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Silent Aircraft Initiative Concept Risk Assessment

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February 2008

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Abstract

A risk assessment of the Silent Aircraft Initiative's SAX-40 concept design for extremely low noise has been performed. A NASA team composed of subject-matter experts and systems analysts developed a list of 27 risk items, and evaluated the level of risk for each item in terms of the likelihood that the risk would occur and the consequences of the occurrence. The following risk items were identified as "high risk," meaning that the combination of likelihood and consequence put them into the top one-fourth of the risk matrix: structures and weight prediction; boundary-layer ingestion (BLI) and inlet design; variable-area exhaust and thrust vectoring; displaced-threshold and continuous descent approach (CDA) operational concepts; cost; human factors; and overall noise performance. Risk management strategies of either mitigation, avoidance, assumption, or transfer were recommended for each risk. In addition, several advanced-technology baseline concepts were created to serve as a basis for comparison to the SAX-40 concept. These comparisons indicate that the SAX-40 would have significantly greater research, development, test, and engineering (RDT&E) and production costs than a conventional aircraft with similar technology levels. Therefore, the cost of obtaining the extremely low noise capability that has been estimated for the SAX-40 is significant. The recommendation from this assessment is that the next iteration for this design should strive to achieve an appropriate balance among a variety of metrics, such as maintenance costs, fuel burn, emissions, and noise. The SAX-40 concept design proved successful in focusing attention toward low noise technologies and in raising public awareness of the issue.

1.0 Introduction

On November 6, 2006, a group called the Silent Aircraft Initiative (SAI) gave a public presentation to the Royal Aeronautical Society on research that was conducted over the previous three years. The research focused on producing a conceptual design for a fuel-efficient mid-range commercial transport that is inaudible outside of a typical airport boundary. The conclusion of the presentation stated that the group had achieved its goal of producing a credible conceptual design that meets the objectives of a functionally silent and fuel-efficient aircraft. Dubbed the SAX-40, this 215-passenger commercial transport concept has garnered a high level of attention, evidenced by both the large amount of press coverage associated with this particular briefing and the SAI effort in total. A Web survey yielded over 40 references in a few minutes (see Appendix A), including full-length articles in Aerospace Engineering and Aviation Week and Space Technology. The SAI team also presented their research at the 2007 Aerospace Sciences Conference in January 2007 to a standing-room-only crowd. Clearly, this research has resonated not only within the relatively small aircraft design community but has also caught the attention of a much broader public segment.

Within the NASA Fundamental Aeronautics Program, the Subsonic Fixed Wing (SFW) project has declared goals for reducing noise, emissions, and fuel burn relative to the levels found in today's commercial transports. Near- and far-term goals have been established, with the assumption that the near-term solution will resemble a conventional “tube with wings” approach, whereas the far-term solution will resemble a hybrid wing/body approach, widely known as the blended wing/body (BWB) concept. The SAX-40 is an example of this hybrid wing/body concept and is, therefore, aligned quite well with NASA’s far-term goals. Many of the technologies that have been utilized for the SAX-40 are highly relevant to NASA’s technology research portfolio.

Given the high relevance and large amount of public interest generated by the SAX-40 concept, an assessment was performed to gain additional insight into the feasibility of the concept and to identify the key enabling technologies to facilitate the development of NASA’s technology research portfolio. Therefore, this qualitative risk assessment was performed. A more detailed, quantitative technical assessment is a potential follow-on activity that may be performed if it is deemed worthwhile.

The next section provides background information on SAI and the SAX-40 concept. Then, the qualitative risk assessment process is presented. Then, the results of the risk assessment are summarized. One shortcoming of the SAI effort that was identified during this assessment was the lack of an advanced-technology baseline (ATB) design to provide a consistent basis for comparison. SAI was aware of this shortcoming and had considered including just such a baseline case, however, resource constraints prevented its inclusion. A NASA ATB was developed, and this effort is presented in the section following the risk assessment results. The final section contains conclusions and recommendations.

