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# Evaluation of an Aircraft Concept With Over-Wing, Hydrogen-Fueled Engines for Reduced Noise and Emissions

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September 2002

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## Executive Summary

Throughout the world the environmental impacts of all industries, including aviation, are under scrutiny. It is widely believed that environmental issues will be an ever present and growing concern for aviation. Aviation faces a particularly difficult challenge due to its projected rapid growth (faster than Gross Domestic Product and most other industries) and the demanding performance requirements associated with air transportation. In some industries technology is already available to greatly reduce environmental impacts, the issue is simply the cost of implementation. In the case of aviation, however, there are no simple solutions. On the other hand, a sustainable air transportation system, which is able to meet society's demand for minimal environmental impact, is an important factor in future economic growth.

Of the various environmental impacts of aviation, aircraft noise and emissions are at the forefront. Because of the importance of these issues to the future of aviation, a "Quiet Green Transport" (QGT) study was chosen as one of the initial studies conducted in NASA's Revolutionary Aerospace Systems Concepts (RASC) Program. The objective of the QGT study is to develop and evaluate commercial transport aircraft concepts that significantly reduce or eliminate aircraft noise and emissions. Modeling and evaluation of the first concept considered in the study, Concept A, is described in this report. Concept A is a strut-braced wing configuration with over-wing, ultra-high bypass ratio, hydrogen fueled turbofan engines. Projected benefits of Concept A include complete elimination of all aircraft emissions except NO<sub>x</sub> 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<sub>x</sub> emitted by the aircraft during takeoff and landing operations is also reduced by 18%. With near term technology assumptions, the total amounts of NO<sub>x</sub> and water vapor emitted by Concept A over the entire flight are higher than today's conventional aircraft. These penalties can be addressed through future technology advances. In addition, Concept A was designed to cruise at a reduced altitude to provide the potential to eliminate the formation of persistent contrails, minimizing the impact of its water vapor emissions.

In addition to developing concepts, another objective of RASC studies is to identify the technology advances necessary to bring the concepts to reality. The most revolutionary technology advances required for Concept A are related not to the aircraft itself but to the liquid hydrogen (LH<sub>2</sub>) fuel used. In order for Concept A to be practical, large scale, economical, environmentally friendly production of LH<sub>2</sub> is needed. With current technology, environmentally friendly production methods are only viable on a small scale and/or are very expensive. Widespread availability of LH<sub>2</sub> is necessary for Concept A to become a reality. Furthermore, if the production of LH<sub>2</sub> is not "environmentally friendly," the environmental benefits of Concept A are diluted. The technology issues associated with hydrogen fuel are currently being addressed in many research projects, including those directed by the Department of Energy Hydrogen Program.

Since Concept A is revolutionary, representing a fundamental change from current aircraft, there are a number of challenges associated with the design which would require engineering and development to solve. However, the technology advances needed to build such an aircraft could probably be available in the near term. Even so, noise and emission benefits would be greatly enhanced through application of advanced technologies in a few key areas. The NO<sub>x</sub> emissions of Concept A could be greatly reduced by utilization of advanced combustors. NASA and others are currently developing combustor concepts which offer the potential for significant NO<sub>x</sub> reduction. H<sub>2</sub>O and NO<sub>x</sub> emissions are both sensitive to advances in the areas of aircraft drag, engine fuel efficiency, and airframe structural weight. The overall noise characteristics of Concept A were found to be mainly sensitive to airframe noise. Advanced technologies for airframe noise reduction could significantly augment the noise benefits of Concept A.



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# 1. Introduction

## 1.1 Aviation and the Environment – Current Outlook

Many industries today have an increased awareness of the environmental impact of products they produce and services they provide. In some cases this is driven by existing or proposed government regulations, while in other cases it is driven by a desire to be seen as “green” by consumers. The idea of using “green” as a selling point to consumers is even stronger in other areas of the world than in the United States. Growing attention to environmental issues is likely due to the increased understanding of how future public health and welfare is being adversely impacted by today’s activities. The trend toward “green” has not been overlooked by the aviation industry. For example, on Boeing’s commercial airplane website catch phrases like, “Concern for the environment...at Boeing it comes naturally” are found throughout the promotional literature (ref. 1). The Boeing 767 family of aircraft is called, “the right choice for the environment” because of lower noise and emissions compared to the similarly sized Airbus A330 (ref. 2). Airbus states that its new A380 design, “...brings new standards of comfort, better economics, in an aircraft that is more environmentally responsible...” and refers to the A380 as a “new green giant”(ref. 3). In addition to aircraft manufacturers, the service providers (i.e. airlines) have also begun to address environmental issues. Some airlines have formal environmental goals or objectives and publicize the ways in which they have reduced the environmental impact of their operations (refs. 4,5,6). The Star Alliance, a global alliance of 15 air carriers including U.S. carrier United Airlines, issued an Environmental Commitment Statement in May 1999. One of the commitments is, “we will strive to develop and use technology that is environmentally sound and we will promote enhanced environmental standards in our purchasing of new aircraft, equipment, and facilities” (ref. 7). Lufthansa, a member of the Star Alliance, has a corporate goal to, “Reduce specific fuel consumption by 30 percent from 1991 to 2008, and by 35 percent by 2012”(ref. 5).

Despite the greater attention being paid to environmental issues by the aviation industry, the environmental challenges faced by the industry are significant. These challenges stem from a rapid growth in the demand for air travel and a “greening” of other industries, including other modes of transportation. Although aviation’s impact on the environment can be fairly significant near airports, in global terms aviation’s current contribution to environmental problems is relatively small. However, the negative environmental impacts from aviation are growing. Unconstrained the demand for passenger air travel is projected to nearly triple over the next 25 years. The growth in air cargo is projected to be even faster, increasing 4.5 times over the same period (ref. 8). At the same time, other industries will be reducing their relative environmental impact in response to stricter regulations and the availability of new, revolutionary technologies. Figure 1, based on data in reference 9, illustrates the projected increase in the relative contribution of aircraft to regional NO<sub>x</sub> emissions. An upward trend is also predicted for the relative contribution of aircraft to global warming as shown in figure 2, from reference 10. Despite the relatively small current contributions, some environmental groups have been calling attention to the environmental impacts of aviation for several years (e.g., refs. 11 and 12). As the contribution of aviation to environmental problems grows in the future, the calls for action will likely become louder.

The capacity issues expected to face aviation in the future are also closely tied to the environmental issues. Aircraft noise already constrains air transportation through curfews, noise budgets and limits, and slot restrictions. One of the barriers to construction of new airports and/or expansion of operations at existing airports is the negative environmental impact on surrounding communities. According to the National Science and Technology Council (NSTC) report, *Goals for a National Partnership in Aeronautics Research and Technology* (ref. 13), “Environmental issues are likely to impose the fundamental limitation on air transportation growth in the 21<sup>st</sup> century.” Environmental concerns could

constrain growth of the air transportation system either directly, such as through noise and emission limits, or indirectly through opposition to new airports on the basis of environmental concerns. If the air transportation system is not able to grow at a rate sufficient to meet demand, there will be an increase in air transportation costs and negative economic impacts.

The environmental impact of aviation is a broad topic involving many aspects, including, but not limited to: 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 produced noise and emissions. Although there are numerous facets to an environmentally friendly aircraft, the present study is focused only on aircraft noise and emissions characteristics. Reducing noise and reducing emissions are two of the five strategic objectives under the NASA Aerospace Technology Enterprise “Revolutionize Aviation” goal (ref. 14). The NSTC report, *National Research and Development Plan for Aviation Safety, Security, Efficiency, and Environmental Compatibility* (ref. 15) states, “...developing technology for reducing noise and emissions are essential to sustaining aviation’s vitality...”

Over the past fifty years, aircraft and engine manufactures have made great strides in reducing noise and emissions (though usually not motivated strictly by concern for the environment.) In fact, Boeing presents a perspective that aircraft of today are quieter and cleaner than other forms of transportation (ref. 1). However, the rate of aircraft noise and emission reductions from evolutionary technology improvements is slowing. For example, figure 3 from reference 10 shows the reduction in specific fuel consumption since the introduction of the jet transport. Clearly the rate of improvement in fuel efficiency has slowed drastically in the past two decades. A similar trend also exists for aircraft noise levels. The rate of noise and emissions reduction from evolutionary improvements in airframe and engine technology cannot keep pace with the projected growth in air travel and a steady rise in the negative environmental impacts of aviation will result. In addition, the relative size of aviation’s impacts will grow as other industries move beyond evolutionary technology improvements to fundamental changes (e.g. fuel cell powered cars). To reverse these trends, revolutionary approaches to aircraft noise and emissions reduction are needed.

## **1.2 Aviation and the Environment - Possible Future Scenarios**

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. It is also necessary to consider possible future environments that will dictate the desired design attributes. It is impossible to predict what the world will be like many years in the future, but based on today’s environment plausible futures can be extrapolated.

Because of population and economic growth, the demand for air travel is projected to continue growing. Certainly a number of scenarios could be postulated in which the demand for air travel stagnates or even declines. However, if air travel grows as predicted, the environmental issues noted above will continue to be a concern.

It is reasonable to expect that noise will continue to be an important aspect of future aircraft. Already aircraft noise is an issue that daily affects how airlines operate. Because of aircraft noise regulations imposed by the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA), and noise related restrictions and fees imposed by individual airports, there is currently a fairly strong economic incentive for airlines to consider noise characteristics in the purchase of

aircraft. Quieter aircraft tend to provide the airline with more flexibility in utilization, as well as a hedge against possible future reductions in regulated noise limits during the ~30 year lifetime of the aircraft. As important as noise is today, it will probably be even more of an issue in the future. As the number of operations grows, the noise generated by each individual aircraft will have to decrease to avoid growth in the area around the airport subjected to excessive total noise levels. In addition, it is likely that as the capacity limits of the current hub-and-spoke airline route structure are reached, a transition to more point-to-point service will occur. In this case, much of the growth in operations will occur at airports which currently have low traffic and little noise. Moving to a more distributed air transportation system would make aircraft noise an issue for even a greater segment of the population than it is today. Therefore, strong incentives for aircraft noise reduction will likely continue to exist in the future.

