Analysis Methodologies

There is an inherent difficulty in the study of advanced, unconventional concepts in that most analysis tools are based on and tailored to existing design paradigms. Furthermore, detailed information is not generally available for the advanced, future technologies which may be incorporated in the concepts. The analysis for this study, therefore, was performed at a somewhat high, conceptual level. In some cases significant tool development was necessary to adequately model elements of the concept. In other cases simplifying assumptions were made to allow the use of existing tools.

5.1 Aircraft Performance Analysis

Aircraft performance and sizing analysis was performed with the LaRC Flight Optimization System (FLOPS) computer code. Much of the analysis capability in the FLOPS code is gear to conventional aircraft designs and is inadequate for analysis of unconventional concepts. FLOPS does have the flexibility, however, to accept user inputs which override or adjust the internal calculations. This provides a capability to model unconventional designs in a limited way, assuming there is sufficient information available external to FLOPS to appropriately build the FLOPS input.

5.1.1 Fuel Cell Propulsion System

The fuel cell based propulsion system for Concept B represents a fundamental change from current aviation propulsion systems. Characterization of this system, therefore, required new models and analysis tools. As mentioned in Section 2.1, aircraft using this type of propulsion have been investigated by NASA in the past. However, the models used in these studies were really no more than rough assumptions for each of the major system components (derived from a number of different sources). The components were not integrated into a complete system and there was no capability to analyze the propulsion system as a whole. The Quiet Green Transport study, along with elements of other NASA projects such as the GRC Zero CO_2 Emissions Technology project, provided sufficient need to justify building a special analysis capability for fuel cell/electric propulsion systems. The Airbreathing Systems

Analysis Office at GRC has developed such a capability. This capability is incorporated into the Numerical Propulsion System Simulation (NPSS) analysis code and makes it possible to obtain an "engine deck" (i.e., thrust and fuel flow versus Mach, altitude, and throttle setting) for a fuel cell/electric system just as is routinely done for gas turbine engines. The fuel cell propulsion system analysis model is a combination of models for the various components: fuel cell, electric motor, propulsor, power electronics, power distribution, and fuel distribution.

The PEM fuel cell model incorporates data from multiple sources. Thermodynamic models were obtained from the GRC Electrochemistry Branch, GRC Airbreathing Systems Analysis Office development, the Fuel Cell Handbook produced by the U.S. Department of Energy (ref. 14), and other textbook sources. Chemical performance is based on the simple hydrogen and oxygen chemistry of a PEM H_2 fuel cell. Actual (non-ideal) performance is determined using a polarization curve (voltage vs. current density), which is analogous to a compressor or turbine map for a jet engine. The primary polarization curve used in the analysis is shown in figure 6. Physical data (weight and volume) for the fuel cell stack is scaled from data published by General Motors, representing an industry "best-built" stack. Balance-of-plant data including compressor, thermal management, and humidity control are calculated using correlations developed by the GRC Electrochemistry Branch.

The electric motor model was developed following analysis of data from four leading motor/inverter producers in the electric vehicle motor industry (Ecostar, Solectria, AC Propulsion, and UQM Technologies). Data from UQM Technologies, which has a substantial amount of data publicly available, forms the basis for the model. A motor efficiency map vs. power and torque obtained from UQM Technologies is included in NPSS to provide efficiency values over off-design conditions. Motor data from UQM Technologies were scaled to power levels needed for the Concept B propulsion system. In the Concept B propulsion system the power output of the electric motor is converted to thrust by turning a ducted fan. The ducted fan is a conventional aircraft propulsion system component and is modeled using efficiency maps for the fan of a turbofan engine.

In addition to the primary components of the propulsion system (fuel cell, electric motor, and ducted fan), there are also a significant number of ancillary systems such as power electronics, power distribution, and fuel distribution. Major components included in the power electronics are the fuel cell controller (humidity, temperature, flow regulation), fuel cell voltage regulator (in form of converter, battery, etc.), and motor inverter/controller (for both the fan and compressor motors). The size of power electronics is determined by power level and efficiency (which determines cooling required). Primary weight and volume data for the power electronics is based on the same sources as the electric motor data; that is, UQM Technologies and other electric vehicle motor manufacturers. The general configuration and other additional information were obtained from GRC experts. The power distribution system includes the necessary electrical cabling and interfaces. The weight of this part of the system ultimately depends on the actual physical layout of the system since cable lengths are dictated by the proximity of components and cable thickness is determined by electrical current requirements. The fuel distribution system includes H_2 transport, valves, and external manifolds. Weight of this system depends on the physical layout, fuel flow, and thermal insulation required. Since the actual layout of the power and fuel distribution systems is not known at the current level of analysis, the weight for these systems is modeled as an appropriate percentage of the fuel cell weight.

There are many uncertainties in the estimates made with the current fuel cell propulsion system model, including power electronics weight, volume, and performance; system transient performance; detailed thermal characteristics and thermal management system performance; and airframe integration. Validation of the model has been performed, but only at the component level. The component models used for Concept B are scaled versions of models originally developed for general aviation aircraft propulsion. While the general aviation systems are sized close to existing hardware being developed for the automobile industry, scaling to the higher power levels associated with Concept B introduces additional uncertainty in the models.

5.1.2 Blended-Wing-Body Airframe

The BWB airframe has been the subject of a number of past studies (ref. 15) and a lot of detailed analysis work has been performed. Although the current version of FLOPS does not specifically address BWB type configurations, it is possible to develop a BWB FLOPS model by specifying appropriate adjustments and overrides in the input such that the FLOPS results are consistent with the available detailed analysis results. When FLOPS is "calibrated" in this manner, the accuracy of the calibration factors, and therefore the FLOPS results, beyond the baseline BWB design is uncertain. The highly integrated nature of a BWB airframe presents additional issues with using a calibrated model. For a conventional aircraft, the wing, fuselage, empennage, engines, etc. can to some extent be sized and analyzed independently and are generally treated independently by FLOPS. For example, the FLOPS model of a wing from one aircraft could be combined with the fuselage of another without substantially compromising the validity of the FLOPS analysis of the resulting aircraft. In the case of a BWB, however, it is not proper to treat the wing and fuselage (center body) as independent components. The calibration factors found for a BWB only have relevance for the integrated design, not the individual components.

The airframe model used for Concept B was based on a "calibrated" FLOPS model of a Boeing 450 passenger class BWB design used previously in studies for the NASA Ultra-Efficient Engine Technology (UEET) program. Since Concept B only carries 225 passengers, a 450-passenger BWB airframe is larger than needed. The fuel cells and hydrogen fuel do add internal volume requirements beyond a conventional propulsion system, however. The level of detail available for the propulsion system components did not justify performing detailed component layouts and fuselage arrangements. Instead, volume requirements for Concept B were addressed with a high-level, iterative sizing procedure which considered passenger cabin (based on Boeing 450BWB passenger layout), cargo (based on an existing airplane with passenger load equivalent to Concept B), fuel (based on required fuel weight and fuel density), and propulsion system (based on required thrust and propulsion system model). An estimate of the internal volume available was calculated based on the total volume between 25% and 75% chord and an assumed usable volume factor of 0.75. The Boeing 450 BWB geometry was iteratively scaled until the estimated volume available and required were equal. Considering the limitations of FLOPS modeling discussed above, scaling of the configuration was restricted to "photographic" scaling. In other words, all components were scaled together equally in all dimensions. A minimum scale factor limit was set such that sufficient height was provided for the passenger cabin. Scaling the airframe clearly introduces uncertainty in the accuracy of the FLOPS model. Even so, this approach does not offer all the modeling flexibility desired for Concept B. The ratio of volume required to wing area required is significantly higher for a LH_2 aircraft than a kerosene aircraft. When the 450 BWB is photographically scaled to meet Concept B's volume requirements, the resulting wing area is larger than needed. The performance of Concept B was negatively impacted in some cases because of the inability to model a more optimum geometry. However, independent scaling of the wing and fuselage size implies a completely different shape, which could not be accurately represented with the 450 BWB FLOPS model. Existing tools for analysis of more generic BWB shapes (ref. 16) were found to be too detailed and too complex for use in this high-level, feasibility study.

Takeoff and landing aerodynamic estimates for Concept B were based on Boeing aerodynamic predictions for the Boeing 450 passenger BWB design. The continuous moldline technology flap system of Concept B was assumed to have the same aerodynamic performance as the conventional flap system of the Boeing design.

5.1.3 Distributed Propulsion

One of the unconventional aspects of Concept B is the distributed propulsion system. Originally this approach was selected for the expected noise benefits. Early in the concept development it became clear that the choice of electric propulsion could also lead to a series of small propulsion units due to practical limits on electric motor size. At the time this study was conducted, a number of the calculation routines in FLOPS implicitly assumed that the total number of engines was no more than four. To prevent specifying more than four engines from resulting in unrealistic extrapolation of some equations, modifications to the FLOPS inputs and code itself were required. More recent versions of FLOPS account for the possibility of a distributed propulsion system with more than four engines.

An interesting area of consideration for a distributed propulsion aircraft is the application of "one-engine-out" performance requirements. FAR Part 25 for commercial transport aircraft includes a number of climb gradient requirements which must be met under various situations with one engine inoperative. The required climb gradients differ for aircraft with 2, 3, or 4 engines, increasing as the number of engines increases. There is no guidance given in FAR Part 25 for applying the requirements to aircraft with more than 4 engines. One possible approach would be to simply continue increasing the required climb gradient as the number of engines increases. With many engines the resulting climb requirements are unreasonable. Another approach would be to treat the aircraft as a four-engine aircraft and evaluate the climb performance against the four-engine requirements with one-fourth of the engines inoperative. However, as the total number of engines increases, the probability of one-fourth of them failing becomes much smaller than the probability a single engine failure on a four-engine aircraft. Although for a given probability of engine failure (per hour of operation), the probability of having an in-flight failure of one engine increases with the number of engines on the aircraft, the probability of multiple engine failures is still relatively small. For example, assuming the probability of engine failure is $5x10^{-5}$ per flight hour, on a four-engine aircraft the probability of at least one engine failing is $2x10^{-4}$ per flight hour. On an aircraft with forty engines, the probability of at least one engine failing increases to $2x10^{-3}$ per flight hour. However, the probability of at least two engines failing on the forty-engine aircraft is only $1.95x10^{-6}$, which is two orders of magnitude less than the probability of a single engine failure on a four-engine aircraft. The probability of one-fourth of the engines (10) failing is only $8.3x10^{-35}$ compared to a probability of $6.25x10^{-18}$ that all four engines of the four-engine aircraft will fail. Therefore, from a probability perspective, assuming failure of one-fourth of the engines on an aircraft with many engines is unrealistic. A third possibility is to simply assume that the FAR Part 25 requirements for aircraft with four engines can be interpreted as applying to aircraft with "4 or more" engines. This approach was used in the evaluation of Concept B. FAR Part 25 also includes some climb gradient requirements for "all-engines-operating" conditions. Usually the "one-engine-out" conditions are more demanding and those are the ones addressed by FLOPS. However, because the amount of thrust lost with one engine inoperative for an aircraft with many engines is small, the required thrust could be dictated by an "all-engines-operating" requirement. A check of "all-engines-operating" climb performance was also performed to address this possibility.

5.1.4 LH_2 Fuel System

The fuel system is an important aspect of any aircraft which uses LH_2 fuel. Although LH_2 has a very high energy content per pound, because of its low density a cubic foot of LH_2 only contains about one-fourth the energy of a cubic foot of jet fuel (kerosene). A LH_2 aircraft needs nominally four times the fuel volume of an equivalent kerosene fueled aircraft. In addition to the fuel volume issues, LH_2 is a cryogen stored at about 20K, so insulation and thermal management are important. While the differences between conventional and LH_2 fueled aircraft are many, LH_2 fueled aircraft have been studied on numerous previous occasions. NASA LaRC sponsored a significant amount of research into hydrogen aircraft and related issues in the 1970's. One of the participants in that research, Daniel Brewer, later wrote *Hydrogen Aircraft Technology* (ref. 17), which summarizes many of the findings from the NASA sponsored studies. The information presented by Brewer in his book was used as a basis for many of the LH_2 related modeling aspects of Concept B, including fuel containment system weight estimates.