2.0 Nomenclature

M – Mach Number

M(L/D) – Mach times lift to drag ratio

σ – stress

*T*3 – combustor inlet temperature

x/c – location as a fraction of wing chord length

Abbreviations

ADS-B – Automatic Dependent Surveillance - Broadcast

AGMA – American Gear Manufacturers Association

AR – Aspect Ratio

AST – Advanced Subsonic Technology

ATB – Advanced Technology Baseline

ATC – Air Traffic Control

BLD – Boundary-Layer Diverter

BLI – Boundary-Layer Ingesting

BWB – Blended Wing/Body

CDA – Continuous Descent Approach

CESTOL – Cruise Efficient Short Takoff and Landing

CFD – Computational Fluid Dynamics

CML – Continuous Mold Line

CMT – Continuous Mold-Line Technology

DARPA – Defense Advanced Research Projects Agency

EIS – Entry into Service

EPNL – Effective Perceived Noise Level

FAA – Federal Aviation Administration

FEM – Finite-Element Model

GRC – Glenn Research Center

HIDEC- Highly Integrated Digital Electronic Control

HPC – High-Pressure Compressor

HPT – High-Pressure Turbine

IGES – Initial Graphics Exchange Specification

IGV – Inlet Guide Vane

LE – Leading Edge

LPT – Low-Pressure Turbine

MDO – Multidisciplinary Design Optimization

NAS – National Airspace System

N-S – Navier-Stokes

NTF – National Transonic Facility

OEW – Operating Empty Weight

OGV – Outlet Guide Vane

OML – Outer Mold Line

P & W – Pratt & Whitney

QAT – Quiet Aircraft Technology

R & D – Research and Development

RDT&E – Research Development Test & Evaluation

SAI – Silent Aircraft Initiative

SME – Subject-Matter Expert

SFW – Subsonic Fixed Wing

TE – Trailing Edge

TOGW – Takeoff Gross Weight

TRL – Technology Readiness Level

TSFC – Thrust Specific Fuel Consumption

UHB – Ultra-High Bypass

2D – Two-Dimensional

3D – Three-Dimensional

3.0 Background

The SAI project was launched by the Cambridge-MIT Institute in 2003 with an initial grant of £2.3M and was co-led by Professor Ann Dowling of the Engineering Department at Cambridge University and Professor Ed Greitzer of Aeronautics and Astrophysics at MIT (ref. 1). The objective of the project was to discover concepts to dramatically reduce aircraft noise to the point at which the noise would be imperceptible outside of the airport perimeter. The team was organized to emphasize a collaborative, multidisciplinary approach involving academia, industry, and government. The team proceeded through three major design evolutions, producing the SAX-10, -20, and, finally, -40. See Figure 1 for depictions of the three designs.

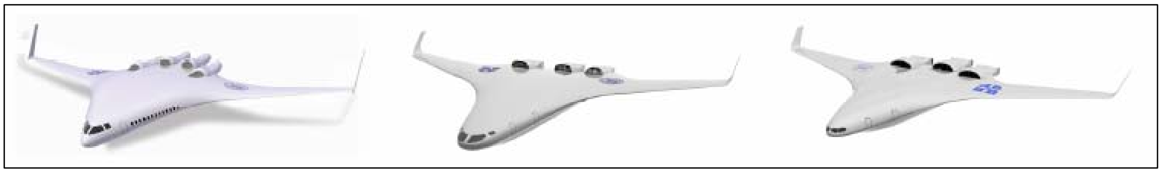

Figure 1. Three generations of the SAI conceptual design.

The first generation design, referred to as the SAX-10 (or SAX-12) was developed using an evolved version of a Boeing design tool called WingMOD (ref. 2). This concept was optimized by seeking minimum takeoff gross weight (TOGW) and utilized four "Granta-252" concept engines, which featured a geared low-pressure turbine (LPT) and boundary-layer diverters. This concept underwent a first round of industry nonadvocate reviews. The second generation, referred to as the SAX-20 (or SAX-29), benefited from a quasi-three-dimensional (3D) airframe design methodology and was optimized for low stall speed to reduce noise. The propulsion concept utilized three "Granta-3201" engine clusters with boundary-layer ingestion; each cluster included a single core that drives three fans through a gear and transmission design. This concept underwent a design review with Boeing and benefited from Boeing-led 3D viscous aerodynamic analysis. The final concept, the SAX-40, features an optimized outer wing that was optimized with 3D design methodology and a refined engine design referred to as "Granta-3401." The refined design retained the SAX-20 concept of three engine clusters, each comprising a single core that drives three fans, and focused on the design of the transmission system. The use of boundary-layer ingestion was retained as well. This concept underwent another round of industry nonadvocate reviews and is the concept that was presented to the public in the fall of 2006 and early 2007. References 3-8 provide a comprehensive description of the SAX-40 concept.

The SAX-40 utilizes a broad set of enabling technologies to meet its design objectives. The BWB planform provides engine noise shielding in the forward sector, increased low-speed capability, and efficient cruise performance. The high-lift system is designed to minimize noise and utilizes a deployable drooped leading edge (LE) and an advanced airfoil trailing-edge (TE) treatment. The large wing area and high angle of attack on approach eliminate the need for flaps. Takeoff and approach noise are greatly reduced through the combined use of faired undercarriage, quiet drag generation via increased induced drag, optimized takeoff thrust management, and low noise approach procedures. In addition, advanced propulsion technology is assumed in the form of the unconventional distributed propulsion concept of a single core that drives three fans. Three of these engine clusters are embedded in the aft section of the airframe and are fitted with variable-area, thrust-vectoring nozzles. The embedded engines are designed to ingest the boundary layer, thus increasing propulsive efficiency.

Clearly, a large array of advanced technologies have been assumed in the development of this concept. The risk assessment process is described in the next section, including the methodology that is utilized to characterize the level of risk that is present in this concept and to identify the highest risk areas to inform technology investment decisions.

4.0 Risk Assessment Process

Because many of the technologies that are mentioned above have been linked in the past to the BWB concept (e.g., noise shielding, embedded BLI engines, advanced high-lift systems), the risk assessment began with a literature search that was focused on the BWB concept. A large volume of material is available in this area, and the earliest references date to the mid-1980's. A BWB chronology was created (Appendix B) that summarizes approximately 60 BWB references that focus on system-level studies. Numerous other references were found that address individual discipline areas; however, to keep the effort manageable not all of these were included in the chronology. The results of this literature search indicate that the BWB configuration arose primarily as a result of aerodynamic considerations that were associated with the reduction of drag by minimizing wetted area. Consequent challenges in the areas of structures, propulsion, and stability and control have been the subject of a large research effort over the years. The BWB configuration has been considered for a wide variety of applications, beginning with a large (800-passenger) commercial transport, then a smaller (450-passenger) transport, and then, briefly, as a potential sonic cruiser solution. Shortly thereafter, the BWB was studied for its suitability as a large commercial freighter; as the basis for a family of various-sized commercial transports with high commonality; and as a military tanker, bomber, and cargo aircraft. For its application, SAI utilized the BWB configuration for a 215-passenger, low noise commercial transport, and indications are that the BWB is being considered for the role of a relatively small, high-value commercial package carrier. The BWB configuration appears frequently as a sample application problem for multidisciplinary design optimization (MDO) methodology development. Because of the lack of full-scale test data, validation is a major challenge, and relatively few system-level studies have been performed. Furthermore, few of these studies utilize advanced-technology baselines for consistent comparisons.