Future scenarios concerning the importance of aircraft emissions are somewhat more speculative than those for noise. The only aircraft emissions currently regulated are landing-takeoff cycle (LTO) emissions of NO<sub>x</sub>, CO, unburned hydrocarbons, and smoke. Although there are some airports which currently have fees based on aircraft LTO emission characteristics, the incentives for buying lower emission aircraft appear to be much weaker than those associated with noise. For example, only a handful of airlines are buying special low NO<sub>x</sub> engines available for some aircraft because of the extra costs compared to the standard, higher NO<sub>x</sub> engines. There is a strong economic incentive for buying fuel-efficient aircraft, which can have an indirect beneficial impact on emissions as well. Aircraft which are more fuel-efficient tend to have lower emissions (although not always the case for NO<sub>x</sub> emissions). Since fuel cost is a significant portion of airline operating cost, more fuel-efficient aircraft are desirable. The desire for reduced fuel cost has led to continual improvement in aircraft efficiency and reduction in most emissions. But, in today's environment, there is no incentive for using an alternate fuel that results in even lower emissions if it cost more than normal jet fuel.

The differences in the current perspectives on aircraft noise and emissions are due in part to fundamental differences in the two issues. The impacts of aircraft emissions on human health and well-being are much more indirect and uncertain than those of aircraft noise. Aircraft noise has a direct and immediate affect on the "quality of life" of those exposed to it. The effects of aircraft emissions tend to be more long term, and in most cases materialize as part of a larger problem. For example, a "silent aircraft" would probably solve the airport noise issue. However, "emissionless aircraft" would not solve the air quality problems around airports or the global climate change problem. Furthermore, the importance of issues such as global climate change is still somewhat uncertain and the subject of much debate. Despite the current uncertainties, the visibility of issues related to aircraft emissions, and anthropogenic emissions in general, has been growing. It is likely that this trend will continue and as a result in the future there could be economic incentives for aircraft with significant emissions reduction or elimination. These incentives could come in a number of different forms such as emission taxes, emission permit trading, emission caps, etc., or even consumer demand for low emission transportation.

If "green" is important for aviation, 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. A future "hydrogen economy," with hydrogen produced by renewable energy sources and used as an energy carrier, is the goal of much of that research. A transition to alternate fuels such as hydrogen is not something that the aviation industry would likely do alone, but as part of a shift towards these fuels by many industries. Currently, the incentive for using alternate fuels is much stronger in other areas 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. When developing and evaluating the aircraft concept described in this report, it was assumed that a transition to alternate fuels

by many industries would occur in the future, making alternate fuels available to aviation as well. Based on the current direction of research in the Department of Energy (DOE) and Department of Transportation (DOT), hydrogen appears to be a likely alternate fuel candidate.

## 2. Study Overview

The work presented in this report was conducted as part of the “Quiet Green Transport” study of NASA’s Revolutionary Aerospace Systems Concepts (RASC) Program. The RASC vision is to develop and analyze revolutionary concepts (considering a 25-50 year time horizon) that address strategic objectives of the NASA Enterprises and to identify the enabling advanced technology requirements for the concepts. The RASC Quiet Green Transport study addresses the aircraft noise and emission reduction goals of NASA’s Aerospace Technology Enterprise. The Quiet Green Transport (QGT) study actually evolved from a number of recent NASA studies which investigated advanced concepts for reducing noise and emissions. Past studies were generally focused on advanced concepts for either noise or emissions, but did not combine these concepts 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 was performed jointly by NASA Langley Research Center (LaRC) and NASA Glenn Research Center (GRC) which explored aircraft with unconventional propulsion concepts for the reduction or elimination of aircraft emissions. The types of 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 in 2000 as part of the GRC Zero CO<sub>2</sub> Emissions Technology (ZCET) project. Since 1999, MSE Technology Applications, Inc. has been performing a study funded by LaRC to investigate the future possibilities for a totally emissionless transport aircraft. This study has covered a broad range of possible technologies, including breakthrough concepts which challenge traditional views of propulsion and energy systems. Advanced concepts for noise reduction that have been recently investigated include over-wing engine placement and scarf engine inlets. 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 for the current effort.

The ultimate vision for a Quiet Green Transport is the ability to move people (and goods) by air without harming the Earth or degrading the quality of life of its residents. In the context of the QGT study this is interpreted to mean that objectionable aircraft noise 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 QGT study are to define revolutionary aircraft concepts that are aimed toward achieving this vision and to identify the technology advances necessary to make those concepts feasible. Note that while all the concepts investigated in the study are focused on the above vision, not all of the concepts are necessarily capable of fully achieving it. Fully achieving the vision is a very demanding goal which may require technology advances that are unrealistic even in the 25-50 year time horizon considered for RASC studies. Even though “green” technologies are beginning to find application in a number of other areas, and are projected to significantly penetrate many markets in the near future, the design requirements for aircraft application are much more demanding.

A set of three aircraft concepts, developed from “brainstorming” ideas to eliminate aircraft noise and emission sources (or significantly reduce their impacts), were selected for evaluation in the QGT study. The first concept defined and analyzed, referred to as Concept A, is the focus of this report. This is the

“lowest risk/lowest benefit” concept of the three selected and integrates noise and emission reduction features which are lower risk relative to other proposed ideas.

### **3. General Concept Description**

The general arrangement of Quiet Green Transport Concept A is illustrated in figure 4. The concept features “ultra-high” bypass ratio, hydrogen (H<sub>2</sub>) fueled turbofan engines with scarf inlets placed above a strut-braced wing. The hydrogen fuel is stored as a cryogenic liquid (LH<sub>2</sub>) in fuselage tanks. Using H<sub>2</sub> turbofan engines eliminates all aircraft emissions except H<sub>2</sub>O and NO<sub>x</sub>. The over-wing placement and scarf inlets provide shielding of the engine noise relative to the ground. A strut-braced wing configuration was selected for its increased aerodynamic and structural efficiency relative to a conventional wing arrangement. Concept A 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 6°. 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 cruise capability. The optimum cruise altitude for subsonic jet aircraft is usually in the upper troposphere. However, the ambient conditions at this altitude are often conducive to the formation of persistent contrails, which are triggered by aircraft H<sub>2</sub>O emissions and are believed to have a significant environmental impact (ref. 10). It is presently unclear exactly how contrail formation and contrail properties for a H<sub>2</sub> aircraft would compare to today’s kerosene fueled aircraft. But, by providing cruise capability at reduced altitude, where contrail formation is unlikely, it should be possible to fly a cruise profile that avoids the formation of persistent contrails.

### **4. Design Mission Requirements**

The basic design mission requirements selected for the QGT study are a payload capability of 225 passengers (in a 3-class seating arrangement) plus baggage and a range capability of 3500 nmi with full payload. A 225 passenger vehicle was chosen based on the projected future fleet mix shown in figure 5. 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 which represents both a significant portion of projected airport operations and of total seat-miles flown was selected. 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. 16). Previous studies of “zero emission” aircraft have indicated that the feasibility of some concepts is very sensitive to the range requirement. With a 6000 nmi range requirement these concepts would be penalized by a range capability that 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 and was selected as the design range requirement. The design mission profile is illustrated in figure 6. 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.

## 5. Modeling and Analysis Methodologies

There is an inherent difficulty in the study of unconventional concepts in that most analysis tools are based on and geared to existing design paradigms. Furthermore, the details of the concepts are generally not well defined. The analysis for this study, therefore, was performed at a fairly high, conceptual level. In some cases significant tool development was still 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. (Note: a specially modified version of FLOPS was developed to automate sizing of fuselage fuel tanks and fuselage length.) An existing FLOPS model for a current technology, conventional baseline aircraft was used as a starting point for Concept A to ensure consistency in the modeling. The major changes to the conventional aircraft model necessary to model Concept A were: changing to a strut-braced wing, changing to liquid hydrogen (LH<sub>2</sub>) fuel, incorporating the new LH<sub>2</sub> engine, and adding reduced altitude cruise capability. Concept A was initially modeled using current to near term technology assumptions, establishing a technology baseline from which the impact of possible future technology advances could be assessed.

The FLOPS code has some limited capability to model strut-braced wings. A “wing strut-bracing factor” is provided in the structural weight equations to represent the structural weight reduction realized from strut bracing. However, previous studies of strut-braced transport aircraft deemed this factor insufficient (ref. 17). Furthermore, there is no ability to account for a strut-braced wing in the FLOPS internal aerodynamic estimates. Aspects of a design which cannot be properly modeled internal to FLOPS can be easily handled through user input which overrides the internal calculations. For the strut-braced wing of Concept A, this input was derived from a number of previous studies of strut-braced wing transonic transport aircraft performed by the Virginia Tech (VT) Multidisciplinary Analysis and Design Center for Advanced Vehicles (ref. 17,18,19,20,21). In the VT studies, multidisciplinary optimization was performed to determine optimum strut-braced wing and conventional designs. Although the design mission for Concept A is somewhat different from that in the VT studies, the VT optimum designs and the differences between the strut-braced and conventional optimums was used as a guide in selecting the wing geometry for Concept A. A critical part of modeling the strut-braced wing is the structural weight estimate. As noted above, FLOPS alone is not sufficient for this task. The VT studies employed higher order weight estimation methods for the wing and strut based on finite element structural analysis. Applying this level of analysis to Concept A would have required time and resources not available for the QGT study. However, the results from the VT analyses were used to calibrate the FLOPS weight estimates. In other words, a correction factor was found which when applied to the FLOPS wing weight estimates would result in approximately the wing+strut weight from the VT higher order analysis. This correction factor was then used for the Concept A FLOPS model. Methods described in the VT reports were used as a basis for estimating strut related interference drag penalties and for laminar flow assumptions for the wing and strut surfaces. Landing gear lengths were also derived from the VT strut-braced wing aircraft designs.