5.1.5 "Contrail Avoidance" Cruise

Modeling the reduced altitude, "contrail avoidance" cruise for Concept B was accomplished by simply modifying the mission profile definition. A cruise altitude limit of 25,000 ft for the contrail avoidance mission was selected based on guidance from Dr. Patrick Minnis of NASA LaRC, who has written a number of papers on contrail formation. The actual altitude above which formation of persistent contrails becomes a possibility depends on factors which vary from flight to flight. The aircraft takeoff weight and fuel capacity was sized to be able to complete the full 3500 nmi design range with maximum altitude limited to 25,000 ft. The cruise Mach number at 25,000 ft was reduced to match cruise airspeed with the baseline conventional aircraft. The reduced altitude cruise generally incurs a significant efficiency penalty because the aircraft is not cruising at optimum conditions. While the aircraft weight and fuel capacity was sized for cruise at 25,000 ft, the aircraft is still capable of cruising at higher altitudes. This provides the aircraft with an alternate mission capability to cruise much more efficiently when conditions at higher altitudes are such that contrail formation is not a concern. In practice the actual cruise altitude selected would depend on the atmospheric conditions along the flight path. By the RASC time horizon, increased understanding of the mechanism of contrail formation and improved meteorological observation and prediction capabilities should allow reliable prediction of contrail formation potential along a flight path.

5.2 Noise Analysis

The methodology used to predict the noise characteristics of Concept B is similar to that used previously for QGT Concept A and described in reference 8. Source and total noise levels were predicted using the Aircraft Noise Prediction Program (ANOPP). ANOPP uses empirical methods to compute the far-field noise levels of the individual sources—fan, core, turbine, jet, and airframe. The effects of atmospheric absorption and ground attenuation are computed as the sound propagates to a set of observer locations on the ground. Overall noise levels at the observer are expressed as effective perceived noise level (EPNL), which accounts for frequency weighting, tone protrusion, and duration of the noise-producing event. During the study of Concept A, ANOPP's source noise modules were calibrated using representative noise levels from reference 18 for a "generic" small-to-medium size twin engine commercial aircraft. These calibration factors were used for noise analysis of the conventional baseline and the Concept A and Concept B QGT configurations. Takeoff and landing flight paths for Concept B were computed using the FLOPS detailed takeoff and landing module and low speed aerodynamic predictions based on Boeing BWB data. Single-event noise level contours for takeoff and approach were computed using the Integrated Noise Model (INM). Noise-Power-Distance (NPD) tables for input to INM were generated with ANOPP. Aircraft performance and thrust coefficients were calculated from the propulsion system performance characteristics and the low speed performance computed by FLOPS.

Assumed noise benefits for the unique features of Concept B are summarized in table 2. Concept B uses hydrogen fuel cells to power external ducted fans for propulsion. As a consequence, the external "engines" do not have compressors, burners, and turbines like a turbofan engine would. It was assumed that generation of power by the fuel cells does not add additional external noise sources. The ducted fans are equipped with swept stators, which were accounted for by reducing the fan inlet and exhaust rotor-stator interaction tones by 8 EPNdB based on references 19 and 20. The reduction in total fan noise was less due to the contribution of broadband noise to the complete spectrum. The ducted fan exhaust nozzles are equipped with chevrons, which were assumed to provide a 2 EPNdB reduction in jet noise based on reference 21. This reduction was applied at all power settings although measurements of chevron effectiveness are currently only available at full power and it is possible that the reduction may not be the same at reduced power settings. The benefits of continuous moldline technology flaps were estimated by assuming that the deflected flaps produced no additional noise relative to the undeflected configuration. Concept B employs a 12° glide slope during approach as an operational measure for reducing noise. At a given distance from the runway the aircraft altitude is higher, which reduces the noise propagated to the ground. Executing this steep approach requires that the engines operate at idle and devices be employed to cause a rather large increase in drag, or alternatively that some type of in-flight thrust reversing be used. It was assumed that additional "quiet" sources of drag are used (the technology for which is not currently available). If "noisy" drag devices are used to achieve the steep approach angle, the additional noise could offset the reduction associated with higher approach altitudes.

Noise shielding effects of the BWB airframe were estimated using an insertion loss function which varied with frequency, directivity angle, and azimuth angle. The values were based on the Clark and Gerhold experimental results for a wedge-shaped airframe (ref. 22). The shielding estimates were extended to directivity angles beyond those measured in the experiment. It was assumed that there is still some shielding at forward angles since the top-mounted engines are hidden by the front of the airframe. The shielding at aft angles was assumed to gradually reduce to zero. In addition, the shielding was assumed to vary linearly with frequency at all angles so that the peak shielding is approximately 15 dB at 50 Hz and 25 dB at 10 kHz. The insertion loss function vs. directivity angle and azimuth angle at 400 Hz is illustrated in figure 7. Shielding benefits were applied only to the fan inlet and exhaust noise since jet noise is typically generated well downstream of the nozzle.

6. Concept Evaluation Results

6.1 Current Technology Baseline

A baseline model of the Concept B propulsion system with current technology assumptions was developed using the fuel cell propulsion system analysis described in Section 5.1.1. The highest electric motor power output deemed reasonable with current compact motor technology was 1 MW peak and 671 kW continuous. Although higher power motors do exist, they are designed for industrial ground applications and therefore are extremely large. This power limitation sized the individual fuel cell propulsion units. Many of these individual units are necessary since 10's of MW of propulsive power are required for a large aircraft. Distributed propulsion is therefore a necessary feature by virtue of the limited power capability of current technology electric motors. With current technology a fuel cell propulsion system is very large and heavy. The estimated "engine" weight of 7076 lb for each fuel cell propulsion unit is comparable to the weight of an engine for the baseline conventional aircraft (8600 lb). However, the conventional aircraft only has two engines compared to the 10's of fuel cell propulsion units needed to provide the same amount of thrust. Figure 8 illustrates the weight and volume build-up for the fuel cell based power system (i.e., the components needed to produce output shaft power, does not include the ducted fan propulsor). The fuel cell system, electric motors, and power controls/electronics are similar in weight and size, and those three components account for a large majority of the total weight and volume. It is important to note that the fuel cell system only accounts for about 30% of the total power system weight and volume. To achieve significant reductions in system weight and volume it will be necessary to advance not only fuel cell technology, but also electric motor and power electronics technology.

The large weight penalty associated with the current technology fuel cell power system becomes clear when the specific power (power output per unit weight) is compared to conventional aircraft propulsion systems. The specific power of the current technology fuel cell power system is only 0.14 kW per lb. Weight and power data for existing aircraft piston engines and aircraft turboshaft engines are plotted in figure 9. The specific power of aircraft piston engines is about 0.5 kW per lb, more than three times greater than the fuel cell power system. In other words, for an equal output shaft power an aircraft piston engine would tend to be less than one-third of the weight of the fuel cell based system. Since current commercial transport aircraft use gas turbine based propulsion systems, not piston engines, a more relevant comparison is between the fuel cell based system and aircraft turboshaft engines. (Note: Although transport aircraft usually have turbofan, not turboshaft, engines, turbofan engines are characterized by thrust level instead of power. As with the fuel cell power system, the primary purpose of turboshaft engines is to produce shaft power, making a more "apples-to-apples" comparison possible.) There is more scatter in the turboshaft data than the piston engine data, but most points lie in the 1.5 to 3.0 kW per lb range. The scatter in the data is probably at least partly due to the range of technology levels represented since no attempt was made to distinguish between old and state-of-the-art engines. Also, there are often inconsistencies in how the weight and power level are reported by various manufacturers. Based on the data in figure 9, the specific power of the fuel cell based system is at least an order of magnitude lower than conventional gas turbine based systems. Very substantial weight reduction (70-95%) is necessary for the fuel cell power system to be comparable to today's conventional aircraft propulsion systems. One of the expected benefits of a fuel cell based system is an increase in efficiency. An increase in efficiency over conventional propulsion systems would offset to some extent the propulsion system weight penalty by reducing the fuel weight required to perform the mission.

Given that the current technology fuel cell power system is more than an order of magnitude heavier than a conventional aircraft gas turbine system, it is no surprise that Concept B is infeasible with current technology assumptions. Not only would a current technology Concept B not meet the feasibility criterion for this study (gross weight comparable to a current technology conventional aircraft with same range/payload), the design does not "close." In other words, meeting the design requirements is impossible. The sea level static thrust-to-weight ratio (T/W) of the current technology fuel cell based propulsion system is only 0.23. The aircraft as a whole needs a T/W of about 0.27 to meet the design mission requirements. Even if the rest of the aircraft weighed nothing, the propulsion system would still be too heavy for the design to work. This result was not unexpected. A current technology baseline is important, however, to establish a reference point from which the technology advancements required for feasibility can be measured.

Simply finding that the concept is infeasible with current technology does not provide any insight into how far technology needs to advance to make it feasible. An approach was developed to quantify the "degree of infeasibility" and allow more extensive evaluation. In this approach an artificial negative increment in empty weight is introduced which enables the design to "close" and become feasible. A "feasibility metric" is then defined based on the required change in empty weight necessary to make the concept feasible. The required change in empty weight can be divided by a reference weight, such as the target gross weight, to make the metric a non-dimensional percentage. Calculation of the feasibility metric, *fm*, is shown in equation 1:

$$fm = \frac{\Delta W_{\text{empty}}\ \text{for feasibility}}{(\text{Target Gross Weight})} * 100 \qquad (1)$$

A negative value for *fm* indicates that the concept requires technology advances to become feasible.

The significance of the feasibility metric approach is that it allows a technology sensitivity analysis to be performed for the concept even though the baseline design is impossible. Normally in a technology sensitivity analysis the relative importance of technology areas is determined by looking at the sensitivity of characteristics such as gross weight or fuel burn to technology advances. However, this type of analysis is only possible with a baseline design that "closes." A different type of metric is necessary for a concept like Concept B which is impossible without technology advances. With the feasibility metric the relative importance of various technology areas can be assessed by examining changes in the feasibility metric value as advanced technology assumptions are applied.

Using the above approach a baseline version of Concept B (with current to near-term technology assumptions) was analyzed. A target gross weight for feasibility of 270,600 lb was specified based on a current technology conventional aircraft with the same range/payload capability. Some of the basic characteristics of the configuration are shown in table 3. Wing loading for this configuration is particularly low at 53 lb/ft^2. The 450 passenger BWB model was scaled down by ~18% to approximately match the available internal volume to Concept B volume requirements. The wing area resulting from this photographic scaling is much larger than needed, and the wing loading is lower than desired. The low wing loading coupled with the 25,000 ft altitude "contrail avoidance" cruise results in a very low cruise lift coefficient (C_L), well below the optimum C_L for maximum lift-to-drag ratio (L/D). Although the cruise L/D of 16 is comparable to current conventional aircraft, it is significantly lower than what is usually possible with a BWB airframe.

The low specific power of the current technology fuel cell power system makes total power (thrust) required the dominating factor for the configuration. The critical thrust condition for this configuration was found to be at start of cruise, where a 300 foot-per-minute minimum rate-of-climb constraint (at maximum continuous power) was imposed. With a limit of 671kW (max. continuous) for each fuel cell power unit, a lot of units (45) are needed to obtain the required cruise thrust level. It is likely that an optimized BWB geometry providing sufficient internal volume with higher wing loading would improve cruise L/D and reduce the required propulsion system size.