With the literature search providing context for the current effort, the next step was to define the risk assessment focus, that is, identify the risk to be assessed. The decision was made to assess the risk of the SAX-40 concept in meeting the SAI requirements. A sample risk statement would then be, "If the actual airframe shielding benefits are less than predicted, then attainment of the noise requirements will be jeopardized." A risk assessment includes an estimation of the likelihood of the risk statement being true and a characterization of the consequence if the risk statement is true. To perform this assessment, the SAI requirements were necessary to provide the team with a consistent basis for evaluation. A brief summary of the SAI requirements was developed in conjunction with the SAI team (see Appendix C). The noise requirement was identified as "the aircraft must be inaudible outside of a typical airport boundary." A goal value of 60 dBA was selected, and a typical airport boundary was defined in terms of distances from the sides and ends of the runway. A 2025 Technology Readiness Level (TRL) of 6 (i.e., a system or subsystem prototype is demonstrated in a relevant environment) was assumed for the SAX-40. As such, the known technology investments that are planned for the timeframe between now and 2025 may be used to reduce risk; however, if no known current or planned research efforts exist, then the 2025 technology level is assumed to be similar to today. The mission requirements called for carrying 215 passengers in a three-class configuration on a 5000-nm-range mission with a cruise speed of $M = 0.8$ and a reserve fuel that was adequate for a 200-nm divert and 45 minutes of loiter. Operational requirements included an approach speed of

60.8 m/s (118 knots), a continuous descent approach on a 3.9 degree glide slope, and a 1.2 km (3937 ft) displaced threshold on the runway. No explicit requirements were stated for emissions or costs; however, the general theme was that they should be no worse than competitor aircraft.

The next step was to identify a risk matrix and develop the appropriate definitions for the likelihood and consequence metrics. Figure 2 shows the risk matrix that was selected: a conventional five-by-five layout with low-, medium- and high-risk areas that are defined by green, yellow, and red, respectively.

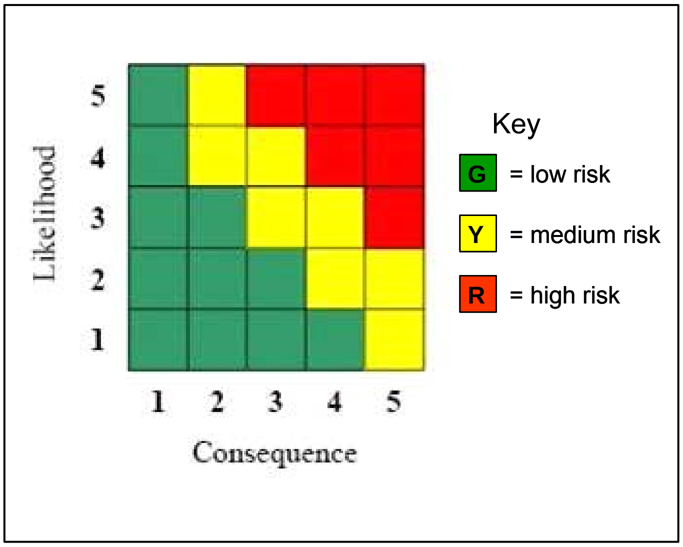

Figure 2. Five-by-five risk matrix.

The likelihood definitions ranged from not likely (rating = 1) to near certainty (rating = 5); the incremental steps between were low likelihood (rating = 2), likely (rating = 3), and highly likely (rating = 4). The consequence definitions were tied to the ability to meet the requirements. The consequences for each risk area ranged from minimal or no impact in meeting the requirement(s) (rating = 1) to unacceptable shortfall where less than 60 percent of the requirement(s) can be met (rating = 5). Incremental steps within this range are shown in Table 1.

Table 1. Definitions of Consequence Metrics

Consequence	
1	Minimal or no impact in meeting requirement(s)
2	Minor shortfall, ~90 - 95% of requirement(s) can be met
3	Moderate shortfall, ~75 - 90% of requirement(s) can be met
4	Significant shortfall, ~60 - 75% of requirement(s) can be met
5	Unacceptable shortfall, < 60% of requirement(s) can be met

Next, based on a review of the SAI-related literature and several working sessions, a list of 27 risk items was developed. The full matrix of risk items is provided in Appendix D. These risk items are summarized by group.

Propulsion:

Risk ID	Risk title
7	Boundary-layer ingestion/inlet design
8	Variable-area exhaust thrust-vectoring nozzle
9	Transmission system
10	Single-core/multiple-fan concept
11	Propulsion-airframe integration/buried engines
12	Low flight idle thrust
13	Low-speed fan with forward swept blades
14	High-pressure compressor design
15	Low noise low-pressure turbine design

Noise:

Risk ID	Risk title
16	Trailing-edge brushes
17	Low noise undercarriage
18	Quiet drag
19	Long ducts with acoustic liners
20	Airframe shielding
24	Overall noise estimates

Aerodynamics:

Risk ID	Risk title
1	Cruise aero performance
2	Deployable drooped leading-edge and continuous Mold-line elevons
3	Stability and control

Layout/Human Factors:

Risk ID	Risk title
5	BWB configuration: human factors
6	BWB configuration: internal layout

Operations:

Risk ID	Risk title
21	Thrust-managed takeoff
22	Displaced threshold and CDA with increased approach angle

Structures:

Risk ID	Risk title
4	BWB configuration: structures, weight
25	Aeroelasticity

Cost, Emissions and Experimental:

Risk ID	Risk title
23	Cost
26	Emissions
27	Experimental

Each of these 27 risk items was assigned to a subject-matter expert (SME). The SME was asked to review the relevant literature and provide an evaluation of the risk statement in terms of the likelihood and consequence metrics that are defined above. In addition, the SME's assembled a list of questions to be provided to SAI that would help to clarify assumptions and provide support for the evaluation (see Appendix E for the list of SME questions). Unfortunately, because of resource constraints, SAI was unable to provide any further clarification beyond the literature that has already been published. The inputs that were collected from the SME's contain descriptions and background information on the risk, an evaluation of the metrics and the rationale for the scoring, a recommendation on how to address the risk (either by avoiding, transferring, assuming or mitigating the risk), and references. The results were compiled and are presented in the next section.