One important aspect of an aircraft which uses LH<sub>2</sub> fuel is the fuel system. Although LH<sub>2</sub> has a very high energy content per pound, because of its low density a cubic foot of LH<sub>2</sub> only contains about one-fourth the energy of a cubic foot of jet fuel (kerosene). So nominally a LH<sub>2</sub> aircraft needs four times the fuel volume of an equivalent kerosene fueled aircraft. In addition to the fuel volume issues, LH<sub>2</sub> is a cryogen stored at about 20K, so insulation and thermal management are important. While the differences between

conventional and LH<sub>2</sub> fueled aircraft are many, LH<sub>2</sub> 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 late 1970's. In fact, one of the participants in that research, Daniel Brewer, later wrote a book, *Hydrogen Aircraft Technology* (ref. 22), 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<sub>2</sub> related modeling aspects of Concept A. Basic fuel tank shape, fuel tank arrangement (integral fuselage tanks fore and aft of passenger compartment), and fuel system weights were based on the results of these earlier studies. To accommodate large LH<sub>2</sub> tanks, the fuselage of the conventional 225 passenger aircraft was replaced by a larger diameter fuselage typical of a 300 passenger aircraft (i.e. Boeing 777). The layout of the passenger compartment (e.g. number of seats abreast) was modified to also be consistent with the new fuselage diameter. Fuselage length was a sizing variable determined automatically by FLOPS to match the fuel volume available to the fuel volume required to complete the mission.

Concept A not only differs from the conventional baseline in airframe design and fuel type, but also in the basic parameters of the engine. The engine model used was based on a scaled down version of the current technology LH<sub>2</sub> engine used in the 2000 ZCET studies. Engine bypass ratio was significantly increased to address the desire for reduced noise for Concept A. Although higher bypass ratio helps to reduce engine source noise as well as improve engine fuel efficiency, problems encountered with thrust lapse at altitude and NO<sub>x</sub> emissions necessitated some design compromises. The final engine design has a bypass ratio of 13.5 with a fan pressure ratio of 1.3 and an overall pressure ratio of 30. Maximum turbine inlet temperature (T<sub>4</sub>) is 3085°R. Cruise specific fuel consumption for this engine is ~0.21 lb of hydrogen per hour per lb of thrust and the thrust lapse from sea level static conditions to cruise is ~80%. The NO<sub>x</sub> emission characteristics of the engine were modeled with a semi-empirical equation representative of current combustor design technology. The emissions of other compounds were calculated based on fuel composition and combustion chemistry.

Modeling the reduced altitude cruise capability for Concept A was accomplished by simply modifying the mission profile definition. The aircraft was sized to complete the 3500 nmi design range with maximum altitude limited to 25,000 ft. (Note that for the 25,000 ft altitude mission the cruise Mach number for Concept A was reduced to match cruise airspeed with the baseline conventional aircraft.) A cruise altitude limit of 25,000ft for this 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 contrail formation becomes a possibility depends on many factors which vary from flight to flight. While the aircraft weight and fuel capacity was sized for cruise at 25,000ft, engine thrust was sized to be sufficient to cruise at 35,000ft (~ optimum cruise altitude). 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

Takeoff and landing noise levels were predicted using the Aircraft Noise Prediction Program (ANOPP), which 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.

The first step in the noise analysis was to calibrate the noise predictions for the conventional baseline to ensure that the noise levels of the individual sources, as well as the total level, were reasonable for that class of aircraft. The individual ANOPP source modules were calibrated using the levels for the individual noise sources, plus the total noise levels, for a “generic” small-to-medium sized twin-engine transport from reference 23. Noise levels were computed at the three FAR 36 observers—sideline, cutback, and approach—using the separate steady flight conditions defined in reference 23 as typical for that specific class of aircraft. The three representative flight conditions are given in Table 1. The fan inlet and exhaust, core, jet and airframe noise levels were computed for each flight condition, and the EPNLs for the individual sources were then calibrated to match the predictions from reference 23. The calibration factors were then used for all subsequent noise predictions for both conventional and advanced configurations.

Low-speed aerodynamic characteristics were not available for the aircraft configurations due to the relatively low fidelity of the aerodynamic analysis methods being used in this study. Instead, the representative flight conditions from Table 1 were used for both the conventional and Concept A configurations; this made it possible to perform noise predictions for both aircraft but any difference in the low-speed aerodynamics of the two aircraft was not captured. Typically, though, the effect of changing low-speed aerodynamics on the noise levels is small compared to the reduction achieved by technologies that reduce the source noise directly.

It was possible to estimate the change in the flight path when assessing the impact of advanced technologies by computing the change in either the thrust required or available climb rate using the following simplified equation of motion:

$$\gamma = T/W - D/L$$

where  $\gamma$  is the flight path angle,  $T/W$  the thrust-weight ratio, and  $D/L$  the drag-lift ratio. Knowing the original thrust, weight and flight path angle gave an “effective” lift-drag ratio for each flight condition. For the sideline portion of the flight path, the new climb angle was then computed from the new engine thrust, gross weight, and percent change in  $L/D$ . For cutback and approach, the required throttle setting was computed from the new maximum thrust, landing weight and landing  $L/D$ .

Most of the reduction in noise for the Concept A configuration relative to the conventional baseline was accomplished through configuration benefits and noise reduction concepts that directly affected the noise levels. These concepts were the scarf inlet, swept fan stators, engine over-wing placement, and nozzle chevrons. The EPNL reductions for each of the noise reduction concepts are shown in Table 2 for each flight condition and are discussed below. For simplicity, the noise reduction for each of these concepts was applied by simply subtracting the overall EPNL benefit from the predicted EPNL for each observer, rather than trying to apply the noise reduction as frequency- and directivity-dependent effects at different throttle settings.

The estimated benefits from the scarf inlet were derived from reference 24. In that study the measured scarf benefit below the aircraft was less than 1 EPNdB, but for a non-optimized inlet contour. Based on the discussion in reference 24, it was assumed for this study that the benefit could be increased to 2 EPNdB through careful aerodynamic and acoustic design of the inlet. Data were not available for the effect of the scarf inlet on the noise radiated laterally to the sideline, and noise reduction along that axis is likely to be less than directly under the aircraft, so no noise reduction was applied at the sideline observer.



The benefits of swept stators were taken from references 25 and 26. An 8 dB reduction in the rotor-stator interaction tones was used at all engine power settings, resulting in a smaller benefit in the total noise when the fan broadband noise was added in. The swept-stator benefit varied for different power settings due to the changing contribution of the interaction tones to the total fan noise. The benefits of engine over-wing placement were based on results presented in reference 27. The configuration analyzed in that report was similar in terms of engine bypass ratio, wing planform and placement of the engines on the wing, so the EPNL benefits of that study were used without modification. The benefits of nozzle chevrons were taken from reference 28. The benefits were only available for full thrust, so it was assumed that the EPNL benefit was independent of engine power setting. It is possible that the reduction in jet noise is smaller at lower jet velocities.

The noise goal of the QGT concepts is to contain “objectionable” aircraft noise within the airport boundary, so it is important to consider how the noise benefits of Concept A translate to a reduction in the size of the community noise contours. Configuration noise characteristics are usually expressed in terms of EPNL while community noise is usually expressed in terms of day-night noise level (DNL) contours. DNL is based on an entirely different frequency weighting than EPNL, but it was assumed that the EPNL and DNL benefits would be approximately the same. The Integrated Noise Model (INM) computer program was used to compute the single-event noise level (SEL) contours for approach and takeoff; SEL is a measure of the contribution of a single aircraft operation to the total DNL at an airport. Since INM uses noise-power-distance (NPD) tables which give the noise level directly below the flight path for a set of throttle settings and aircraft-to-observer distances, it was not possible to capture the directivity effects of the configuration noise benefits, particularly those of the over-wing engine. Instead, the cutback benefit was used for the takeoff flight path and the approach benefit for the approach flight path when computing the noise contours in INM. Computation of DNL contours at a number of airports was carried out using the Noise Impact Model (NIM), part of Logistics Management Institute’s (LMI) web-based Aviation Systems Analysis Capability (ASAC) suite of models.

## **6. Concept Evaluation Results**

### **6.1 Performance and Sizing**

A comparison of Concept A (with state-of-the-art to near term technology level assumptions) to an equivalent conventional aircraft sized for the same mission requirements is shown in Table 3. The two aircraft are compared graphically in figure 7. Estimated gross weight for Concept A is 298,281 lb compared to 270,632 lb for the conventional aircraft. The fuselage of Concept A is 25% wider and 30% longer to provide sufficient fuel volume for the LH<sub>2</sub> fuel. Although the fuselage size for Concept A is much larger than a typical 225 passenger aircraft, it is not unreasonable, being slightly smaller than the fuselage of a Boeing 777-300 (which has a typical 3-class seating capacity of 386 passengers). The large fuselage does have a negative impact on aerodynamic efficiency and aircraft empty weight. On the other hand, the large energy content per pound of hydrogen results in more than a 50% reduction in fuel weight despite the inefficient, low altitude cruise performed by Concept A. Total energy used by Concept A to complete the 3500 nmi “contrail avoidance” mission is 31% greater than used by the conventional aircraft flying an optimum altitude cruise. If Concept A flew the same mission profile as the conventional aircraft, the fuel weight reduction associated with using LH<sub>2</sub> fuel would be even greater. Note that it was not necessary to assume “revolutionary” technology advances for Concept A in order to arrive at a configuration of reasonable size and weight.

## 6.2 Emissions Characteristics

The principal exhaust emissions of current jet aircraft include CO<sub>2</sub>, H<sub>2</sub>O, SO<sub>x</sub>, NO<sub>x</sub>, CO, unburned hydrocarbons (HC), and soot. CO<sub>2</sub> and H<sub>2</sub>O emissions result from complete combustion of hydrocarbon molecules which form the basis of today's jet fuel. SO<sub>x</sub> emissions result from combustion of the small amount of sulfur that 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<sub>x</sub> emissions are a by-product of combustion associated with air being subjected to high temperatures and pressures in the engine. CO<sub>2</sub>, H<sub>2</sub>O, and SO<sub>x</sub> emissions are directly related to fuel composition and rate of consumption. NO<sub>x</sub>, CO, HC, and soot emission rates are very dependent on ambient conditions and engine operating conditions.