The thrust specific fuel consumption in cruise is 0.214 (lb/hr)/lb, which is almost the same as for the H_2 turbofan engine used on Concept A. In other words, the overall efficiency of the fuel cell based propulsion system is not significantly different from that of a gas turbine based propulsion system. Despite the high efficiency of the fuel cell itself, the expected efficiency benefits from fuel cell propulsion have not been realized due to power drains, such as for the intake air compressor, and losses in conversion of electricity to thrust.

The decrease in empty weight necessary for the baseline version of Concept B to meet the 270,600 lb gross weight target is over 311,000 lb, or more than 60% of the estimated operating empty weight, and *fm* equals -115. There is a substantial amount of technology improvement needed to make this concept feasible.

6.2 Sensitivity of Feasibility to Technology Advances

The sensitivity of Concept B feasibility to advances in various technology areas is illustrated in figure 10. To generate these sensitivities 10% improvements in various technology areas were applied to the baseline design one at a time and a new value calculated for the feasibility metric. Care must be exercised when comparing the magnitudes of these sensitivities since the values depend on the component level at which the analysis is performed. For example, the sensitivity to a 10% reduction in the weight of the propulsion system as a whole would be the sum of all the sensitivities for the individual propulsion components shown in the figure. Conversely, sensitivity to improvements in wing structural weight would only be a fraction of the sensitivity to total structural weight shown in the figure.

Since propulsion system weight is the dominating factor in feasibility and the propulsion system is being sized by cruise thrust requirements, feasibility is very sensitive to cruise drag. A reduction in drag reduces the thrust required, which results in a corresponding decrease in the total propulsion system weight and volume. In other words, when the thrust required is reduced 10% it is equivalent to a 10% reduction in the weight and volume of all of the propulsion system components. As evident from figure 10, Δfm for a 10% reduction in thrust required is roughly equal to the sum of the Δfm's for 10% reductions in the various propulsion system component weights and volumes. The increase in feasibility for a 10% reduction in drag is actually more than would occur from simply a 10% reduction in thrust required. Drag reduction has a two-fold benefit. Not only does the required size of the propulsion system decrease because the thrust required decreases, but also the increase in aerodynamic efficiency reduces the amount of fuel consumed, reducing fuel weight and fuel volume.

Feasibility is also relatively sensitive to aircraft structure, fuel cell system, electric motor, and power control/electronics weight. Weight reductions in other areas have a much smaller impact on the feasibility of the concept. Sensitivity to changes in propulsion efficiency, as characterized by specific fuel consumption (SFC), is relatively large. A reduction in SFC improves feasibility by not only reducing fuel weight, but also through drag benefits associated with a reduction in fuel volume requirements.

Note that takeoff and landing aerodynamic improvements are not included in figure 10 because they have no impact on feasibility. The Concept B baseline easily meets takeoff and landing performance requirements. Its low wing loading, which negatively impacts cruise performance, results in very low approach and takeoff speeds, and short takeoff and landing distances. With the propulsion system sized to meet cruise thrust requirements, the thrust available at low speed, sea level conditions is much greater than that necessary to meet FAA climb gradient requirements.

It should be noted that the absolute and relative values of the sensitivities in figure 10 do not remain constant as advanced technology is applied to the concept. For example, if the weights of propulsion system components are reduced, the sensitivity to the weights of these components will decrease relative to aircraft structures weight; i.e., as they get lighter a 10% improvement become relatively less important. One important point illustrated by these sensitivities is that propulsion system weight and size is not exclusively a propulsion technology issue. For example, drag reduction can be used to reduce the thrust required and thereby reduce the propulsion system size and weight. Reductions in airframe weight can also compensate for a heavy propulsion system.

6.3 Advanced Technology Assumptions for Feasibility

There is not a unique set of technology advances which will lead to the feasibility of Concept B and it is not really possible to define hard technology requirements. For example, how much reduction is necessary in fuel cell system weight depends on what advances occur in all the other areas. Ultimately one would want to select the set of technology advances which requires the least amount of resources to achieve, but that optimum set is not easily determined.

The results for the current technology version of Concept B clearly indicate the importance of propulsion system technology advances in achieving a feasible concept. Current technology propulsion system assumptions were reflective of development which has occurred over the past several years for electric automobiles. The recent growing interest in fuel cells and electric vehicles has sparked a significant amount of research which could lead to a lighter weight, more efficient system in the future. To investigate the potential for overall improvement in the propulsion system, projected technology advances for a 25-30 year time horizon were applied to the various components. In making these projections components which today represent relatively new technology were improved more than those which represent relatively mature technology. Fuel cells and electric motors were considered to have the most potential for improvement due to widespread interest in weight and volume reduction for a number of applications. There is also similar interest in power electronics, but there is not as much room for improvement beyond current technology. The power and fuel distribution systems represent relatively mature technologies today and were not improved substantially for the advanced technology system.

With 25-30 year advanced technology assumptions the power-to-weight and power-to-volume ratios of the fuel cell based propulsion system double. Another benefit of the advanced technology system is an increase in the continuous power to peak power ratio. With the advanced electric motor technology assumptions, eighty percent of peak power is available in continuous operation, which allows cruise (continuous) thrust requirements to be met with a lower total peak power and smaller propulsion system. Figure 11 contains a comparison of component weights and volumes for the current technology and advanced technology systems. For the current technology system electric motor technology limited the size of each unit to 1MW (peak). Motor power was no longer a limiting factor for the advanced technology system and a power level of 4MW (peak) was selected with the intent of having a mildly distributed propulsion system (~10 units). In figure 11 weights and volumes have been divided by the peak power levels of the respective systems to facilitate comparison between the two systems. The largest weight per kW reduction for the advanced technology system occurs for the electric motors. Electric motor weight per kW is reduced by ~85%. The advanced technology fuel cell system is also significantly (60%) lighter per kW than the current technology baseline. A more modest 40% reduction is obtained in the weight per kW for the power controls and electronics, and there is little reduction in the power and fuel delivery weights per kW. For the advanced technology system the power controls and electronics becomes the largest weight contributor, with the power and fuel delivery weights also significant fractions of the total weight.

Despite sizable decreases in weight and volume, the 25-30 year projected fuel cell power system technology advances alone are not sufficient to make Concept B feasible. Even with the advanced technology projections the specific power is only 0.31 kW/lb, 40% lower than aircraft piston engines. The resulting T/W ratio of 0.53 is much greater than for the current technology fuel cell propulsion system, but only 10-15% of the T/W for turbofan engines used on current transport aircraft. Applying the advanced fuel cell propulsion system to the Concept B baseline greatly improves the feasibility metric from -115 to -34. However, -34 still corresponds to a large reduction in empty weight (90,000 lb).

Without assuming further advances in the fuel cell power system beyond the 25-30 year projections discussed above, there are significant advances in airframe technology needed to meet the feasibility criterion. One combination of airframe technology advances which is sufficient to reach feasibility given the advanced propulsion system characteristics is a 15% reduction in drag (enroute) and a 30% reduction in airframe weight (structural weight, systems and equipment weight, fuel tank weight). Because the advanced technology propulsion system is still heavy, the required thrust has a significant impact on the aircraft empty weight and feasibility is still sensitive to cruise drag. The BWB configuration is already very efficient aerodynamically but there is potential for additional drag reduction through advanced aerodynamic technologies such as laminar flow control. In addition, some reduction in drag would likely occur from optimizing the geometry for Concept B instead of scaling from an existing BWB design. A 30% reduction in airframe weight is rather aggressive. Since the baseline BWB configuration already incorporates significant use of composite materials, additional weight reduction probably implies the need for new, revolutionary, lightweight materials beyond carbon fiber composites.

With the propulsion and airframe technology assumptions discussed above, the estimated gross weight for Concept B is 289,900 lb, 7% higher than the baseline conventional aircraft. This gross weight was considered close enough to the target weight to meet the feasibility criterion for the study and this set of technologies was used to define an advanced technology, feasible version of Concept B.

6.4 Advanced Technology Concept B

6.4.1 Sizing and Performance

Characteristics of the advanced technology version of Concept B are summarized in table 4. A current technology conventional aircraft sized for the same mission requirements is also included in the table for comparison. The two aircraft are compared graphically in figure 12. Concept B is a noticeably larger aircraft than the conventional baseline. A scale factor of ~0.77 relative to the initial 450 passenger BWB geometry was needed to meet volume requirements for passenger, cargo, LH_2 fuel, and propulsion system components. The wing area resulting from this scaling is significantly higher, and wing loading at takeoff significantly lower, than the conventional aircraft. The low wing loading of Concept B could lead to some ride quality issues. Geometry optimization specific to Concept B would likely result in a slightly higher wing loading. However, since the approach speed for the current configuration is 132 kts, the wing cannot be made much smaller before the approach speed design constraint of 140 kts is encountered. The takeoff wing loading of Concept B cannot be as high as the conventional aircraft for a couple of reasons. First, the C_{Lmax} of the BWB airframe is lower than the conventional design and therefore the wing loading at landing must be lower to achieve the same approach speed. Second, although the takeoff weights of the two configurations are similar, the fuel weight fraction for Concept B is only 7% compared to 31% for the conventional baseline and as a result the landing weight for Concept B is 40% greater than for the conventional baseline. This higher landing weight would necessitate additional wing area to meet the approach speed constraint even if C_{Lmax} was the same as the conventional baseline.

While the gross weight of Concept B is 7% higher than the conventional baseline, the total thrust is 38% lower. For both aircraft the size of the propulsion system is being determined by thrust required at start of cruise. However, with the BWB configuration and drag reduction assumptions, drag at cruise is significantly lower for Concept B (mid cruise L/D of 21.5 compared to 14.3 for the conventional baseline). It is important to observe that even though a 15% drag reduction from the baseline BWB is being assumed, the cruise L/D of 21.5 is comparable to a current technology, conventional BWB. Maximum L/D for Concept B is higher, but the low wing loading and low cruise altitude result in a cruise C_L significantly below that required for optimum L/D. Aircraft thrust-to-weight ratio for the advanced technology Concept B is only ~60% of that for the conventional baseline. Despite this low T/W, Concept B is still able to meet one-engine-out takeoff and landing requirements because it has eight “engines.” In a one-engine-out condition, the two configurations actually have approximately the same T/W (0.16).

Concept B achieves a gross weight similar to the conventional baseline with a higher empty weight and lower fuel weight. Concept B operating empty weight is 61% higher than the conventional baseline. Even with 25-30 year projected propulsion technology advances, propulsion system weight is still a critical driver for Concept B. The fuel cell propulsion units are 35% of the total gross weight and 45% of the operating empty weight. In contrast, the turbofan engines of the conventional baseline are only 6% of gross weight and 12% of operating empty weight. Although the fuel cell propulsion system makes empty weight significantly higher, fuel weight is reduced by more than a factor of four because of the higher energy density of hydrogen and the higher overall aircraft efficiency. The advanced technology fuel cell propulsion system is ~20% more energy efficient than the turbofan engines on the current technology conventional baseline (based on thrust specific energy consumption rate at cruise, (BTU/hr) per lb of thrust). This increase in propulsion efficiency combined with the significant increase in aerodynamic efficiency from the BWB airframe and 15% drag reduction assumption results in a 38% reduction in total energy consumed to perform the mission.

6.4.2 Emissions

The principal exhaust emissions of current jet aircraft include CO_2, H_2O, SO_X, NO_X, CO, unburned hydrocarbons (HC), and soot. CO_2 and H_2O emissions result from complete combustion of the hydrocarbon molecules which form the basis of today's jet fuel. SO_X emissions result from combustion of the small amount of sulfur which remains in jet fuel after it is refined from crude oil. (Note: Fuel specifications limit the sulfur content in jet fuel.) CO, HC, and soot emissions result from incomplete combustion of the fuel. NO_X emissions are a by-product of combustion associated with air being subjected to high temperatures and pressures in the engine. CO_2, H_2O, and SO_X emissions are primarily related to fuel composition and rate of consumption. NO_X, CO, HC, and soot emission rates are very dependent on ambient conditions and engine operating conditions.