5.0 Results

Figure 3 presents the populated risk matrix. The figure shows the number of risks that fall in each section of the matrix. As of this report, 25 of the 27 risk items have been evaluated (#3 Stability and Control and #25 Aeroelasticity were not evaluated because of lack of SME availability). Seven risks fell into the high-risk (red) area of the matrix, and another nine fell into the medium-risk (yellow) area. Before proceeding into a full-scale development effort, a prudent program manager would require that all high-risk and most medium-risk items be avoided, transferred, or mitigated into the low-risk area.

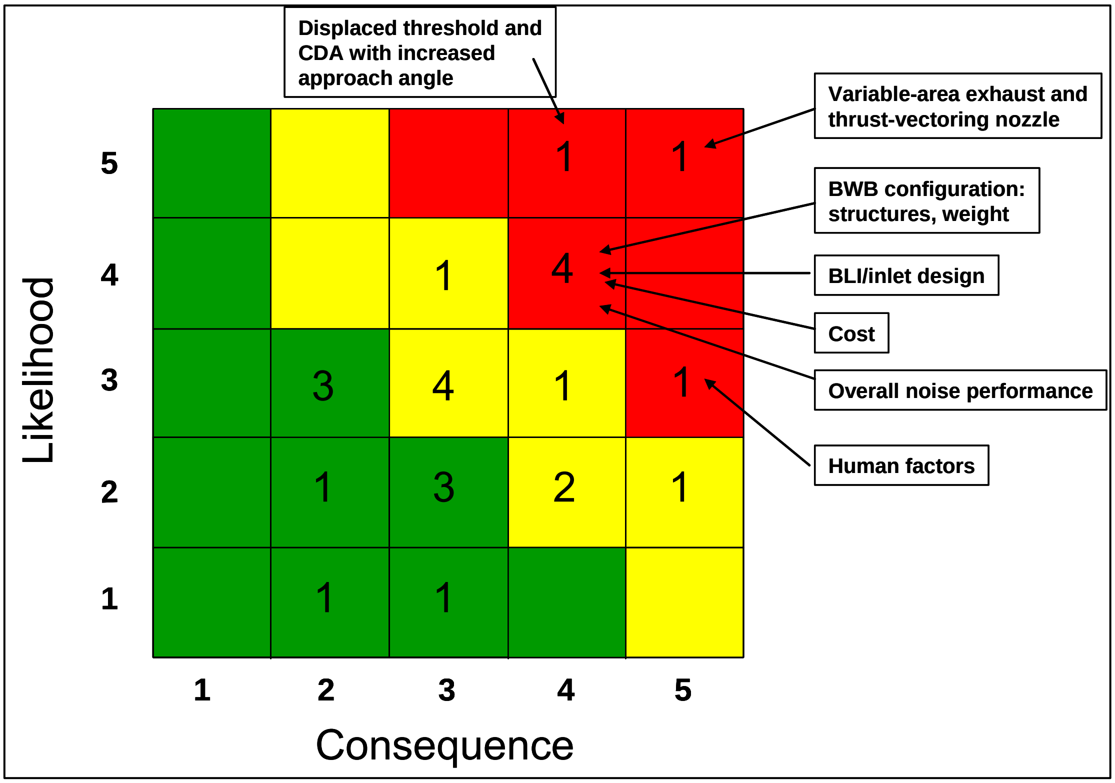

Figure 3. Populated SAX-40 risk matrix.

A brief discussion of each risk item follows.

5.1 High-risk items

5.1.1 Risk #8, Variable-area exhaust thrust-vectoring nozzle

Likelihood = 5, Consequence = 5

Risk statement: If the variable-area/thrust-vectoring nozzle performance is less than predicted, then attainment of the mission and noise requirements will be jeopardized.

Variable-area nozzle: At takeoff conditions, the aircraft requires a 45-percent increase in fan nozzle area (ref. 6). The movement of nozzle flaps for the purposes of changing both throat and exit area is technology that is routinely employed on high-performance military aircraft. Actuator sizes, as well as the upper and lower flap size and weight for an aircraft of this size (relative to high-performance military aircraft) may be significant, but the mechanical technology is off the shelf. State-of-the-art mechanical nozzle-area variation is approximately 20 percent (as compared with the 45 percent that is required by the SAX-40 concept). The integration aspects will be the issues that make or break such a concept because the use of these systems for high-bypass-ratio subsonic engines is uncommon. The items noted above, coupled with design issues such as actuator location, size, and weight, elevate the risk.

Thrust-vectoring nozzle: The same technology that is required to make area changes on the nozzle flaps can also provide the ability to vector the exhaust flow. The F-22 (± 20 degrees of vectoring) employs movable two-dimensional (2D) divergent flaps for both nozzle-area-ratio control and thrust vectoring. The differences here are the sizes and possibly the loads on very large flap systems and whether those actuation systems can be mechanically integrated into either the vehicle structure or the engine structure. This is mitigated somewhat by the lower operating temperatures and pressures of the high-bypass-ratio engines. Regardless, this is not a straightforward integration.