The emission characteristics of Concept A are summarized and compared to the conventional baseline aircraft in Table 4. Results for Concept A are shown for both the design mission with cruise altitude limited to 25,000ft and an alternate mission with cruise at optimum altitude.

By virtue of using hydrogen fuel instead of a hydrocarbon fuel, emissions of CO<sub>2</sub>, CO, HC, and soot are totally eliminated in Concept A. Since the LH<sub>2</sub> does not contain sulfur as jet fuel typically does, SO<sub>x</sub> emissions are eliminated as well. The only emissions from Concept A are H<sub>2</sub>O (as water vapor) from combustion of the hydrogen fuel and NO<sub>x</sub> as a by-product of combustion.

Although switching to hydrogen fuel eliminates several types of aircraft emissions, it does dramatically increase the amount of H<sub>2</sub>O emitted. For an equal amount of energy released, combustion of H<sub>2</sub> results in 2.6 times more H<sub>2</sub>O than combustion of jet fuel. The increase in H<sub>2</sub>O emissions for Concept A relative to the conventional baseline is more (3.3 times) due to the less energy efficient cruise for Concept A.

Even though water vapor is a greenhouse gas just like CO<sub>2</sub>, in many situations H<sub>2</sub>O 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 in CO<sub>2</sub> and H<sub>2</sub>O emissions is the residence time in the atmosphere. The residence time for CO<sub>2</sub> is on the order of 100 years, so the impact of CO<sub>2</sub> emissions on CO<sub>2</sub> concentration is a function of the total CO<sub>2</sub> 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.10). 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 necessary scale directly with the amount of H<sub>2</sub>O emitted. For example, aircraft H<sub>2</sub>O emissions really just act as a trigger for contrail formation. The aircraft emitted H<sub>2</sub>O is actually only a fraction of the total H<sub>2</sub>O content of the contrail that is subsequently formed. So the number of contrails formed can depend more on the number of flights flown than on the amount of H<sub>2</sub>O emitted by each aircraft. Also, the characteristics of contrails depend on what is emitted from the engines in addition to water vapor. The environmental impacts of H<sub>2</sub>O from hydrogen aircraft cannot be simply extrapolated from studies which have investigated conventional jet aircraft burning kerosene fuel. However, as mentioned previously, to address the concerns associated with increased H<sub>2</sub>O emissions from a hydrogen aircraft, Concept A was designed to be capable of cruising at a reduced altitude (25,000 ft) where the potential impacts of the H<sub>2</sub>O emissions should be greatly reduced. Atmospheric studies specific to hydrogen aircraft would be needed to better assess whether this approach is sufficient to eliminate any

potential significant environmental impact from the H<sub>2</sub>O emissions of Concept A.

Simply by paying special attention to NO<sub>x</sub> emissions in the design of the Concept A engine, LTO NO<sub>x</sub> emissions for Concept A were reduced 18% relative to the conventional baseline. This NO<sub>x</sub> emission reduction was not realized for the mission as a whole, however. Total NO<sub>x</sub> emissions for Concept A are 59% greater than for the conventional baseline. The reasons for this significant increase in total NO<sub>x</sub> emissions are twofold. The majority of this increase is associated with the less efficient, lower altitude “contrail avoidance” cruise of Concept A, which results in a 31% increase in total energy used. Part of the increase is also due to the engine design. Higher engine operating temperature at cruise altitude is needed to maintain sufficient thrust capability with the higher bypass ratio engine design. Higher engine temperatures generally result in higher NO<sub>x</sub> emissions. Many past studies of H<sub>2</sub> aircraft have predicted lower NO<sub>x</sub> emissions for H<sub>2</sub> engines due to the special properties of H<sub>2</sub> fuel. According to combustion experts at GRC, however, the type of fuel used does not have a fundamental impact on the amount of NO<sub>x</sub> generated in the engine. The amount of NO<sub>x</sub> formed is mainly dependent on the engine cycle parameters (temperature, pressure, etc.) and the combustor design. The properties of H<sub>2</sub> may, however, enable special advanced combustors which are not possible with kerosene. Advanced combustor concepts currently being developed for jet fuel could also possibly be used to significantly reduce the NO<sub>x</sub> emissions of the Concept A engine. Advanced, low NO<sub>x</sub> H<sub>2</sub> combustors are a technology which would greatly improve the environmental performance of Concept A.

Concept A does not fully achieve the Quiet Green Transport vision because of its NO<sub>x</sub> emissions. NO<sub>x</sub> emissions can possibly be eliminated by moving away from combustion based propulsion to electro-chemical based propulsion, which is being considered in another one of the QGT study concepts. The H<sub>2</sub>O emissions of Concept A are of concern, but an attempt to meet the “no significant environmental impact” criteria has been made through the “contrail avoidance” design mission. This should eliminate the indirect, but potentially significant, impact of water vapor on radiative forcing through the formation of contrails. Based on current understanding, the direct environmental impact of the water vapor emissions is expected to be minimal.

### **6.3 Noise Characteristics**

Figure 8 shows the predicted noise levels at the three FAR 36 observer locations for three cases: the conventional baseline; Concept A with the higher bypass ratio engine but without the noise reductions from Table 2 added in; and finally for Concept A with all benefits accounted for. An additional benefit for Concept A at the approach condition is achieved by the use of a 6° glide slope, which greatly reduces the required throttle setting and doubles the distance between the observer and the aircraft as it passes overhead. With the higher glide slope, the required throttle setting was reduced to such a low level that the engines would probably be at idle power during approach; in this case an idle power setting of 10% thrust was assumed.

Taking into account all of the performance and configuration noise benefits, Concept A has a cumulative reduction in the three noise levels of 33 EPNdB relative to the conventional baseline. The noise benefits would likely be slightly better if it had been possible to account for the improved low-speed aerodynamics of the higher aspect ratio of the strut-braced wing concept. As can be seen in figure 8, the higher bypass ratio engine combined with the configuration noise benefits results in a significant reduction in the noise levels received from all components except the airframe. In fact, the airframe noise level increases a small amount due to a slightly larger wing on Concept A. Since Concept A has its engines placed above the wing, it might be possible to use full-span flaps, which would likely reduce the airframe noise due to the presence of fewer flap edges. This effect was not captured in ANOPP’s original airframe noise

method, which does not separate the flap-edge noise component like newer prediction methods.

Figure 9 shows the single-event noise level (SEL) contours for the conventional baseline and Concept A (including all noise benefits), plus an illustration of how an additional 5 dB improvement in airframe noise would further reduce the size of the contours. The 55 dBA SEL contour area for Concept A is 53% smaller than for the conventional baseline. As shown, reduction in airframe noise, the dominant noise source for Concept A, would enable additional reductions in contour area.

Since DNL, the typical community noise metric, accounts for the impact of every aircraft operation on the total noise levels at a given airport, it is necessary to define which aircraft would have the QGT noise benefits applied to them in the future and which would not in order to calculate the DNL benefits of the QGT concepts. Several different scenarios were examined for replacing the current aircraft fleet mix with aircraft that have the noise benefits of Concept A. The NIM model breaks down the fleet into five general categories: narrow-body short-haul, narrow-body long-haul, wide-body short-haul, wide-body long-haul, and propeller. Long-haul aircraft are defined as aircraft with a stage length of at least 1000 nmi, while short-haul aircraft have shorter stage lengths. Since the Concept A design mission falls into the narrow-body, long-haul class, the first scenario involves replacing all aircraft in that class with newer aircraft that are 11 dB quieter (approximate average EPNL reduction for Concept A at each observer location). The second scenario replaces all turbofan-powered aircraft with newer, quieter aircraft. The final scenario also replaces all propeller aircraft with models that are 11 dB quieter; this could be either through replacing the propeller aircraft with regional jets, or by applying appropriate noise reduction technologies to the propeller aircraft. Figure 10 shows the number of persons living within the 55 dB DNL contour at each airport for projected 2017 aircraft operations and population. (2017 was the last forecast year available from the database used.) A noise level of 55 dB DNL is assumed to be the threshold for “objectionable” noise in the QGT study. Therefore, realizing the goal of containing “objectionable” noise within the airport boundary would correspond to a 55 dB exposed population of zero. Figure 11 shows the total number of persons living within the 55 dB contours of all 11 airports studied, for the different replacement scenarios. As this figure shows, to fully realize the benefits of a QGT configuration, it is necessary that the benefits be applicable to as many classes of aircraft as possible. If QGT type benefits cannot be extended to all aircraft in service in the future, it will be difficult to achieve the QGT noise goal. When the Concept A noise reduction benefits are applied to all aircraft types, the goal of containing “objectionable” noise (i.e. > 55 dB DNL) within the airport boundary is almost fully achieved.

## 7. Technology Requirements

Concept A achieves significant reductions in noise and emissions by incorporating a number of design elements which are fundamentally different from current aircraft. Because many of the systems of Concept A are not “off-the-shelf,” building an aircraft like Concept A would involve an extensive design and development effort. But since the necessary technologies for these systems are either already available today or should be available in the near term, Concept A does not really require “revolutionary” technology advances. Based on the results in Section 6.1, an aircraft like Concept A could probably be built in the fairly near term with only a small increase in gross weight relative to an equivalent conventional aircraft. However, the “practicality” of the concept is limited by current technologies in the areas LH<sub>2</sub> fuel production, transportation, and storage.

For use of LH<sub>2</sub> as an aviation fuel to become a reality, LH<sub>2</sub> must be widely available at a reasonable cost. LH<sub>2</sub> is commercially available today, but not on the scale that would be necessary to fuel a large number of aircraft. With current production technology, LH<sub>2</sub> is at least ~4 times more expensive than jet fuel on an equivalent energy basis. In addition to the economic aspects of LH<sub>2</sub> production, the environmental

aspects must be considered as well. Emissions associated with LH<sub>2</sub> 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. 29), which generates CO<sub>2</sub> emissions. Economical, low environmental impact LH<sub>2</sub> production processes are needed to make LH<sub>2</sub> a practical and environmentally sound fuel choice. Achieving this goal will require significant advances beyond current hydrogen production and liquefaction technology. Additional environmental and economic costs are incurred from hydrogen transportation and storage. Boil-off losses are particularly important for transportation and storage of LH<sub>2</sub>. LH<sub>2</sub> that vaporizes can either be vented or re-liquefied. In either case, this adds to the overall fuel costs. Advances in transportation and storage technology would further improve the viability of LH<sub>2</sub> fuel. Note that the fuel cost at which LH<sub>2</sub> 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 that encourage the use of “green” technology.