The emission characteristics of the advanced technology version of Concept B are summarized and compared to the conventional baseline aircraft and QGT Concept A in table 5. The only substance emitted by Concept B is H_2O. Use of hydrogen fuel eliminates the carbon and sulfur related emissions associated with jet fuel. The use of an electrochemical based propulsion system, instead of a combustion based system, eliminates the NO_X combustion by-product. The use of hydrogen does increase the amount of H_2O emitted compared to the conventional kerosene baseline aircraft. Despite a significant decrease in total energy consumption, the switch to hydrogen fuel increases the total H_2O emissions by 61% to 148,400 lb. Note that the three aircraft compared in table 5 do not have equal levels of technology. Significant technology advances were assumed for Concept B in order to meet the feasibility criterion for the study. Applying similar levels of technology advancement to the conventional baseline and Concept A would result in lower emissions than shown in the table.

Even though water vapor is a greenhouse gas just like CO_2, in most situations H_2O emissions are considered harmless. In fact, automobiles which only emit water vapor are usually referred to as zero emission vehicles. Water vapor emissions are generally not a concern because of the great abundance of naturally occurring water vapor. Another difference between CO_2 and H_2O emissions is the residence time in the atmosphere. The residence time for CO_2 is on the order of 100 years, so the impact of CO_2 emissions on CO_2 concentration is a function of the total CO_2 emitted over the previous 100 years or so. Water vapor, on the other hand, has a residence time on the order of only a couple of weeks (unless emitted in the upper stratosphere or above). Although water vapor emissions are often considered harmless in other situations, they need to be given special consideration in the case of aircraft. The direct radiative effect of water vapor emissions from current subsonic aircraft, which do not fly above the lower stratosphere, is believed to be negligibly small (ref. 4). The indirect effects of these emissions, such as contrail formation, are the primary concern. These indirect effects are complex and to a large extent uncertain. They also do not necessarily scale directly with the amount of H_2O emitted. For example, aircraft H_2O emissions really just act as a trigger for contrail formation. The aircraft emitted H_2O is actually only a fraction of the total H_2O content of the contrail that is subsequently formed. Once the H_2O emission rate necessary for triggering a contrail is exceeded, emitting more H_2O does not directly translate to a larger contrail and greater environmental impact. So the impact of contrails can depend more on the number of flights flown than on the amount of H_2O emitted by each aircraft. Because of the complex mechanisms involved in the indirect effects of H_2O emissions, the environmental impacts of H_2O emitted from hydrogen fuel cell aircraft cannot be simply extrapolated from studies which have investigated conventional jet aircraft burning kerosene fuel. However, to address the possible concerns associated with increased H_2O emissions from a hydrogen aircraft, Concept B was designed to be capable of cruising at a reduced altitude (25,000 ft) where the potential impacts of H_2O emissions are expected to be greatly reduced.

Atmospheric studies specific to hydrogen fuel cell aircraft would be needed to fully assess the potential environmental impacts from the H_2O emissions of Concept B. However, based on current understanding of the direct and indirect impacts of H_2O emissions, Concept B meets the QGT goal to eliminate emission of any substance from the aircraft where it can have a significant environmental impact.

6.4.3 Noise

Figure 13 shows predicted noise levels for the current technology conventional baseline, QGT Concept A, and advanced technology Concept B at the three FAR Part 36 observer locations: sideline, cutback, and approach.

The predicted sideline noise levels are compared in figure 13(a). Noise levels were computed for Concept B with and without the benefits of airframe shielding to show the affect of shielding on the overall noise levels. The fan inlet noise level for Concept B (with shielding) is lower than that of Concept A, which is to be expected due to the shielding of the airframe, while the fan exhaust noise levels are higher. Concept A's engine-over-wing configuration provides shielding of the aft fan noise but no inlet noise shielding. The jet noise is significantly lower for Concept B since the jet noise is produced only by the low pressure ratio fan, and not by high-pressure core flow. Note that the reason the jet noise is different between the two Concept B cases—with and without shielding—is because the measurement point is shifted to a point along the sideline where the noise level is greatest, not because the jet noise prediction is affected in any way by the shielding. The airframe noise for Concept B at the sideline point is significantly lower than the conventional baseline and the Concept A configuration due to the benefits of the continuous moldline technology flaps. Flaps are the primary airframe noise source for sideline noise and the benefit of continuous moldline technology flaps is approximately 18 EPNdB. As with jet noise, the difference between sideline airframe noise levels for the two Concept B cases is solely due to a shift in the sideline measurement point. The total sideline noise level for Concept B is comparable to that of Concept A and significantly lower than for the conventional baseline. The overall sideline noise benefit from airframe shielding is about 5 EPNdB.

The cutback noise levels shown in figure 13(b) indicate similar trends to those at the sideline point, except the jet noise EPNL is actually higher for Concept B than for Concept A. The throttle setting after cutback is much higher for Concept B (80% versus 65% for the conventional and Concept A aircraft). Because Concept B is able to meet one-engine-out takeoff and missed approach climb gradients more easily than a two-engine configuration, it has a significantly lower thrust-to-weight ratio than either the conventional baseline or Concept A. Therefore, it has less excess power during an all-engines-operating takeoff and a higher throttle setting must be used after cutback. To investigate the potential beneficial effect of increased T/W on the noise characteristics of Concept B, a version with two additional "engines" was also analyzed. Increasing the number of propulsion units from 8 to 10 results in a 25% increase in thrust. However, due to the large weight of the fuel cell based propulsion system, the T/W actually only increases 13%. (Note: The gross weight of this version of Concept B is 320,600 lb. Additional advanced technology assumptions beyond those already applied would be necessary for this configuration to meet the feasibility criterion of the QGT study.) For the original advanced technology Concept B the total cutback noise level is approximately 8 EPNdB lower than for the conventional baseline, but 2.5 EPNdB higher than for Concept A. The additional T/W provided by adding two propulsion units results in a noise reduction for all sources such that total cutback noise level is 4.2 EPNdB lower than for the 8 unit version, and 1.7 EPNdB lower than for Concept A. The overall cutback noise benefit associated with the airframe shielding provided by Concept B is about 6 EPNdB.

As shown in figure 13(c), the total approach noise for the advanced technology Concept B is more than 10 EPNdB lower than that of Concept A, and more than 20 EPNdB lower than the conventional baseline. Like Concept A, the approach noise for Concept B is dominated by airframe noise. Because of this, airframe shielding of the fan noise has little affect on the approach noise characteristics. The use of continuous moldline technology flaps gives a benefit of about 4 EPNdB to the approach airframe noise. This benefit is smaller than the benefit to airframe sideline noise because as flap noise is decreased landing gear noise becomes the dominate noise source which dictates the overall airframe noise level. A significant portion of the Concept B approach noise benefit is from the 12° glide slope. The 12° glide slope requires that the propulsion system be reduced to idle and additional sources of drag be employed. Since it might be possible to quickly switch the direction of rotation of the electric motors, another means of providing this force could be using the fans to generate reverse thrust. Over 35,000 pounds of additional drag or reverse thrust is required to maintain a constant velocity during the 12° approach, which is almost half the total sea level static thrust of the propulsion system. The current analysis assumes the additional drag or reverse thrust is produced without increasing the total aircraft noise. It will be a challenge to develop a drag producing device or a thrust reversing system which does not produce significant noise and therefore give back most or all of the noise benefits associated with the high glide slope angle.

Total noise levels at the three FAR Part 36 noise certification points are summarized in table 6. The noise levels of Concept B are lower than Concept A for sideline and approach, but due to the lower T/W of the configuration cutback noise is higher. The improved climb performance provided by the 13% increase in T/W from adding two more propulsion units to Concept B reduces cutback noise by 4 EPNdB, to a level which is lower than that of Concept A. The basic, 8 propulsion unit version of Concept B has a cumulative noise reduction of 43 EPNdB relative to the conventional baseline and 10 EPNdB relative to Concept A. Most of the benefit relative to Concept A is due to the lower airframe noise and the steeper approach angle.

While noise predictions for the three FAR Part 36 observer locations indicate the potential for substantial noise reduction from Concept B, the QGT noise goal is related not to certification noise but to the noise exposure for airport communities. Community noise is better assessed by examining the shape and size of noise contours. A comparison of single-event sound exposure level (SEL) contours for the conventional baseline, Concept A, and Concept B is shown in figure 14. Even though Concept B's sideline and cutback noise levels are comparable to those of Concept A, the takeoff portion of the SEL contours (to the right in the figure) is much larger due to poor climb performance. Concept B produces the same noise level, but is not able to climb as quickly and thus exposes more of the airport community to the noise. The approach contours for Concept B are significantly smaller, especially for the higher

SEL values. Total area of the Concept B 55dBA SEL contour is only 10% less than for the current technology conventional baseline (compared to a 53% reduction obtained with Concept A). As evident in figure 14, the improved climb performance of the higher T/W Concept B results in a significant reduction in the takeoff portion of the noise contours. The reduction in 55dBA SEL contour area relative to the conventional baseline increases to 25%. However, even with the additional T/W, the total 55dBA SEL contour area is still significantly more than for Concept A. Recall that the noise levels for this 10 propulsion unit version of Concept B are lower than for Concept A at all three noise certification points. Even though the certification noise is lower, the noise impact on the airport community would be larger due to the larger contour areas. This case illustrates that noise reduction at the certification points is not always a good indicator of a reduction in community noise.

Achieving the QGT noise goal to contain "objectionable" levels of aircraft noise within airport boundaries requires a significant reduction in contour area, not just a reduction in noise at the certification points. In that context, Concept A is a lower noise concept than Concept B. The large contour areas of Concept B are a result of the low T/W. The noise results for the 10 propulsion unit version of Concept B indicate there are noise benefits to be realized from increasing the T/W above that which is required from a minimum aircraft performance standpoint. However, increasing the T/W of Concept B is difficult due to the heavy fuel cell based propulsion system. The desire for an aircraft which is both "quiet" and "green" may, therefore, lead to some compromises. Selection of a heavy, but "green", fuel cell based propulsion system for Concept B makes achieving large reductions in contour area difficult. One possible compromise approach would be to supply additional takeoff thrust with H_2 fueled turbofan engines, instead of additional fuel cell propulsion units. This would make increasing aircraft T/W easier, since adding thrust would incur a much smaller weight penalty. The concept would not have zero NO_X emissions at takeoff, but the NO_X emissions should still be significantly less than those of Concept A.

When the QGT Concept A noise reduction benefits are assumed across all aircraft types, the QGT noise goal of containing objectionable noise within the airport boundary is almost fully achieved (ref. 8). The additional noise reduction concepts included in Concept B were intended to enable the QGT noise goal to be fully met. A substantial noise reduction of 10 EPNdB (cumulative) relative to Concept A was obtained for the FAR Part 36 observer locations. However, the poor climb performance of Concept B, which was associated with minimizing the weight impact of a heavy fuel cell based propulsion system, led to a concept which would have higher community noise than Concept A. The QGT noise goal is therefore not met with Concept B. It is possible that an alternative concept, such as replacing the fuel cell based propulsion system with H_2 turbofan engines, could enable the QGT noise goal to be met at the expense of no longer fully meeting the emissions goal.