Additional risk is associated with the aeropropulsive interactions of trimming when vectoring nozzles occupy a large amount of the TE of the center wing. A vortex lattice method was used to determine the lift, drag, and moment characteristics; however, the vectored engines behave as jet flaps, and the literature is not clear on whether this effect was taken into account. This effect could be estimated by modifying the SAX-40 planform with extended TE flaps, but the literature contained no indication that this was done. Even at low idle, the effect on the lift, drag, and moment of the configuration could be dramatically changed, thus invalidating the force and moment balance.

Variable-area nozzle and thrust vectoring are critical aspects of the SAI strategy. The SAI team acknowledged that no mechanical design details exist for either the variable-area nozzle or the thrust-vectoring mechanisms. The SAX-40 aircraft will not meet performance and noise goals without the technology. Therefore, the risk associated with integrating a variable-area thrust-vectoring nozzle with the airframe must be mitigated.

Recommendation: Mitigate the risk.

Mitigation strategy: The variable-area nozzle and thrust-vectoring technologies are mechanically feasible. The risk arises from the integration of the nozzle and the actuators into the aircraft. To properly evaluate the integration of the nozzles into the airframe, detailed prototype designs must be evaluated. No design work has been performed on the nozzle system to date. The first step in mitigating this problem will be to initiate a contract with an engine manufacturer to propose and evaluate several candidate mechanical nozzle designs that incorporate a variable-area thrust-vectoring system.

5.1.2 Risk #22, Displaced threshold and CDA with an increased approach angle

Likelihood = 5, Consequence = 4

Risk statement: If the use of a displaced threshold and CDA with an increased approach angle have penalties, then attainment of the noise and operations requirements will be jeopardized.

A number of operational issues exist with the use of CDA approaches and a displaced threshold. An additional factor is the slow approach speed compared with that of conventional commercial jet traffic. The main issues are summarized here:

An approach angle of 3.9 degrees is not compatible with conventional traffic that uses 3.0 degree approaches. Current-day conventional air traffic control (ATC) procedures cannot mix like traffic (i.e., traffic in the same category, such as commercial jet transport) that are arriving at different approach angles.

An approach speed of 118 knots is as much as 28 percent slower than current commercial jet aircraft of similar size (ref. 4). Large differences in approach speeds make optimizing approach spacing difficult, and slower approach speeds reduce runway arrival rates. Future flight-deck-based technology designed to provide precise spacing capability could make this less of an issue, but runway arrival rates will still be reduced by slow approaches. The effect on runway arrival rates is estimated in reference 4:

"The loss of capacity due to an approach speed of 118 knots, the approach speed of the Silent Aircraft, could be between 5 and 20% depending on the traffic mix and buffer size."

Displaced landing thresholds reduce the safety margin for pilot errors and mechanical failures (e.g., brakes, reverse thrusters), and may not be compatible with existing taxiway exits, runway markings, lights, ramp accessibility, and so on. However, displaced landing thresholds have been successfully used at Frankfurt airport (for enhanced wake avoidance). The shorter landing distance of the SAX-40 mitigates these issues to some extent. Displaced landing thresholds cannot be used with the shorter runways at many smaller airports.

Instrument approach procedures would need to be developed for the unique approach path. This would require time for procedure development and certification, in addition to costs that might have to be partially absorbed by the sponsoring airline or airport.

The likelihood is low that SAX-40 operations, with a combination of significantly slower approach speeds, steep CDA descents, and displaced thresholds, could be successfully integrated with conventional traffic during peak hours at busy airports in current-day operations. A loss of 5 percent or more in capacity would not be acceptable during these periods, and this loss is one of the big obstacles to the acceptability of CDA's (even conventional ones that use standard glide slopes) in higher density facilities.

No issues are anticipated outside of peak operating hours, however. If the SAX-40 aircraft could make use of night operations (as a result of its quieter flight operations), use lower-density airports, or utilize a dedicated runway (which would require significant SAX-40 traffic to justify), many of the concerns expressed here could be alleviated.

Future technologies can potentially mitigate the current-day problem with mixing conventional and nonconventional approaches. Greater use of CDA's for conventional aircraft, perhaps with steeper glide slopes, is also possible in the future, but capacity loss as a result of the low-speed approach of the SAX-40 could still be a problem.

Assessing the risk that is associated with SAX-40 operation in future air-traffic environments requires extrapolation of the stage of deployment of technologies that are currently in the research and development phase. National Airspace System (NAS)-wide deployment of some of the enabling technologies, such as ADS-B (Automatic Dependent Surveillance-Broadcast) is imminent. However, some of the tools that would enable SAX-40 operations (such as airborne precision spacing in conjunction with custom CDA approaches) require several years of further research. In the far term, the unique operational profile of the SAX-40 aircraft potentially could be more easily accommodated.

Recommendation: Avoid the risk.

The aircraft should be designed to operate in the range of conventional jet-transport-category aircraft. If possible, retaining the slow-speed approach capability in addition to the conventional speed, for use at nonpeak times and less busy airports would be worthwhile if the additional cost is justifiable.

The aircraft should be designed so that using a non-CDA approach without displaced thresholds still provides a worthwhile noise reduction benefit. Thus, the aircraft can fly with conventional approaches into large airports at busy times with a mix of conventional jet traffic. At off-peak times or at less busy airports, the SAX-40 can use a slow-speed approach, CDA, and displaced threshold where runway length permits. The SAX-40 potentially could be used at night at some airports that have curfews or quotas on night operations.