The hydrogen technology requirements noted above are not specific to Concept A, or even to aviation. They relate to a widespread push for “green” energy and are being addressed in research programs such as the DOE Hydrogen Program. The DOE Hydrogen Program conducts “research and engineering development in the areas of hydrogen production, storage, and utilization, for the purpose of making hydrogen a cost-effective energy carrier for utility, buildings, and transportation applications” (ref. 30). Primary research thrust include: projects that introduce renewable-based options for producing hydrogen, projects that decrease the cost of producing hydrogen from natural gas, developing hydrogen-based energy storage and electrical generation systems, demonstrating fueling systems for hydrogen vehicles, developing and lowering the cost of technologies to produce hydrogen directly from sunlight and water, and developing codes and standards for hydrogen technologies (ref. 30).

The design and construction of Concept A presents a number of challenges that would require extensive engineering and development to address. Note that design of a hydrogen-fueled engine is not the major challenge. Only minor modifications are required to convert a conventional engine to hydrogen. In fact, a turbojet engine capable of burning hydrogen or kerosene was flight tested by the NACA in 1956 (ref. 31). Achieving an ultra-high bypass ratio for the engine is a challenge, however, and would require technology advances in areas such as the fan gearbox and exhaust nozzle. The LH<sub>2</sub> fuel system is also one of the challenges. LH<sub>2</sub> 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 an LH<sub>2</sub> aircraft to be practical, the LH<sub>2</sub> fuel system must be reliable, maintainable, and have a long operational life.

The airframe and propulsion-airframe integration concepts present design challenges as well. Although strut-braced wings are used for some general aviation aircraft, application to a transonic transport aircraft is somewhat different. Early VT studies showed a large weight penalty associated with preventing strut buckling (ref. 17). In order to avoid this weight penalty it is necessary to avoid compression loads on the strut. The fuselage-strut attachment concept presented in the VT studies is a “telescoping sleeve mechanism” which makes the strut inactive in compression (ref. 17). Although this approach appears feasible, additional development in this area would be required. A primary concern with a transonic strut-braced wing is the interference drag associated with the strut. Through careful aerodynamic design using computational fluid dynamics (CFD) tools, it should be possible to design the strut intersections with minimal interference drag. The engine integration and inlet design for Concept A are also unconventional

and optimal integration of the over-wing engine pods and design of the scarf inlet are important.

The above challenges associated with the design of Concept A can probably be classified as mainly engineering problems rather than technology problems. In other words, the problems can be solved through careful engineering and design with current or near term technology. (One possible exception is the LH<sub>2</sub> fuel pumps, which may require additional technology advances to reach the performance needed for aircraft application. Some of the pump reliability and maintainability issues associated with a hydrogen aircraft may also be faced in efforts to design reusable launch vehicles with aircraft-like operations and mission turnaround. The NACA hydrogen engine flight test program did use a pump-fed system for the last three flights (ref. 32). However, the fuel system was not subjected to the wide range of conditions that would be encountered in normal operation of a LH<sub>2</sub> fueled aircraft.)

## 8. Technology Sensitivities

Future advances in aircraft related technology areas would have a significant positive impact on the noise and emission characteristics of Concept A.

Emissions that are already eliminated by virtue of the nature of the design cannot be reduced further through technology advances. However, technology advances can reduce the remaining H<sub>2</sub>O and NO<sub>x</sub> emissions. The sensitivity of H<sub>2</sub>O and NO<sub>x</sub> emissions to aircraft related technology areas is shown in figure 12. These sensitivities were calculated by assuming a 10% improvement in each technology area individually, resizing the aircraft, and recalculating the emission characteristics. Although the environmental impact of Concept A's H<sub>2</sub>O emissions is expected to be small, it is still likely that less H<sub>2</sub>O is better. H<sub>2</sub>O emissions (which are directly related to fuel consumption) are most sensitive to drag (i.e. aerodynamic efficiency) and engine specific fuel consumption (i.e. engine efficiency), with a 10% improvement resulting in a 13.6% and 12.0% reduction in H<sub>2</sub>O emissions respectively. The next largest sensitivity is airframe structural weight with a 10% improvement resulting in a 3.5% reduction in H<sub>2</sub>O emissions. The sensitivities for NO<sub>x</sub> emissions are similar, except that NO<sub>x</sub> emissions are dependent not only on fuel consumption but also the NO<sub>x</sub> emission index (EI). A 10% improvement in average NO<sub>x</sub> EI would translate directly into a 10% reduction in NO<sub>x</sub> emissions. The NO<sub>x</sub> EI is largely a function of combustor design. Low NO<sub>x</sub> combustors for conventional kerosene fueled engines are the subject of current research at NASA and elsewhere. This low NO<sub>x</sub> technology should be applicable to hydrogen engines and perhaps could even be enhanced using the special properties of hydrogen. There is opportunity, therefore, for advanced combustor technology to greatly improve the NO<sub>x</sub> emission characteristics of Concept A and eliminate the increase in NO<sub>x</sub> relative to the "state-of-the-art" conventional baseline that is shown in Table 4.

Figure 13 shows the sensitivity of noise characteristics (EPNL at the three FAR 36 observer locations) to the independent improvements in key technology areas. In addition to the technology areas in the emissions sensitivity analysis, noise specific technology areas were added for these sensitivities. In the case of the noise technology areas for which "percent reduction" is not meaningful, the levels of the individual sources were reduced by 5 EPNdB instead. (This increment was considered roughly equivalent to the "10% improvement" increments used in the other technology areas.) As expected, the most significant contribution comes from an improvement in the airframe noise level since that component is the dominant source for Concept A. Fan noise and jet noise reduction have small but measurable effects on the overall noise characteristics. There is very little sensitivity of Concept A's noise characteristics to aircraft performance related technology areas such as weight, drag, engine efficiency, etc. Several technology improvements actually have a slight—though nearly negligible—detrimental affect on cutback noise due to a smaller performance-sized engine and thus a higher required

throttle setting to meet the required climb gradient after cutback. The technology areas most important with respect to emissions are not significant potential contributors to additional noise reduction for Concept A. For this concept, by far the most important technology area for noise reduction is airframe noise.

## 9. Concluding Remarks

A study of “Quiet Green Transport” aircraft concepts has been initiated as part of NASA’s RASC program. The ultimate goal established for these concepts is 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 the first concept, Concept A, has been completed.

With extensive engineering and development, it is believed that an aircraft based on Concept A could be built in the relatively near term, since the technologies necessary to enable the revolutionary aspects of the aircraft design are largely in place today. Significant reductions in aircraft environmental impacts could be achieved with this concept. Projected benefits of Concept A include complete elimination of all aircraft emissions except NO<sub>x</sub> 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<sub>x</sub> emitted by the aircraft during takeoff and landing operations is also reduced by 18%. Concept A does not fully achieve the noise and emission goals set for the Quiet Green Transport study. Fully achieving these goals will require more radical approaches to noise and emission reduction/elimination, as are being considered in the other concepts of the QGT study.

The emission benefits of Concept A are mainly derived from a switch from kerosene to hydrogen fuel. Use of hydrogen as an aircraft fuel has been demonstrated in the past, but implementation of the technology has been hampered by the high cost of hydrogen production and the lack of a hydrogen fuel infrastructure. For Concept A to become a viable concept, revolutionary technologies which make hydrogen fuel production economical and environmentally friendly are needed. 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. The use of hydrogen fuel greatly increases aircraft emissions of water vapor. 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 A.

There are a number of aircraft related technology areas important to Concept A. All of the unconventional elements of the design would require development, and advanced technology may be required to enable some of these elements. One example is the LH<sub>2</sub> fuel system. Even though a LH<sub>2</sub> fueled aircraft engine was demonstrated in flight over forty years ago, there is some uncertainty concerning the ability to build a LH<sub>2</sub> fuel system which meets the demands of commercial aircraft service. Concept A would benefit, therefore, from research in the area of highly reliable and maintainable, long life LH<sub>2</sub> fuel systems. The environmental performance of Concept A would be greatly enhanced by technology advances in two key areas: combustor design and airframe noise. There is potential for significant reductions in NO<sub>x</sub> emissions through the development of low NO<sub>x</sub>, hydrogen combustors. Advanced low NO<sub>x</sub> combustor concepts for kerosene fueled engines are already under development and could likely be applied to a future hydrogen engine. There is also a possibility that by designing the combustor to take advantage of the properties of hydrogen, NO<sub>x</sub> emissions could be reduced even further. Because of a reduction in engine source noise and shielding provided by the over-

wing placement and scarf inlets, airframe noise is the dominant noise source for Concept A. The noise characteristics of Concept A would benefit greatly from technologies aimed at airframe noise reduction.