7. Technology Assessment

Not only does Concept B not meet the feasibility criterion for this study with near term technology assumptions, but it is also impossible to meet the design mission requirements. By far the overwhelming technology issue for Concept B is the large size and weight of a fuel cell based aircraft propulsion system. For a given power level, a fuel cell based system with current technology is 3.5 times heavier than typical aircraft piston engines and 10-20 times heavier than aircraft turboshaft engines. For significant weight reduction all components of the propulsion system need to be addressed. For a current technology system the fuel cell, electric motors, and power controls/electronics are equally important contributors to the total weight and volume. Reduction in total size and weight of the propulsion system can be accomplished indirectly by reducing the total power (thrust) requirement for the aircraft. Therefore, airframe technologies, such as drag reduction, as well as propulsion technologies are important in dealing with the propulsion system size and weight problem. Twenty-five to thirty year projected technology advances for the fuel cell based propulsion system are not sufficient to make Concept B feasible without significant advances in other areas as well. For example, a 30% reduction in airframe weight coupled with a 15% reduction in drag (relative to a near term technology BWB) is one combination of technology advances which would result in concept feasibility if the projected propulsion system technology advances were realized. Since the baseline BWB is a highly efficient airframe which already incorporates significant amounts of composite construction, those weight and drag reductions are aggressive and likely require revolutionary technology advances.

In addition to fuel cell propulsion there are a number of other technology area important for Concept B. A significant portion of the airframe noise reduction benefit of Concept B is derived from the use of continuous moldline technology flaps. A number of different approaches to seamless, gapless changes in aircraft geometry are currently being researched. These technologies need to be matured to make the continuous moldline flap system assumed for Concept B viable. Part of the noise benefit of Concept B is derived from a substantial steepening of the approach angle from today's standard 3° approach. Additional drag or reverse thrust is required for the aircraft to fly such a trajectory. To realize noise benefits from the steep approach, a technology to generate this retarding force without adding a significant noise source must be devised. Developing a LH_2 fuel system for aircraft applications may present some challenges. LH_2 fuel has been used extensively for rocket propulsion, but the requirements for aircraft fuel systems are different. Fuel systems for rocket motors do not operate continuously for extended periods of time and in some cases are refurbished or replaced between missions. For a LH_2 aircraft to be practical, the LH_2 fuel system must be reliable, maintainable, and have a long operational life. There are some issues associated with distributed propulsion which would need to be addressed as well. One is that the cost and time required for engine maintenance increases as the number of engines increases. In order to avoid this significant issue the propulsion system needs to have high reliability. The increased maintenance cost could possibly be mitigated by a self-health monitoring system which focuses maintenance activities where they are most needed.

Large-scale, economical, environmentally friendly production and delivery of LH_2 are needed for Concept B to be practical. Achieving this goal will require significant advances beyond current hydrogen production and liquefaction technology. LH_2 is commercially available today, but not on the scale which would be necessary to fuel a large number of aircraft. With current production technology LH_2 is at least 4 times more expensive than jet fuel on an equivalent energy basis. Note that the fuel cost at which LH_2 will be a competitive fuel choice in the RASC time horizon is unknown. That value will be largely dependent on how much the costs of conventional fuels rise in response to the predicted decrease in supply. Equally important are the possibilities for market-based incentives such as carbon taxes or carbon permit trading which encourage the use of "green" technology. In addition to the economic aspects of LH_2 production, the environmental aspects must be considered. Emissions associated with LH_2 production or the electricity used in production can potentially negate the environmental benefits of the aircraft. Zero emission production methods exist today, but they are much more expensive than less environmentally friendly methods. Currently the most economical method to produce hydrogen is steam reforming of methane (ref. 23), which generates CO_2 emissions. Additional environmental and economic costs are also incurred from hydrogen transportation and storage. Addressing current obstacles to the widespread use of hydrogen is the focus of a significant amount of research. In January 2003, the President of the United States announced a $1.2 billion hydrogen fuel initiative which includes substantial funding to develop the technologies and infrastructure to produce, store, and distribute hydrogen.

Revolutionary technology advances in a number of different areas are required to make Concept B feasible and to realize the environmental benefits of the concept. Compared to QGT Concept A, there is substantially more technology development that would be required. The additional technology development required may not be completely justified from the perspective of the additional environmental benefit. For example, the technology requirements are largely driven by the use of a fuel cell based propulsion system. The main benefit of this propulsion approach is the elimination of NO_X emissions. However, given the significant gap between current fuel cell propulsion technology and that necessary to make a fuel cell based system comparable in weight to a turbofan engine, pursuing technology to greatly reduce NO_X formation in H_2 turbofan engines might be a more rational approach to addressing the NO_X emission issue.

8. Concluding Remarks

A study of "Quiet Green Transport" aircraft concepts has been conducted as part of the NASA Revolutionary Aerospace Systems Concepts program. The ultimate goals established for these concepts were to restrict objectionable aircraft noise to within airport boundaries and to eliminate aircraft emission of any substance where it can have a significant environmental impact. Evaluation of noise and emission reduction benefits and technology requirements for two concepts has been completed. The evaluation of the second concept, Concept B, has been described in this report.

Key features of Concept B include a BWB airframe, a distributed H_2 fuel cell based propulsion system, continuous moldline technology flaps, a steep landing approach, and a restricted altitude cruise. With current fuel cell and electric system technology, the weight of a fuel cell based propulsion system is too large for it to be used on a transport size aircraft. An advanced technology propulsion system has been defined by making projections of the potential advancement for various system components in the 25-30 year time horizon. Although the projected advances are significant, fuel cell based propulsion would still be much heavier than conventional aircraft propulsion. Aggressive airframe technology assumptions, in addition to the 25-30 year fuel cell technology assumptions, are necessary for Concept B to be comparable in takeoff gross weight to a current technology conventional aircraft with the same range and payload capability.

Projected benefits of an advanced technology Concept B relative to today's conventional aircraft include the complete elimination of all aircraft emissions expect H_2O and the potential to eliminate the formation of persistent contrails, 8 to 22dB EPNL reduction in noise at the FAA noise certification points (43dB EPNL cumulative reduction), and a 10% reduction in the area exposed to noise levels of 55dBA and greater during takeoff and landing operations. Achieving the full noise benefits of Concept B requires successful development of continuous moldline technology flap systems and a means to generate drag or reverse thrust on approach which is quiet relative to other noise sources.

Revolutionary advances are needed in areas related to LH_2 fuel in order for it to be a practical and environmentally sound fuel choice. Since hydrogen is an attractive fuel for many other uses besides aircraft, once it becomes economical an infrastructure should evolve which aviation will be able to utilize. There is some uncertainty concerning the ability to build a LH_2 fuel system which meets the demands of commercial aircraft service. Concept B would benefit, therefore, from research in the area of highly reliable and maintainable, long life LH_2 fuel systems. The use of hydrogen fuel greatly increases aircraft emissions of water vapor. However, atmospheric science investigations specific to hydrogen aircraft are needed to fully understand the impacts of these emissions and ways to mitigate their effect. A possible mitigation strategy (reduced cruise altitude) to greatly reduce or eliminate the occurrence of persistent contrails was included in the design of Concept B.

Since H_2O is the only emission from Concept B, the direct effect of these emissions in the troposphere is believed to be negligibly small, and the indirect effect of contrail formation has been mitigated through reduced cruise altitude, Concept B meets the QGT goal to eliminate emission of any substance from the aircraft where it can have a significant environmental impact. The noise benefits of Concept B do not meet the QGT noise goal, and in fact are farther from reaching that goal than Concept A due to the noise contours being "stretched out" by poor climb performance. The heavy, fuel cell based propulsion system makes improving climb performance difficult. There is potential to shrink the noise contours, at the expense of some airport area NO_X emissions, by adding small H_2 turbofan engines to augment the takeoff and climb thrust. Using H_2 turbofan engines having revolutionary low NO_X combustors may be a more balanced noise/emissions approach than the zero NO_X approach taken for Concept B. Based on currently known propulsion options, however, it is unlikely that the T/W problems of a fuel cell based propulsion system could be overcome with a different zero NO_X propulsion system.

The matrix of possible approaches to reducing or eliminating noise and emission related impacts of aircraft is large. In the RASC Quiet Green Transport study various options have been combined into two possible aircraft concepts. The evaluation of these two concepts has demonstrated a trade-off between environmental benefit and technology requirements as well as the potential for trade-offs between noise and emission benefits. Concept A achieves significant environmental benefits without the need for revolutionary aircraft technologies; i.e., the basic aircraft concept does not appear to require technology "breakthroughs" in order to be possible. Concept B, on the other hand, does require revolutionary technology advances in order to become a reality. The zero NO_X benefit of Concept B comes at the cost of a significant increase in the technology advances required. Of additional concern is the increase in community noise for Concept B relative to Concept A. In this particular case the desire to eliminate all harmful emissions had a negative impact on community noise characteristics. This situation demonstrates that, depending on the concept considered, there could be a trade-off between efforts to reduce noise and efforts to reduce emissions.

The focus of the RASC Quiet Green Transport study has been on aircraft concepts and technology requirements. Ultimately, the viability of the QGT concepts depends on much more than just technical feasibility. For these, or other, environmentally focused concepts to be viable they must be competitive in the future market place. Some of the issues which will influence the future competitive position of QGT concepts include the availability of hydrogen fuel and an associated infrastructure, the degree to which the external costs of environmental impact become internalized in the airline business (e.g., noise and emission related fees and taxes, permit trading, etc.), and the research and development expenditures required to achieve the necessary technology advances (and the degree to which these efforts can leverage similar efforts in other industries). The assessment of these types of issues was well outside the scope of the Quiet Green Transport RASC study.

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Table 1. Common Types of H_2 Fuel Cells

	Electrolyte	Operating Temperature	Typical Applications	Comments
Alkali	Potassium hydroxide	150-200ºC	Space (Apollo, Shuttle)	Expensive, requires pure H_2 and O_2
Molten Carbonate	Carbonate salts	650ºC	Large stationary power plants	Complex, need CO_2 source or recycling system
Phosphoric Acid	Phosphoric acid	150-200ºC	Small stationary power, mobile power	Extended warm-up period, large and heavy
Proton Exchange Membrane	Polymer membrane	~80ºC	Small stationary power, mobile power	Quick start-up, high power density
Solid Oxide	Ceramic	Low T: 650-800ºC High T: 1000ºC	Large stationary power plants	Some interest in use for mobile power (APU)

Table 2. Concept B Configuration Noise Benefits

	Sideline	Cutback	Approach
Fuel Cells	No core noise	No core noise	No core noise
Swept Stators	8 dB fan inlet and exhaust tones	8 dB fan inlet and exhaust tones	8 dB fan inlet and exhaust tones
Nozzle Chevrons	2 dB jet noise reduction	2 dB jet noise reduction	2 dB jet noise reduction
Continuous Moldline Flaps	No noise above undeflected	No noise above undeflected	No noise above undeflected
12º Approach Glide Slope	-	-	No added noise due to drag devices
BWB Airframe Shielding	Fan inlet and exhaust reduction (see figure 7)	Fan inlet and exhaust reduction (see figure 7)	Fan inlet and exhaust reduction (see figure 7)

Table 3. Characteristics of Concept B Current Technology Baseline

# of Passengers	225
Design Range, nmi (25k ft cruise alt.)	3500
Wing Area (trapezoidal), ft^2	5120
Wing Loading (takeoff), lb/ft^2	53
Wing Span, ft	197
L/D (mid cruise)	16.0
Thrust per "engine" (SLS), lb	1640
Number of "engines"	45
T/W (takeoff, SLS)	0.27
SFC (mid cruise), (lb/hr)/lb	0.214
Specified Gross Weight, lb	270,600
Operating Weight Empty, lb	504,600
Payload Weight, lb	47,025
Max. Available Fuel Weight, lb	30,000
Empty Weight Adjustment, lb	-311,100
Feasibility Metric	-115