5.1.3 Risk #4, BWB configuration: structures, weight

Likelihood = 4, Consequence = 4

Risk statement: If the SAX-40 structural and subsystem weights are greater than predicted, then attainment of the mission requirements will be jeopardized.

The SAX-40 center-body design is a noncircular pressure vessel, most likely with inefficient packaging of useful volume (i.e., cabin, cargo) within the vehicle outer mold line (OML). Accurate structural weight estimation of the primary structure (i.e., pressure vessel, wing) and the secondary structure (e.g., the structure between the pressure vessel and the OML) is a challenging problem. A number of the enabling technologies (ref. 5) that are necessary to achieve a viable design also pose some risk for structural weight prediction. The deployable drooped LE of the wing is an unknown contributor to both the structural and subsystem weight. Flap elimination will probably reduce the weight in comparison with traditional wings, but the large wing area may add more weight. Undercarriage fairings for noise reduction will add weight. Propulsion system integration with the airframe and distributed propulsion may reduce the weight. Analysis of the effects of the integration of engine acoustic liners within the airframe, structural analysis of the noncircular pressure vessel, and mechanical design of subsystems (i.e., thrust vectoring) were not performed. Fabrication and manufacturability (ref. 5) of noncircular pressure vessels and their impact on preliminary weight estimates are unknowns.

Empirical correlations have been used extensively to predict the SAX-40 weight ("…the structural weight calculation was based on empirical formulae, which yields a serious challenge…," ref. 9). A great deal of empirical data exists for the calculation of the weights of wings, tails, landing gear, and every other component on a conventional commercial aircraft. However, the structure of the SAX-40 has many differences from that of conventional commercial aircraft. The BWB design incorporates a noncylindrical pressurized cabin into the center wing, highly tapered outer wings, and large winglets with control surfaces at the wingtips. These structures are not modeled well by existing empirical fuselage and wing weight estimation tools. For this reason, several WingMOD (ref. 2) designs were used to produce a least-squares quadratic response surface model. This surface was then used to predict the structural weight of the SAI aircraft.

In the BWB (refs. 10 and 11) noncircular pressurized fuselage, the stress levels may be one order of magnitude higher than those for a conventional design (ref. 12). The high stress and weight problem that is associated with the BWB pressurized cabin can be explained by examining Figure 4.

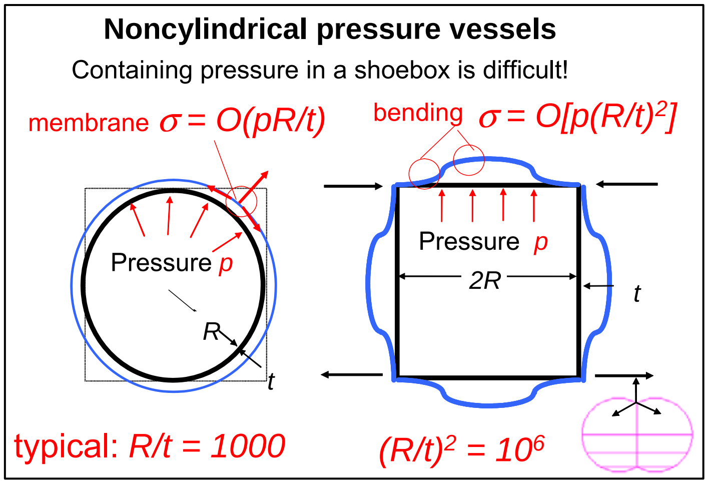

Figure 4. High bending stress associated with a noncylindrical pressure vessel.

Figure 4 illustrates both a cylindrical and a square-box fuselage under internal pressure *p*. In a cylindrical pressure vessel of radius *R* and skin thickness *t*, the pressure is resisted by uniform stretching; the resulting membrane stress is equal to *p*(*R*/*t*). In the BWB box-like fuselage, the nearly flat upper cabin wall resists the pressure by bending deformation. Let us model the flat upper cabin wall as a simply supported beam or plate of length *l*, with thickness *t*; then, the maximum bending stress is equal to 0.75*p*(*l*/*t*)2. If we assume that *R* is of the same order as *l*, then the bending stress is one order of magnitude higher than the membrane stress. The problem is aggravated by the nonlinear effect of the compressive load as it acts on the deflected beam or plate; hence, significant effort must be made to design an efficient structure with a minimal weight penalty that results from the noncylindrical fuselage.

Recommendation: Mitigate the risk.

Mitigation strategy: To obtain an efficient structure, one must increase the bending stiffness without increasing the weight. Several alternative concepts must be developed and compared to determine the best approach. The options include a deep sandwich shell with lightweight, high-strength composite skin or a stitched composite frame and stiffener construction. Durability, fracture toughness, and manufacturing issues play a major role. One manufacturing process that appears highly promising is the use of stitched composite technology. Additional options include the use of a multi-bubble or multi-lobe concept, as shown in the inset sketch in Figure 4. With proper design, the resultant adjacent bubble membrane stress could be balanced by tension in the intra-cabin wall. However, because of manufacturing concerns, the multi-bubble and deep sandwich constructions may be high risk. Significant research and development investment is required to develop and test these alternatives.

5.1.4 Risk #7, BLI and inlet design

Likelihood = 4, Consequence = 4

Risk statement: If the SAX-40 inlet design and use of BLI does not result in the predicted performance, then attainment of the mission and noise requirements will be jeopardized.