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Table 1. Representative Flight Path Parameters for a Small/Medium Twin Transport

	Sideline	Cutback	Approach
Net thrust, % of maximum	100	65	22 / 10
Climb angle, deg.	9	4	-3 / -6
Altitude at observer, ft.	1000	1900	394 / 788
Sideline distance, ft.	1476	0	0
Airspeed, knots	188	192	155
Landing gear	Up	Up	Down

Table 2. Concept A Configuration Noise Benefits

	Sideline	Takeoff	Approach
Scarf Inlet	none	2 dB fan inlet	2 dB fan inlet
Swept stators	8 dB fan inlet and exhaust tones	8 dB fan inlet and exhaust tones	8 dB fan inlet and exhaust tones
Engine over-wing placement	12 dB fan exhaust 12 dB core	8 dB fan exhaust 9 dB core	5 dB fan exhaust 8 dB core
Chevrons	2 dB jet	2 dB jet	2 dB jet

Table 3. Comparison of Concept A and Conventional Baseline

	Conventional	Concept A
# of Passengers	225	225
Design Range, nmi	3500 @ opt. alt.	3500 @ 25Kft
Wing Area, ft <sup>2</sup>	2170	2350
Wing Loading (takeoff), lb/ft	124.7	126.9
Wing Span, ft	131.7	148.5
Fuselage Diameter, ft	16.5	20.3
Fuselage Length, ft	176	230
L/D mid cruise	14.3	13.3
Thrust per engine (SLS), lb	43,371	51,620
T/W (takeoff, SLS)	0.321	0.346
SFC mid cruise ((lb/h)/lb)	0.586	0.211
Operating Weight Empty, lb	138,611	211,447
Payload Weight, lb	47,025	47,025
Block Fuel Weight, lb	74,621	34,648
Max. Available Fuel Weight, lb	84,996	39,809
Gross Weight, lb	270,632	298,281

Table 4. Comparison of Concept A and Conventional Baseline Emission Characteristics

	Conventional Opt. Alt. Mission	Concept A Opt. Alt. Mission	Concept A Design Mission
Total Aircraft CO <sub>2</sub> Emissions, lb	235,429	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 <sub>2</sub> O Emissions, lb	92,306	258,162 (+180%)	309,750 (+235%)
Total Aircraft H <sub>2</sub> O Emissions above 25,000ft, lb	83,881	237,068 (+183%)	0 (-100%)
Total Aircraft NO <sub>x</sub> Emissions, lb	810	962 (+19%)	1291 (+59%)
LTO Cycle NO <sub>x</sub> Emissions, lb	37.8	31.1 (-18%)	31.1 (-18%)

\* Methods not available for estimating amount emitted; CO<sub>2</sub> and H<sub>2</sub>O estimates assume complete combustion.

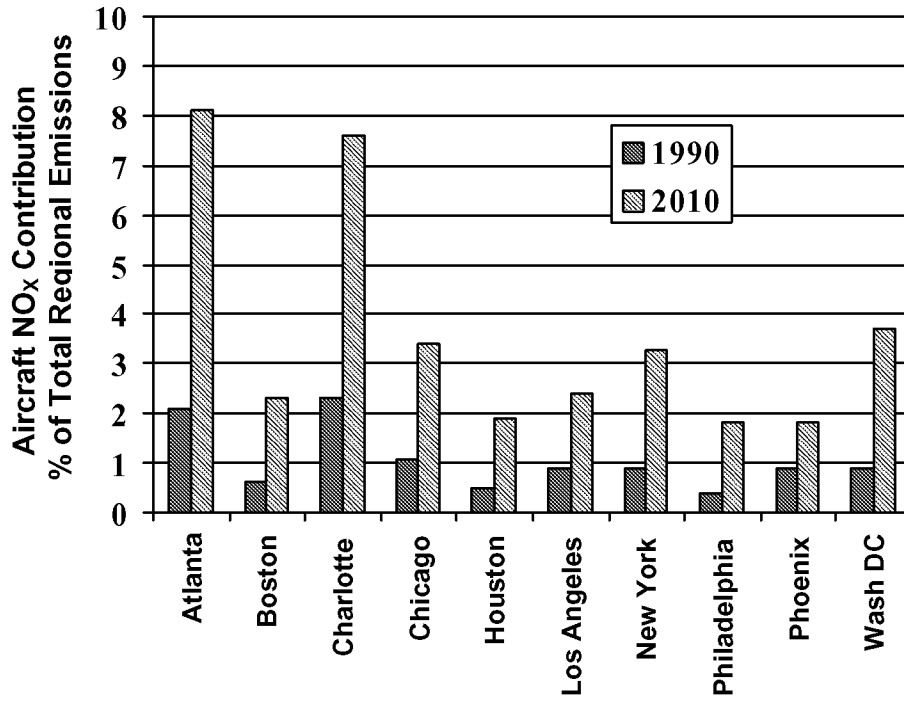


Figure 1. Past and projected aircraft contribution to regional NO<sub>x</sub> emissions (data from ref. 9).

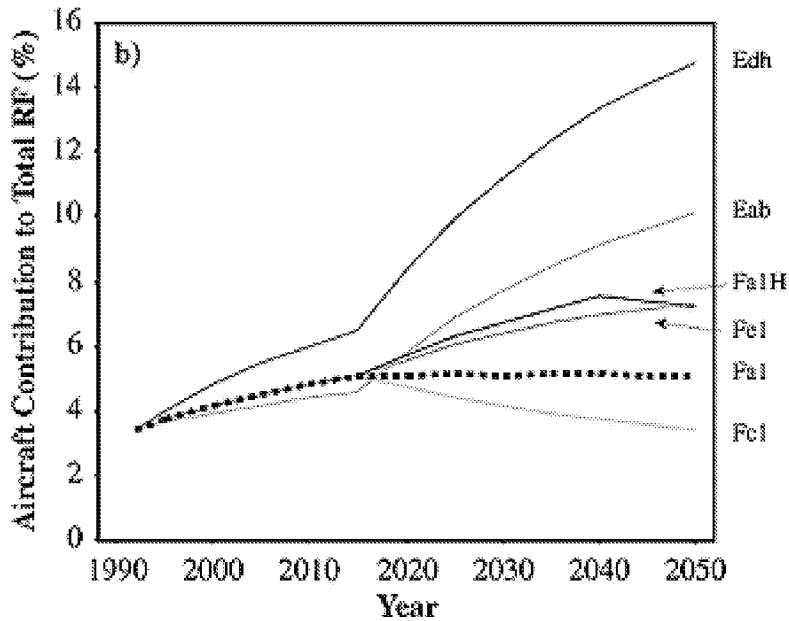


Figure 2. Past and projected aircraft contribution to radiative forcing (RF) (ref. 10).

(Edh, Eab, Fa1, etc. refer to different scenarios defined in reference 10, aircraft emissions were only estimated for 1990, 2015, and 2050 – values for other years were interpolated)

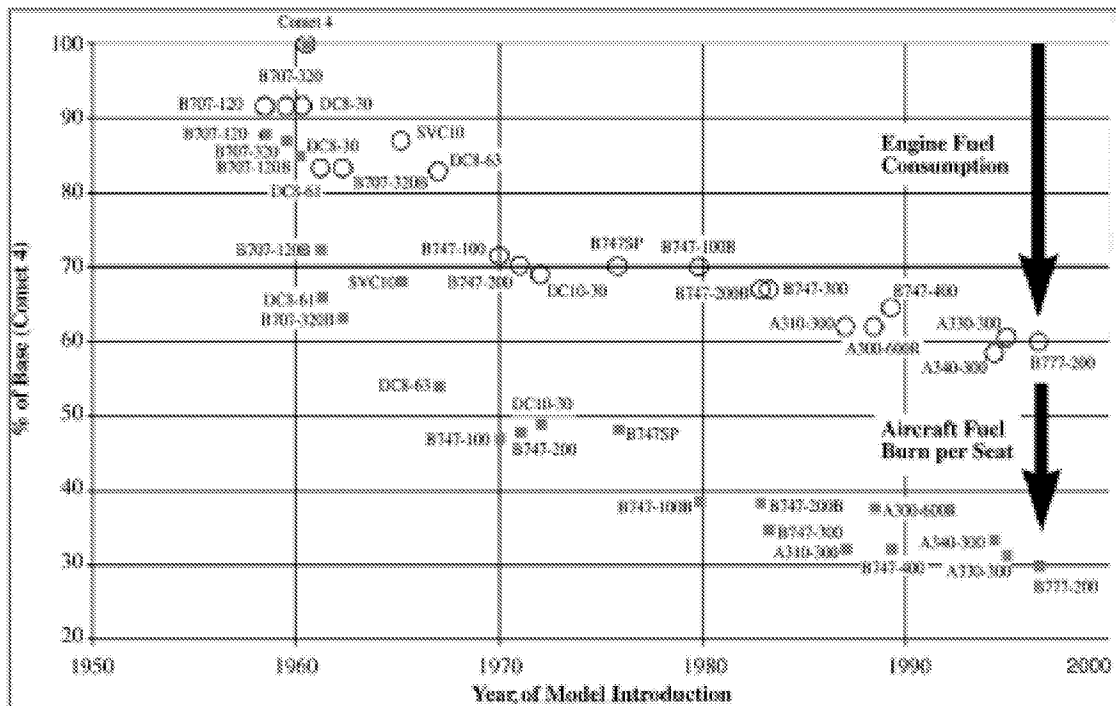
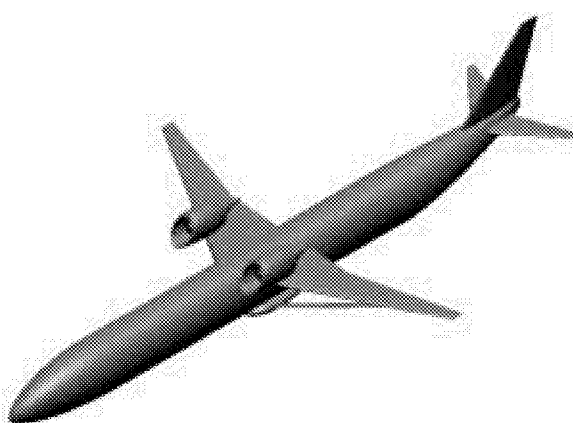


Figure 3. Historical trends in engine and aircraft fuel efficiency (ref. 10).