Table 4. Comparison of Current Technology Conventional and Advanced Technology Concept B

	Conventional	Concept B
# of Passengers	225	225
Design Range, nmi	3500, opt. alt. cruise	3500, 25k ft alt. cruise
Wing Area (trapezoidal), ft^2	2170	4570
Wing Loading (takeoff), lb/ft^2	125	63
Wing Span, ft	132	186
Fuselage Length, ft	176	121
L/D (mid cruise)	14.3	21.5
Thrust per Engine (SLS), lb	43,400	6,730
Number of Engines	2	8
Total Thrust (SLS), lb	86,800	53,800
T/W (takeoff, SLS)	0.32	0.19
SFC (mid cruise), (lb/hr)/lb	0.586	0.166
Operating Weight Empty, lb	138,600	223,900
Payload Weight, lb	47,025	47,025
Max. Available Fuel Weight, lb	85,000	19,000
Gross Weight, lb	270,632	289,900
Fuel Weight Fraction	0.31	0.07
Engine Weight Fraction	0.06	0.35
Total Aircraft Energy Consumption, BTU	1.37×10^9	0.857×10^9

Table 5. Comparison of Emission Characteristics

	Current Technology Conventional Opt. Alt. Mission	Concept A 25k ft Altitude Mission	Concept B 25k ft Altitude Mission
Total Aircraft CO_2 Emissions, lb	235,400	0 (-100%)	0 (-100%)
Total Aircraft CO Emissions, lb	Not calculated*	0 (-100%)	0 (-100%)
Total Aircraft Unburned Hydrocarbon Emissions, lb	Not calculated*	0 (-100%)	0 (-100%)
Total Aircraft Particulate Emissions	Not calculated*	0 (-100%)	0 (-100%)
Total Aircraft H_2O Emissions, lb	92,300	309,750 (+235%)	148,400 (+61%)
Total Aircraft H_2O Emissions above 25,000ft, lb	83,900	0 (-100%)	0 (-100%)
Total Aircraft NO_X Emissions, lb	810	1291 (+59%)	0 (-100%)
LTO Cycle NO_X Emissions, lb	37.8	31.1 (-18%)	0 (-100%)

* Methods not available for estimating amount emitted; CO_2 and H_2O estimates assume complete combustion.

Table 6. Comparison of Total Noise Levels at FAR Part 36 Observer Locations

	Current Technology Conventional	Concept A	Concept B	Concept B (w/ 2 additional "engines")
Sideline EPNL, dB	96.0	84.3 (-11.7)	82.8 (-13.2)	82.0 (-14.0)
Cutback EPNL, dB	90.2	80.0 (-10.2)	82.5 (-7.7)	78.3 (-11.9)
Approach EPNL, dB	98.5	87.4 (-11.1)	76.7 (-21.8)	77.7 (-20.8)
Cumulative Reduction	-	33.0	42.7	46.7

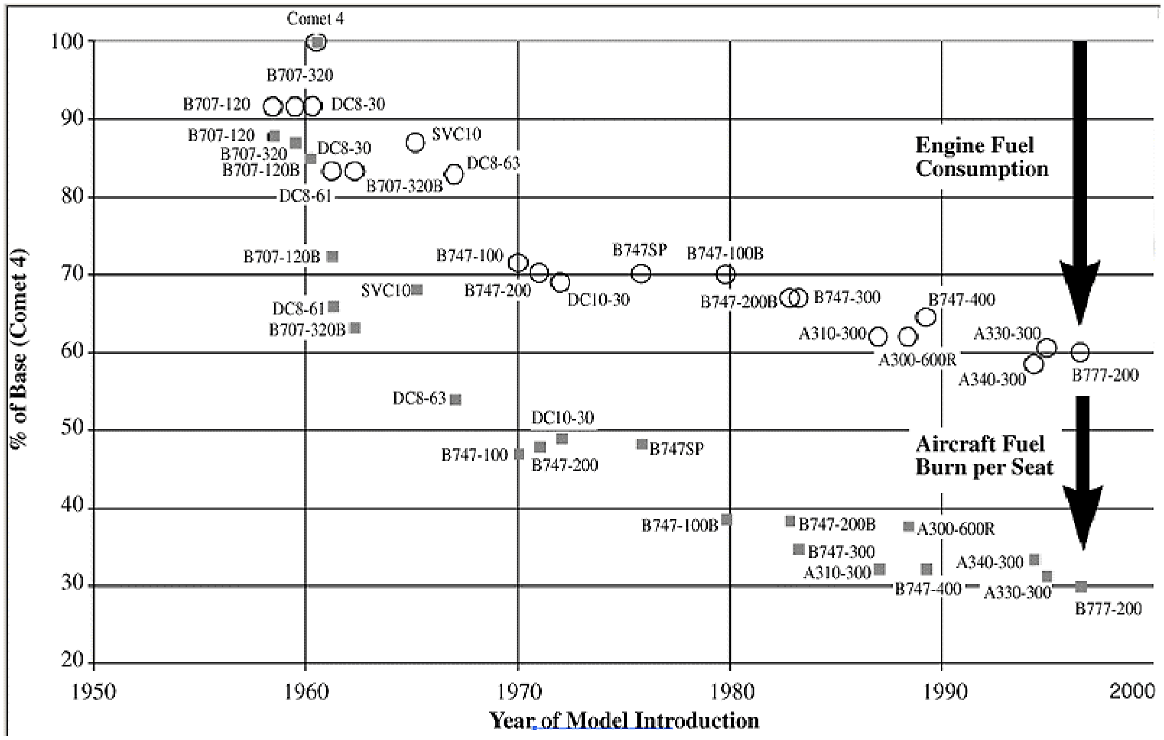


Figure 1. Historical trends in engine and aircraft fuel efficiency (ref. 4).

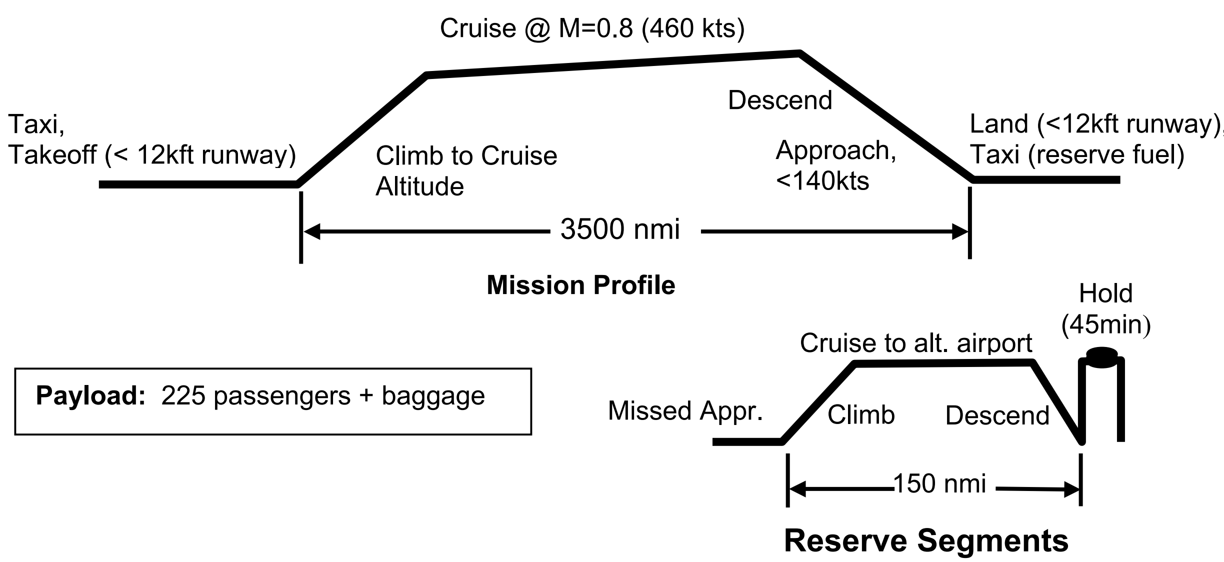
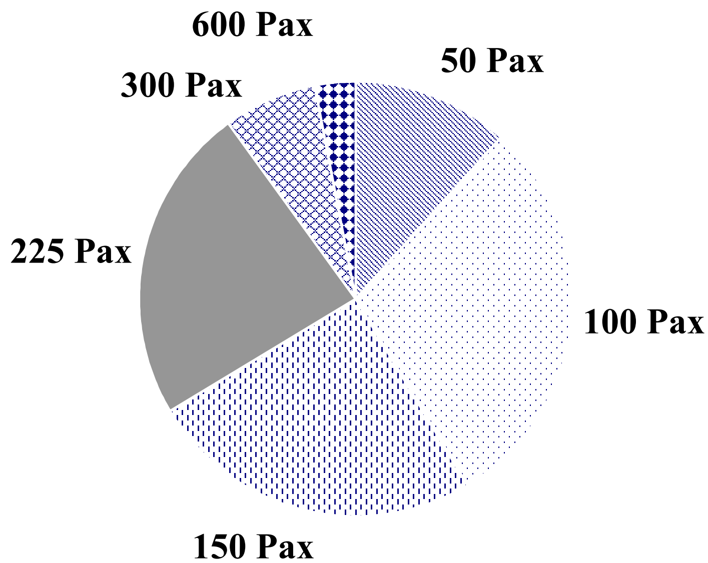
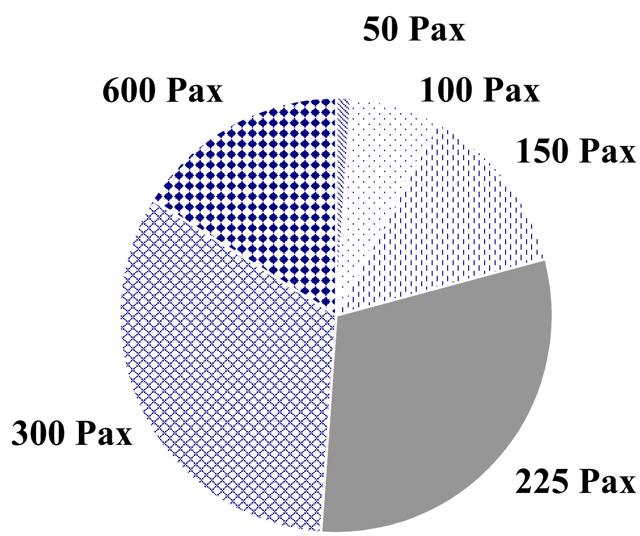


Figure 2. Quiet Green Transport study mission.

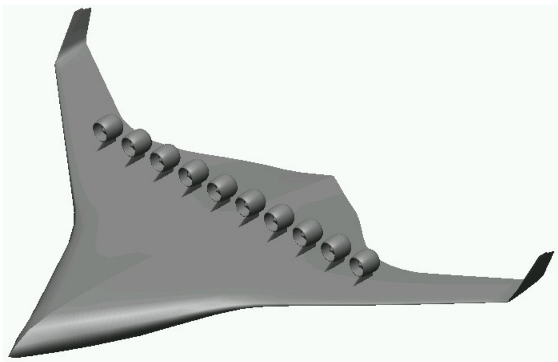


(a) Number of operations.



(b) Number of available seat-miles flown.

Figure 3. Projected aircraft fleet mix for 2025.



Basic Concept

- H_2 fuel cell propulsion, LH_2 fuel
- Distributed propulsion
- Blended-Wing-Body (BWB) airframe
- Continuous moldine technology flaps
- Steep approach (12°)
- "Contrail Avoidance" cruise

Expected Benefits

- Only H_2O emitted by aircraft
- Reduced total "engine" source noise
- Increased aerodynamic efficiency
- Forward and aft "engine" noise shielding
- Reduced flap noise
- Reduced approach noise
- Potential to eliminate contrails

Figure 4. Quiet Green Transport Concept B description.