Several issues and concerns are associated with this risk item:

1. The SAX-40 literature has provided no indication that the SAX-40 employs inlet flow control to reduce distortion levels down to acceptable values. Numerous studies have suggested that for this class of subsonic inlets, where a thick boundary layer is being ingested and where the inlets are offset vertically and transitioning in geometry from a D shape to a circular shape, some type of flow control within the inlet duct is required to reduce distortion (ref. 13). The use of passive control devices (e.g., vortex generators), active flow control (e.g., jets), or a combination of the two have been used to achieve significant reductions in inlet flow distortion for this class of inlets. Without such devices, those studies have indicated unacceptably high levels of inlet distortion.

2. To complicate things further, the current propulsion system configuration has three main inlets with D-shaped apertures, each of which feeds three fans that are powered by a single core engine. The distortion characteristics of such a configuration are cause for concern, as referred to in item 1, as is the "sharing" of the inlet airflow amongst the three fans within each inlet duct. This sharing is of particular concern during crosswind and engine-out-climb operations and when one or two of the three fans are not operating.

3. The concerns expressed in items 1 and 2 relate to both dynamic distortion and steady-state distortion and, as a consequence, lead to additional concerns about high-cycle fatigue on the three-fan/duct system.

4. Finally, the required inlet flow-control devices will likely need to be integrated with the acoustic liners on the walls of the inlet duct. The aerodynamic performance of the flow-control devices and the acoustic performance of the liners may be affected by this integration and will need evaluation, as will the affect of the distortion on noise.

All previous studies point to the absolute need for some type of inlet flow control for boundary-layer ingesting, shape-transitioning centerline-curving subsonic inlets to mitigate steady-state and dynamic inlet distortion. With the added complication of each of the three inlets feeding three fans, the need for such flow control is probably even more necessary. By not including an inlet flow-control strategy in the current concept, the likelihood of unsatisfactory inlet performance is high. Other factors that add to the current high risk are the lack of consideration of high-cycle fatigue on the fan system and the effects of the interaction between flow control and the acoustic liners.

BLI is assumed to be of significant benefit to achieving improved engine propulsive and aerodynamic efficiency and, thus, reduced fuel burn. The current approach of seemingly ignoring the need for inlet flow control to properly manage the incoming boundary layer and, hence, provide acceptable levels of flow distortion to the fan system significantly increases the likelihood that the concept of BLI will not be successful and the benefits not achieved.

Recommendation: Mitigate the risk.

Mitigation strategy:

1. Consider appropriate inlet flow control devices and then perform computational fluid dynamics (CFD) studies to further develop the concept details for this highly complex inlet design.

2. Perform experimental verification of the resulting concept(s) in both low-speed (takeoff and approach) and high-speed (cruise) wind tunnels.

3. Demonstrate acceptable inlet performance (recovery, steady state, and dynamic distortion) to ensure the success of the concept.

5.1.5 Risk #23, Cost

Likelihood = 4, Consequence = 4

Risk statement: If the costs of developing, producing, and operating the SAX-40 outweigh the benefits, then attainment of the mission requirements will be jeopardized.

The BWB is not the typical “tube with wings” concept, so the cost of RDT&E will be relatively significant. Aircraft costs are historically highly correlated with weight. As shown in the next section regarding the development of an ATB design, the SAX-40 would likely outweigh the ATB by a significant margin (and, assuming SAX-40 feasibility, the SAX-40 would also be significantly quieter). Therefore, the RDT&E, as well as the production costs, will likely be relatively high for a significant portion of the life cycle of the vehicle. Some of these increased costs may be offset if airports assess noise fees or if night operations are increased.

Additionally, the engine placements above the wing, the fact that the engines are embedded in the airframe, and the fact that multiple engines and fans are used, will significantly impact the maintenance costs. Maintenance cost is a function of required labor hours and the amount of down time and turnaround time when the aircraft is on the ground and not serving customers. Several smaller engines and fans are more difficult to maintain than one larger engine because the many parts are smaller and harder to inspect. Because the engines are embedded in the airframe, the small, multiple parts are harder to reach, inspect, and replace when faulty. Finally, the SAX-40 engines are completely new technology and have a degree of complexity inherent to them, which makes the maintenance process more specialized and, therefore, more costly, at least for the first set of aircraft units.

Recommendation: Mitigate the risk.

If lower operating costs (because of lower noise and increased fuel efficiency) offset the increase in procurement and maintenance costs, then the SAX-40 concept may prove to be economically viable. Tradeoffs between performance and cost, as well as cash flow and life-cycle cost analyses, should be performed. Activity-based cost estimations should be developed for this type of unconventional vehicle to quantify the costs of new technologies, new maintenance procedures, and new material production.

5.1.6 Risk #24, Overall noise estimates

Likelihood = 4, Consequence = 4

Risk statement: If the overall noise performance is less than predicted, then attainment of the noise requirements will be jeopardized.

Although the SAI requirements were not stated in terms of certification noise, the implication is that the design would be certified to operate in the commercial airspace with existing and future aircraft. Therefore, several concerns are associated with this risk, primarily the following:

1. The noise calculations require changes to the operational rules in the terminal area (e.g., displaced threshold, use of a variable-area nozzle on takeoff) and also assume that “credit” can be obtained for those techniques during certification. Permission would have to be granted before credit for such procedures would be allowed; additionally, the likelihood that permission for a displaced threshold touchdown would be granted in typical air traffic scenarios is questionable at best. (Reference risk #22.)

2. The landing gear may not be “buildable.” (Reference risk #17.) No hydraulic lines are visible, and the fairing goes over the top of the wheels (like a car fender). Many design, fabrication, and operational issues are associated with this concept, including cooling, brakes, and so on.