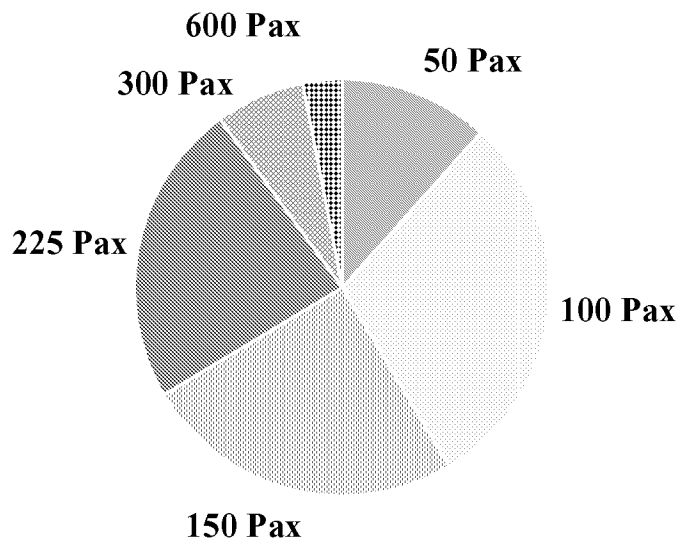
**Basic Concept**

- High bypass ratio  $H_2$  turbofan engines,  $LH_2$  fuel
- Over-wing engine placement
- Scarf Inlets
- Strut-Braced Wing airframe
- Steep approach ( $6^\circ$ )
- “Contrail Avoidance” cruise

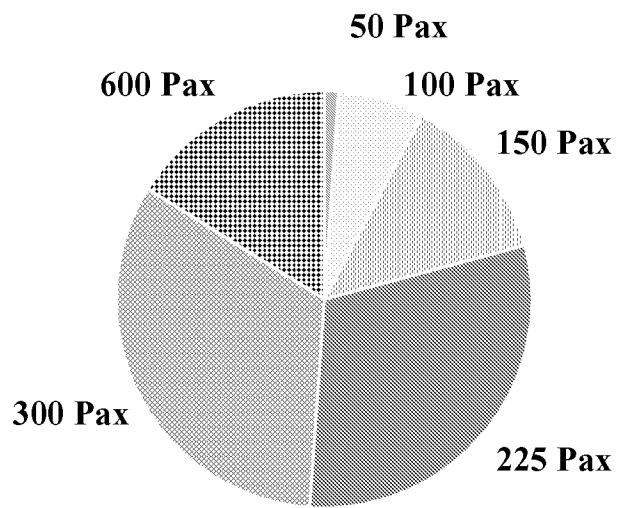
**Benefits**

- Elimination of aircraft emissions of  $CO_2$ ,  $CO$ , hydrocarbons,  $SO_x$ , soot
- Forward and aft noise shielding
- Increased wing aero and structural efficiency
- Reduced approach noise
- Potential to eliminate contrails

Figure 4. Quiet Green Transport Concept A description.



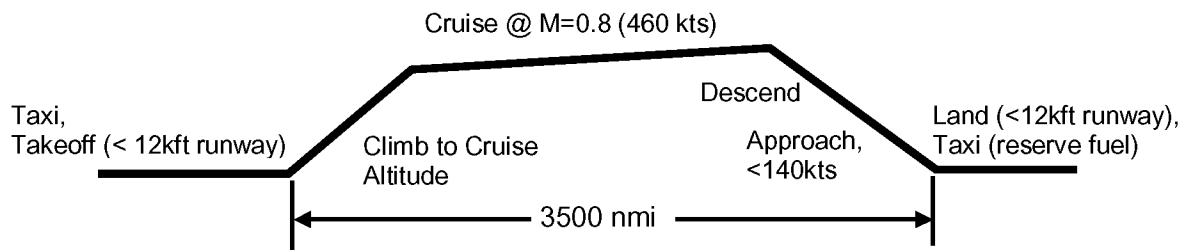
(a) Number of operations.



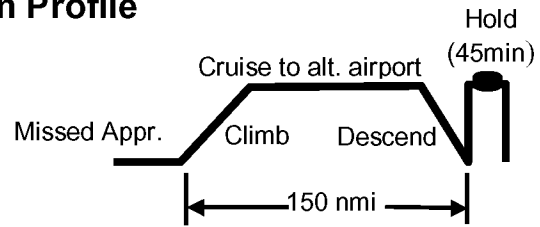
(b) Number of available seat-miles flown.

Figure 5. Projected aircraft fleet mix for 2025.





**Mission Profile**



**Reserve Segments**

Figure 6. Quiet Green Transport study mission.

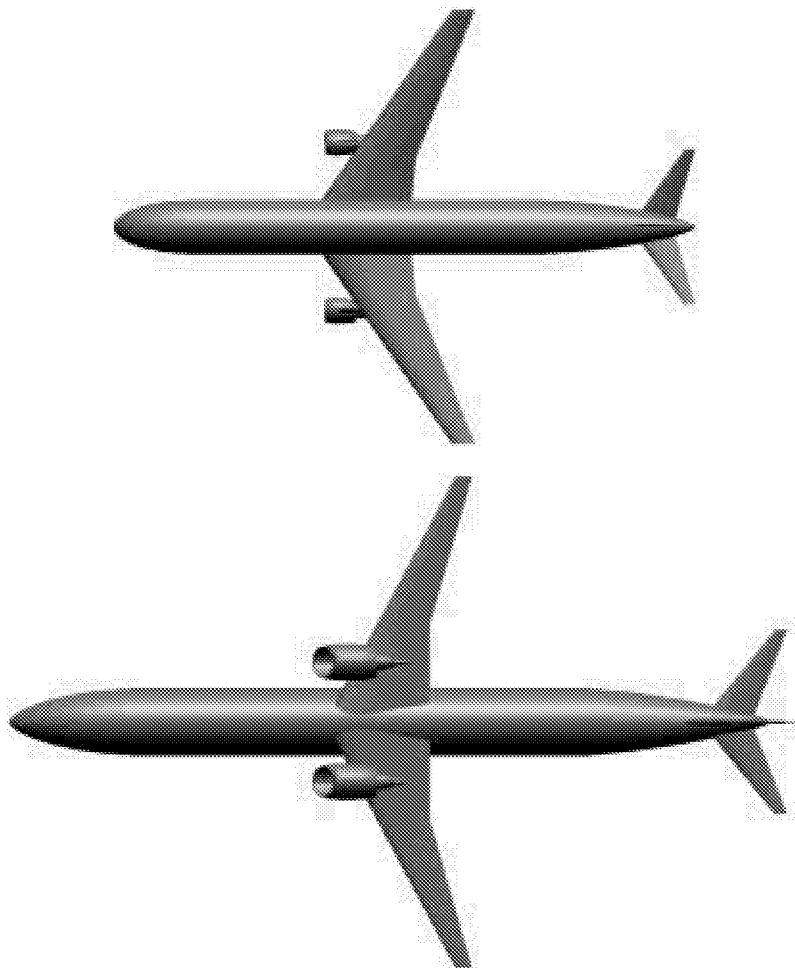


Figure 7. Size comparison of Concept A and conventional baseline.

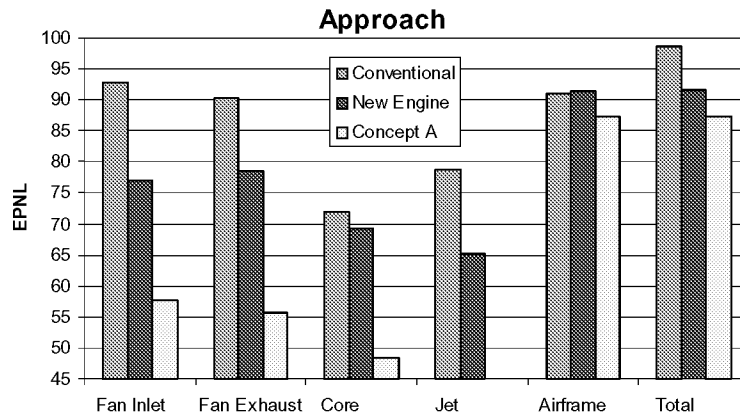
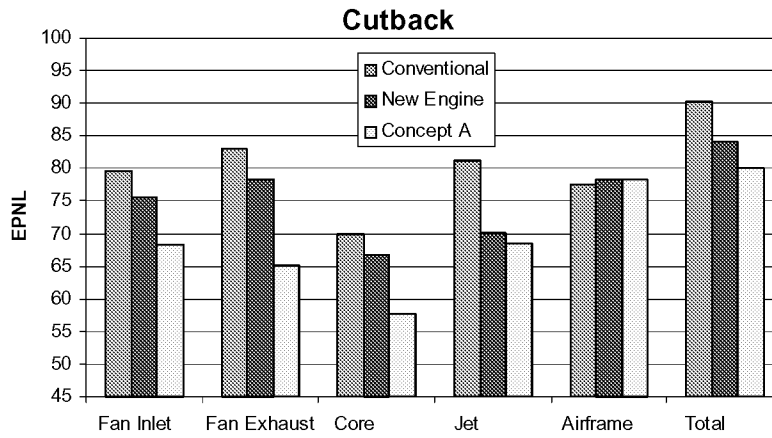
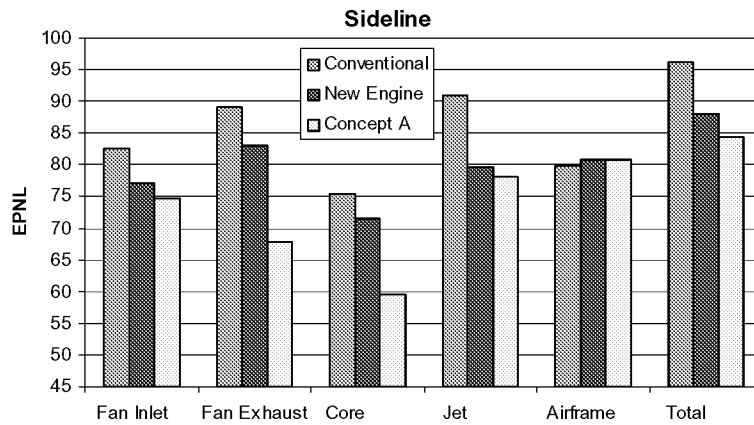


Figure 8. Calibrated noise predictions for conventional baseline, Concept A without configuration noise benefits, and Concept A with configuration noise benefits.