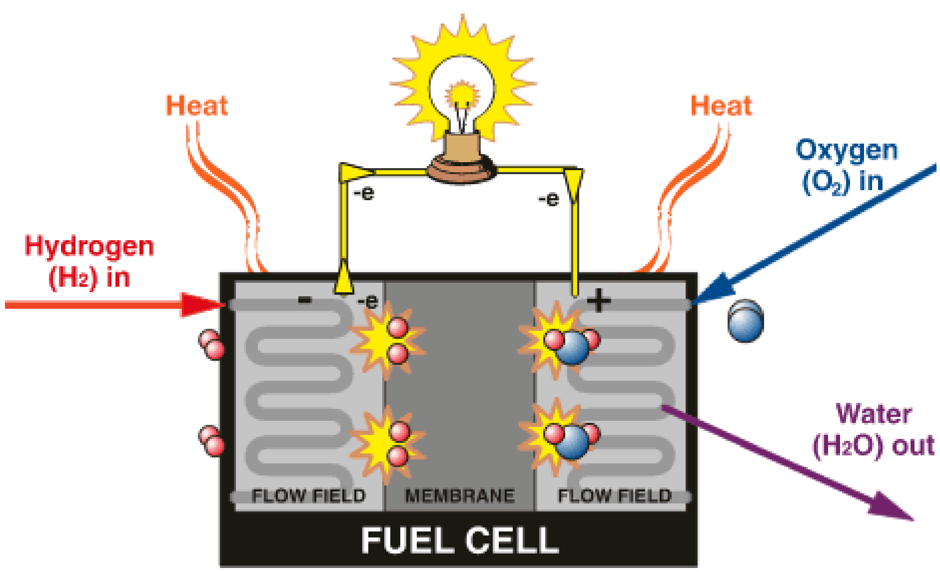


Figure 5. Illustration of H_2 fuel cell process.

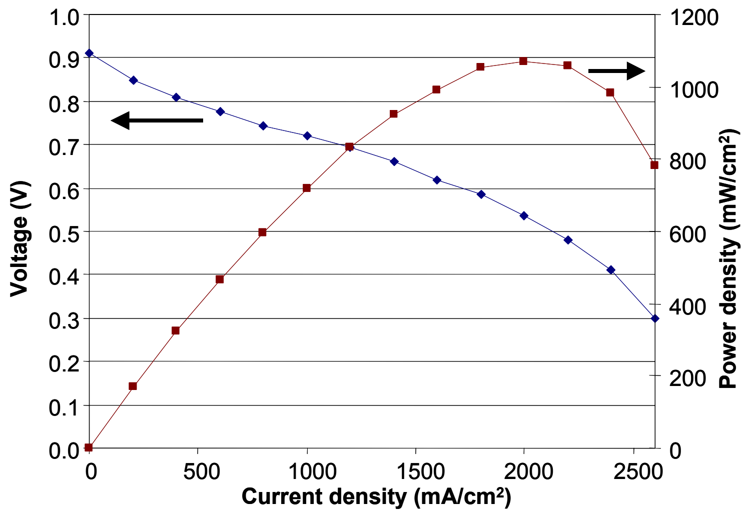


Figure 6. Primary polarization curve used in PEM fuel cell model.

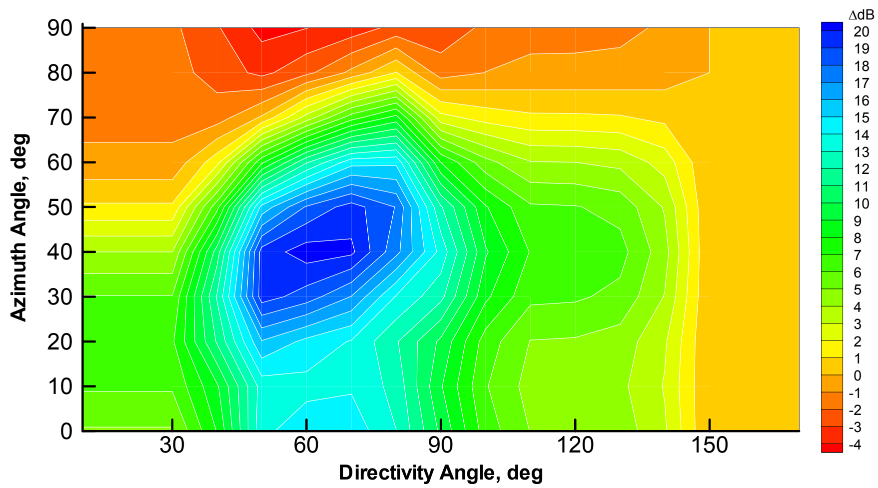


Figure 7. Assumed noise shielding effects of BWB airframe at 400Hz.

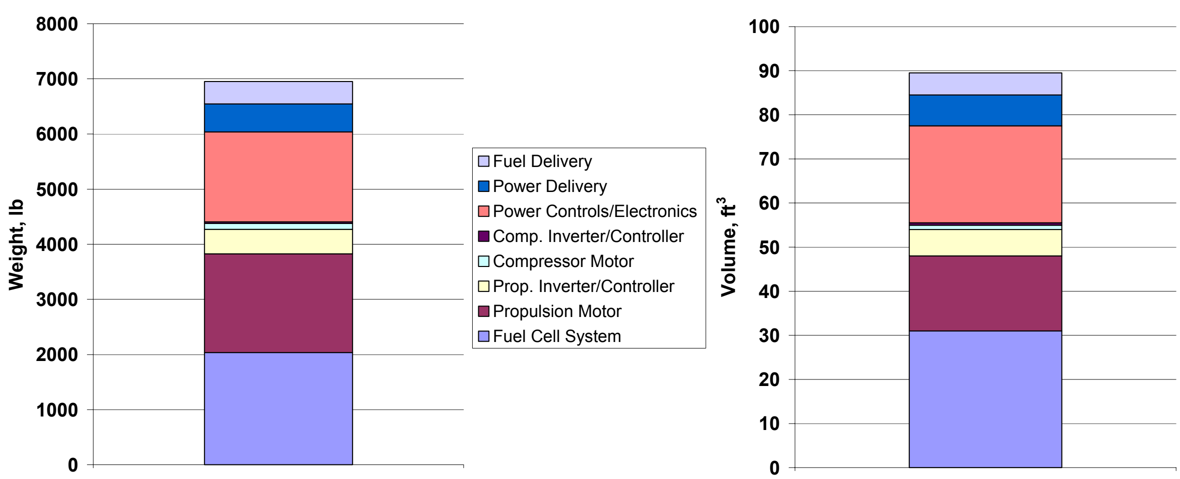


Figure 8. Component weight and volume build-up for current technology fuel cell based power system.

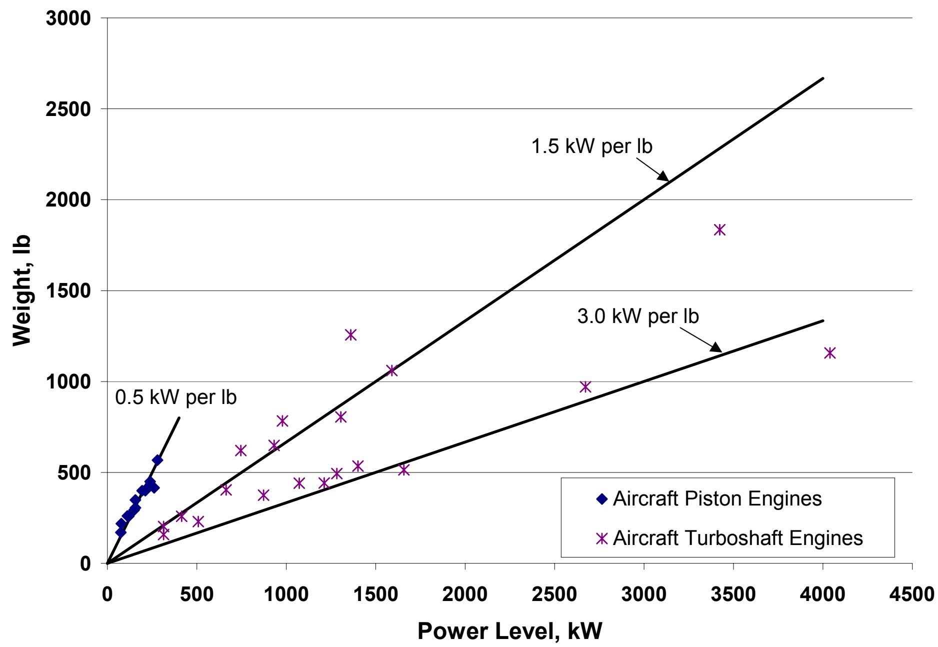


Figure 9. Specific power of conventional aircraft propulsion systems.

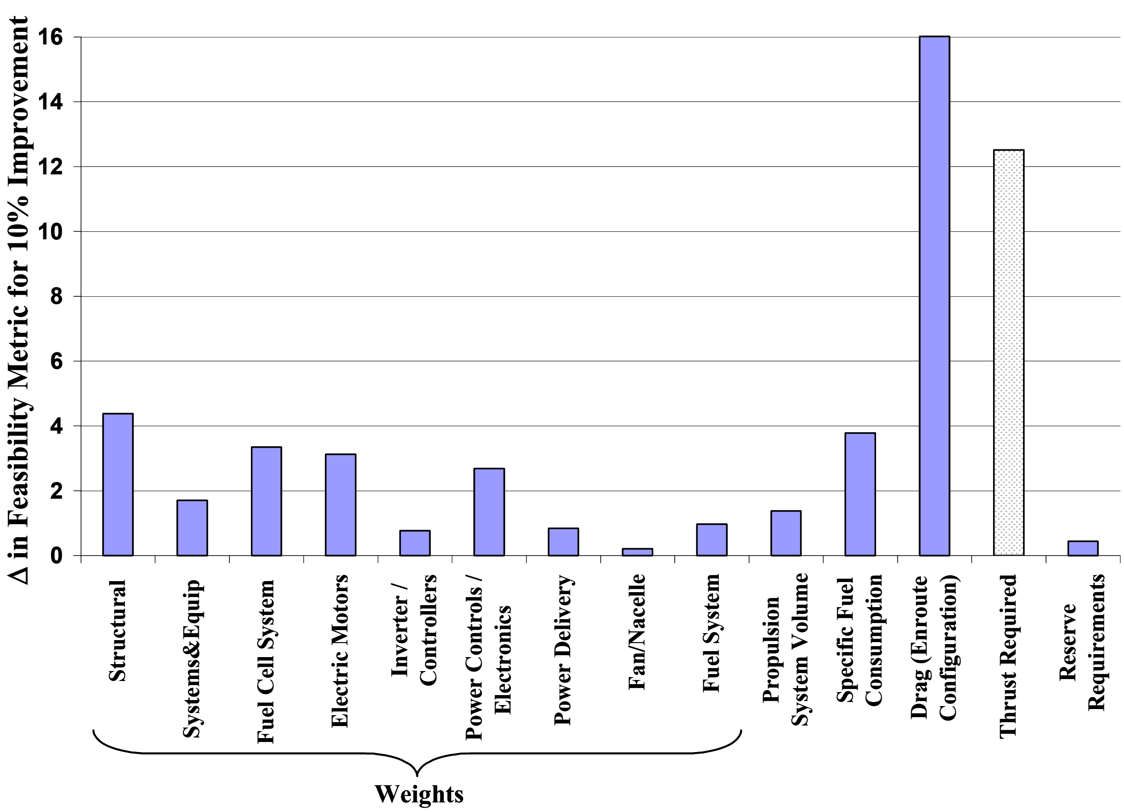


Figure 10. Sensitivity of Concept B feasibility to technology advances.