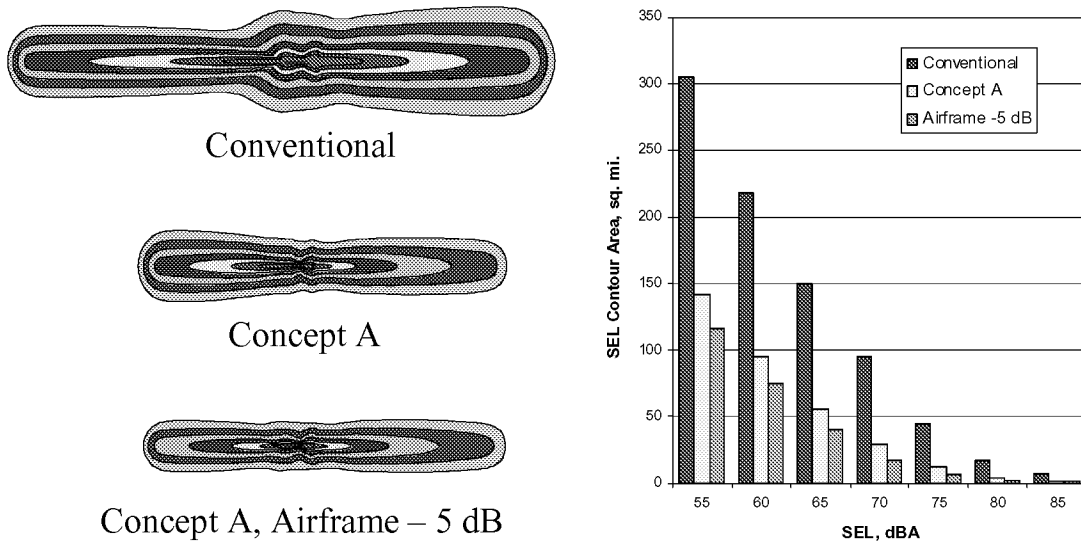


Figure 9. Single-event noise level (SEL) contours (55 to 85dBA in 5dBA increments) for conventional baseline and Concept A.

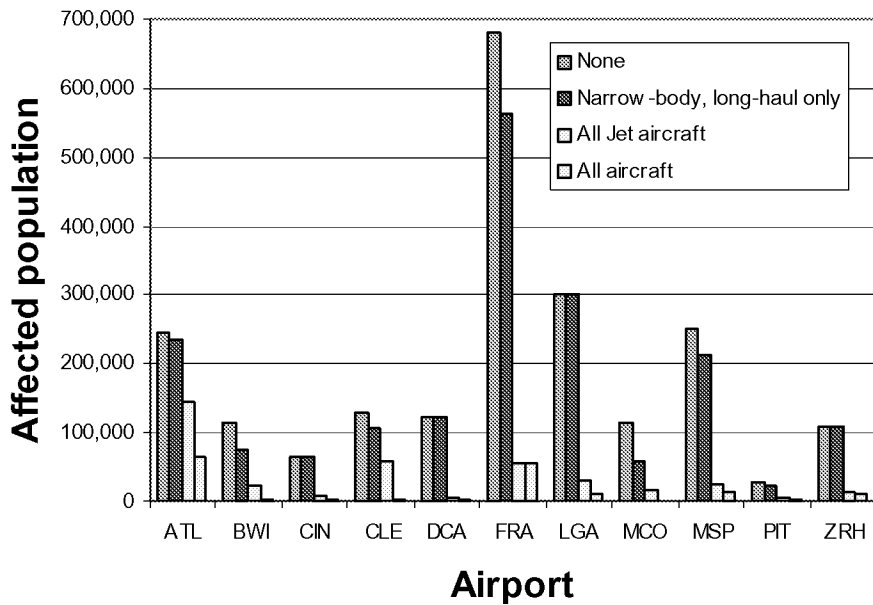


Figure 10. Population exposed to 55 dBA DNL in 2017 at 11 representative airports for various QGT fleet replacement scenarios.

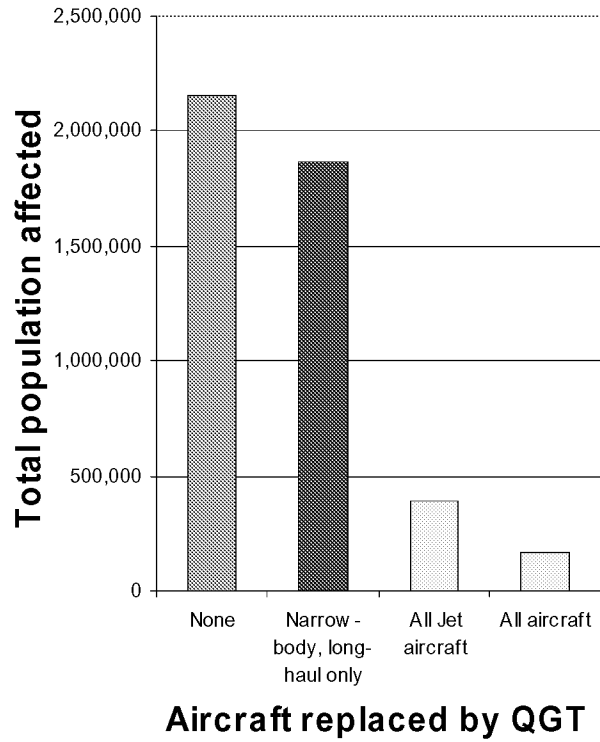


Figure 11. Total population within 55dBA DNL contours in 2017 at the 11 airports studied for various QGT fleet replacement scenarios.

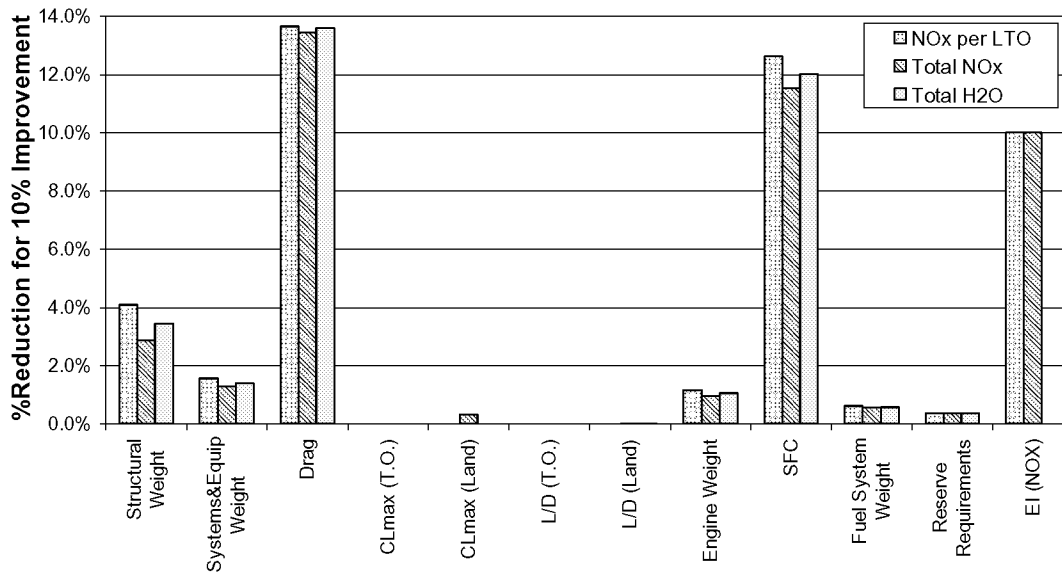


Figure 12. Sensitivity of Concept A H<sub>2</sub>O and NO<sub>x</sub> emissions to technology advances.

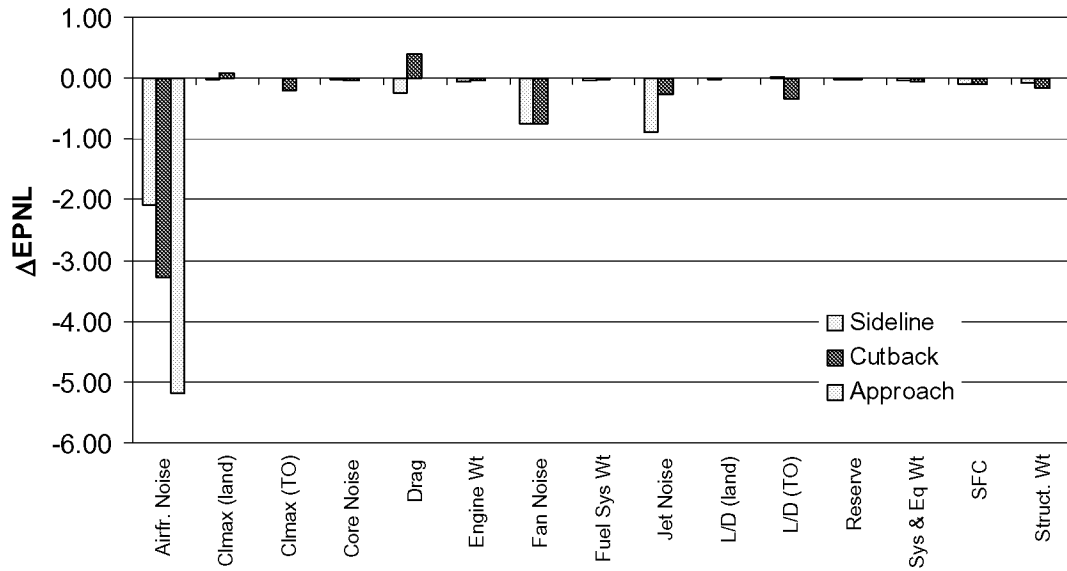


Figure 13. Sensitivity of Concept A noise characteristics to technology advances.

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13. ABSTRACT (Maximum 200 words) This report describes the analytical modeling and evaluation of an unconventional commercial transport aircraft concept designed to address aircraft noise and emission issues. A strut-braced wing configuration with over-wing, ultra-high bypass ratio, hydrogen fueled turbofan engines is considered. Estimated noise and emission characteristics are compared to a conventional configuration designed for the same mission and significant benefits are identified. The design challenges and technology issues which would have to be addressed to make the 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 seeks to develop revolutionary concepts that address strategic objectives of the NASA Enterprises, such as reducing aircraft noise and emissions, and to identify enabling advanced technology requirements for the concepts.			
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