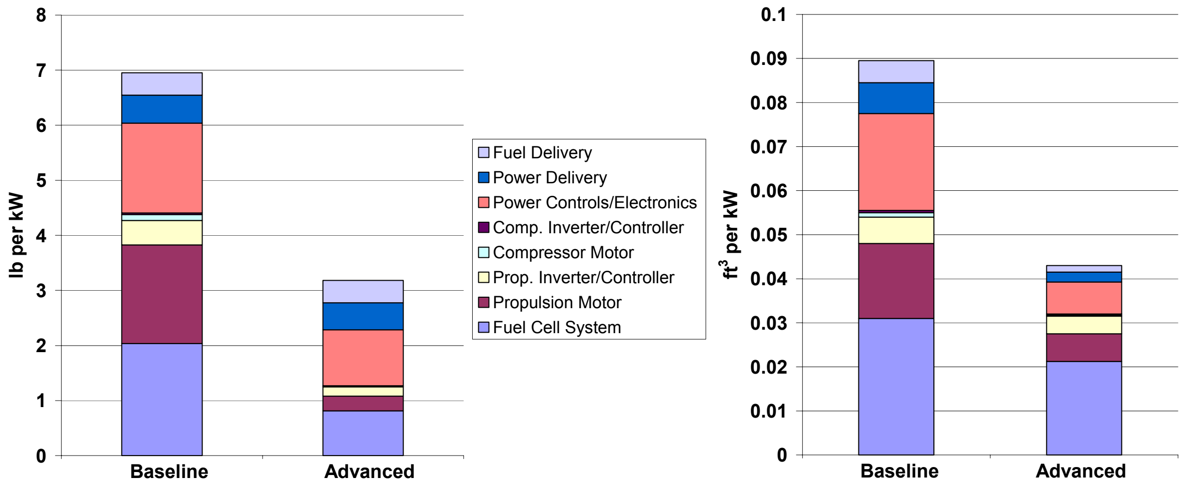


Figure 11. Comparison of current technology and advanced technology fuel cell based power systems.

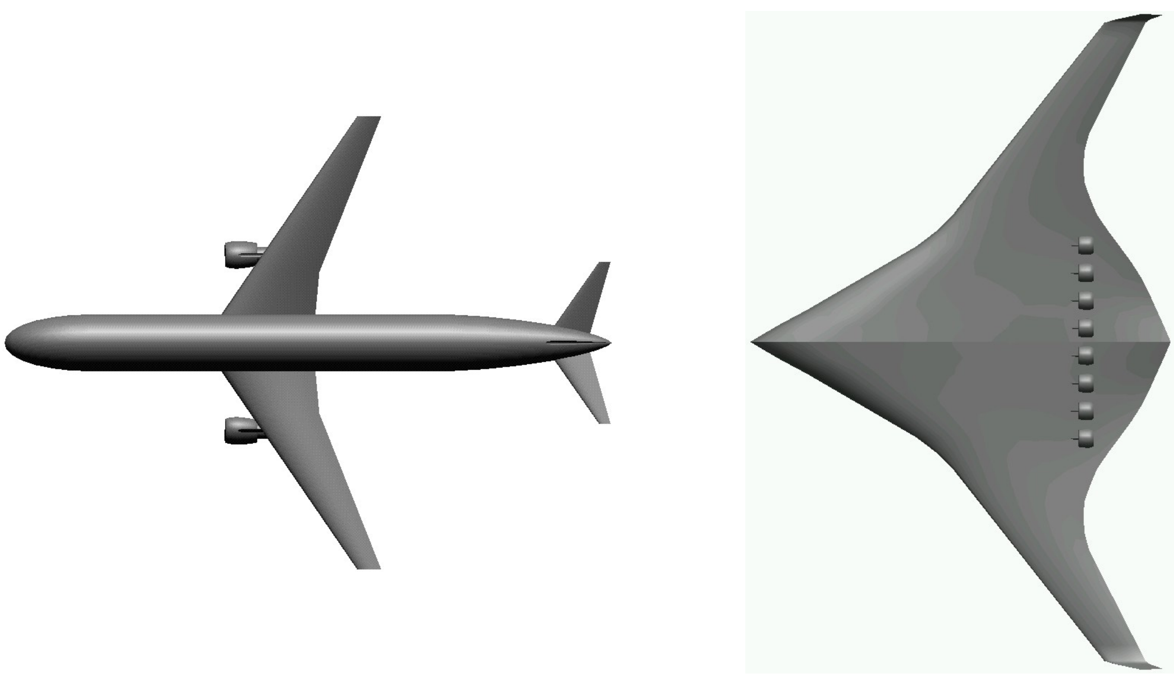
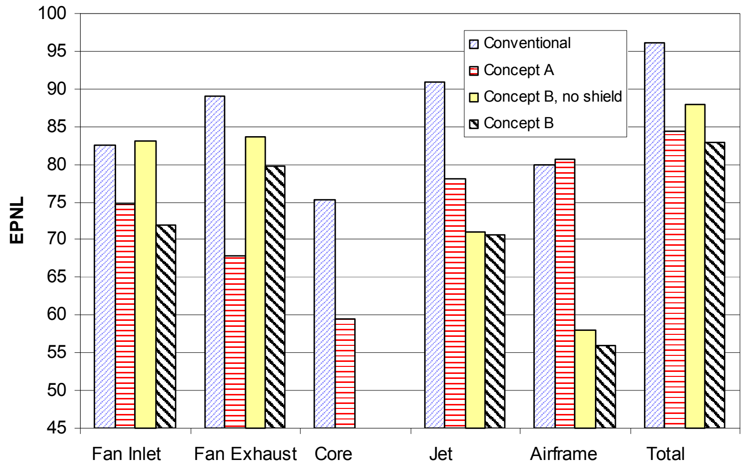
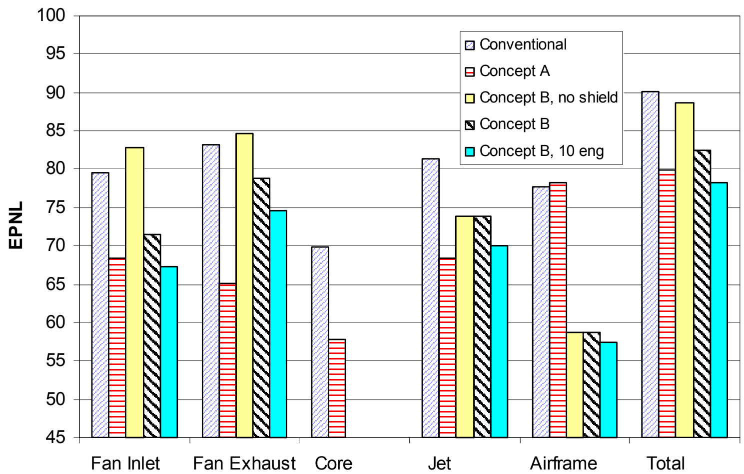


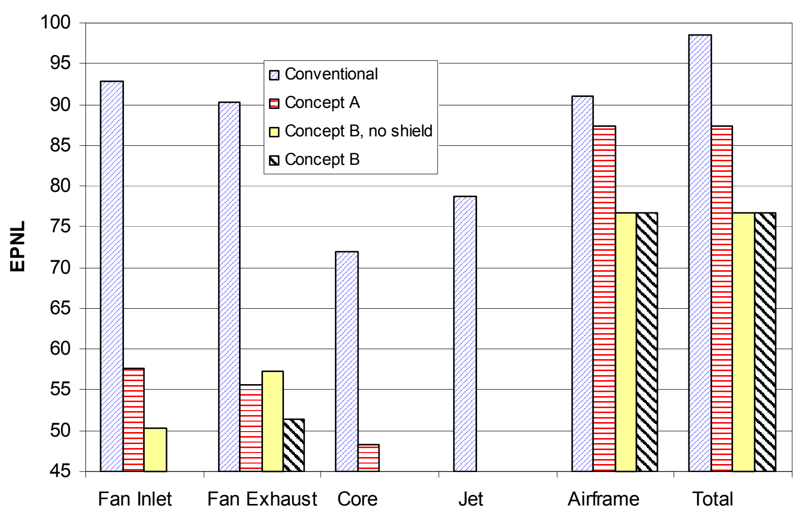
Figure 12. Size comparison of conventional baseline and Concept B.



(a) Sideline.



(b) Cutback.



(c) Approach.

Figure 13. Calibrated noise predictions for conventional baseline, Concept A, and Concept B.

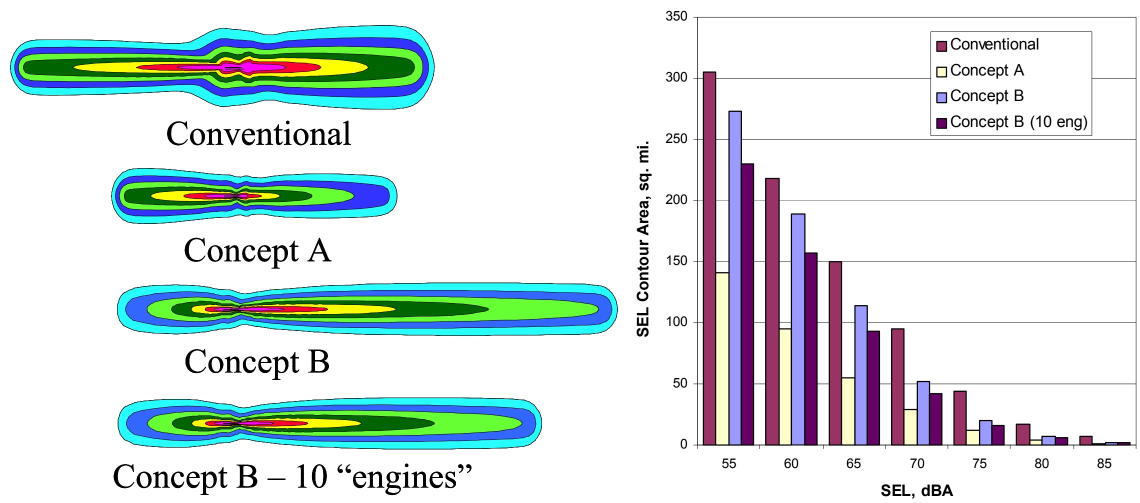


Figure 14. Single-event noise level (SEL) contours (55 to 85dBA in 5dBA increments) for conventional baseline, Concept A, and Concept B.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-02-2004

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Evaluation of a Hydrogen Fuel Cell Powered Blended-Wing-Body Aircraft Concept for Reduced Noise and Emissions

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Guynn, Mark D.; Freeh, Joshua E.; and Olson, Erik D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
23-755-81-11

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18342

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2004-212989

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 01
Availability: NASA CASI (301) 621-0390 Distribution: Standard

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://techreports/larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT
This report describes the analytical modeling and evaluation of an unconventional commercial transport aircraft concept designed to address aircraft noise and emission issues. A blended-wing-body configuration with advanced technology hydrogen fuel cell electric propulsion is considered. Predicted noise and emission characteristics are compared to a current technology conventional configuration designed for the same mission. The significant technology issues which have to be addressed to make this concept a viable alternative to current aircraft designs are discussed. This concept is one of the "Quiet Green Transport" aircraft concepts studied as part of NASA's Revolutionary Aerospace Systems Concepts (RASC) Program. The RASC Program was initiated to develop revolutionary concepts that address strategic objectives of the NASA Enterprises, such as reducing aircraft noise and emissions, and to identify advanced technology requirements for the concepts.

15. SUBJECT TERMS
aircraft noise, aircraft emissions, blended-wing-body configurations, fuel cells, liquid hydrogen, aircraft design

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	46	STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)* (301) 621-0390

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18