3. No effective perceived noise level (EPNL) calculation details are available. If the likelihood of obtaining credit for the landing procedure alone is

questionable, then the likelihood of obtaining approval for the variable-area nozzle is even less. With the additional reduced benefits from a realistic quiet gear design, this risk is significant. If certification "credit" for the SAX-40 for either the displaced threshold landing or the variable-area nozzle on takeoff cannot be obtained and if the low-noise gear benefits are reduced, then a significant shortfall will exist with respect to the projected noise benefit.

Recommendation: Assume the risk.

Even if only two-thirds of the predicted noise benefit is achieved, the aircraft will still be relatively quiet. Additionally, even if credit for the variable-area nozzle is not given for certification, the capability potentially may still be allowed operationally, resulting in noise-reduction benefits to communities that are not reflected in the aircraft's certification numbers.

5.1.7 Risk #5, Human factors

Likelihood = 3, Consequence = 5

Risk statement: If the SAX-40 human-factors characteristics negatively impact the concept feasibility, then attainment of the requirements will be jeopardized.

Human factors comprises many elements, some that are interrelated and others that are independent. Specifically, human factors includes passenger acceptability, which can be defined as passenger comfort (e.g., windows, number of seats in a row between aisles), ride quality (e.g., wing loading, seat displacement from roll axis), internal noise, and vibration. Human factors also includes emergency egress and airport compatibility requirements.

The passengers are the ultimate customers; if they are not satisfied, they will not fly. Passenger comfort is a subjective metric and may be difficult to assess with confidence. Because the SAX-40 will have fewer window seats than a conventional "tube with wings" and may contain rows of seats with more than three adjacent seats between the aisles, human factor issues must be studied.

Ride quality is also subjective, because the SAX-40 has not been flight tested. One way to measure passenger acceptability is to conduct a public survey; however, if such data do not exist, a Web site forum can provide a feel for public reaction on a topic or concept. A current Flight International Web site discussion post indicates a distinct concern regarding ride quality in the public opinion (ref. 14). Some challenges in this area have also been identified in previous BWB studies. The general geometry of the BWB lends itself to an unsteady ride. The vehicle's inherent vulnerability to turbulence results from its low wing loading and the placement of all of the control power along the same surface. However, according to Liebeck (ref. 15) the ride quality of a 450-passenger BWB concept is not much worse than that of a conventional design. The analysis presented in reference 15 was performed using NASA Langley Research Center's motion-based flight simulator, but not much information was provided on the details of the test or the assumptions involved.

No analysis was performed on cabin noise or vibration levels. However, with the engines placed directly behind the passenger cabin and embedded in the airframe, these issues will have to be considered during design. Significant acoustic liner technologies will have to be implemented to reduce the reverberation of forward fan noise within the vehicle's structure.

Although the remaining two concerns relate to the passengers, they are subject to Federal Aviation Administration (FAA) regulations rather than passenger opinion. The first concern is the emergency egress regulation, which requires that all passengers be able to exit the plane within 90 s and that an emergency exit be located no further than 60 ft away from each passenger seat (ref. 16). The cabin size of the SAX-40 is less than 100 ft long and approximately 40 ft wide; thus, even if the emergency exits are located only in the front and back of the aircraft, the distance from each seat to an exit will be less than 60 ft (ref. 4). We can safely assume that, after the detailed layout of the cabin is known, simulations and algorithms can be used to optimize the layout to meet the egress requirements (ref. 17).

Airport compatibility requirements can be satisfied by the SAX-40 concept in terms of runway and taxiway separations. However, the airport design and gate operations will most likely require modifications to obtain optimal passenger boarding and aircraft servicing. Boeing proposed an x-shaped terminal for the large 800-passenger BWB (ref. 18). A similar or star-shaped terminal may also be appropriate for the SAX-40.

Recommendation: Mitigate the Risk.

Mitigation strategy:

1. Perform flight tests or high-fidelity flight simulations to ensure that the ride quality is acceptable.

2. Conduct a survey and simulations with test subjects to assess the cabin layout comfort level.

3. Execute an acoustic/vibration test to simulate the effects of embedding the engines and the effects of noise that is propagated through the aircraft structure both with and without acoustic liners. Ensure that the acoustic liner that is chosen for SAX-40 is sufficient.

4. Determine the level of airport modifications or adaptations that are required and the likelihood that the changes will be made.

5.2 Medium-risk items

5.2.1 Risk #1, Cruise aerodynamic performance

Likelihood = 4, Consequence = 3

Risk statement: If the SAX-40 cruise aerodynamic performance is less than predicted, then attainment of the mission requirements will be jeopardized.

The information used in this assessment was obtained primarily from two AIAA papers (refs. 5 and 19) that were prepared by the SAX-40 designers and from two Boeing proprietary internal presentations that summarize the CFD evaluations of the SAX-30 configuration and compare it with their BWB-450-1L vehicle (refs. 20 and 21). Supplemental information was obtained from interviews with the Boeing principal investigator on the project, as well as from a researcher from NASA Langley Research Center who was involved in the CFD design and testing of a BWB concept with a different propulsion installation.

The following items were identified as contributing to the uncertainty in the published cruise performance predictions, based on the methodologies used by the SAI team:

1) Limitations of the quasi-3D, linear, and inviscid aerodynamic analysis and design methods.
2) Lack of propulsion system in the aerodynamic predictions.
3) Lack of realism in wing load capability.
4) Propulsion-airframe integration and thrust/drag bookkeeping (ref. 3).

These concerns were in some cases addressed in a partial manner by the SAI team or by the Boeing studies but in general did not allow for a full quantitative assessment of the impact on the final vehicle performance. These concerns are discussed in more detail in the following paragraphs.

Based on the quasi-3D design methodology used by the SAI team, the SAX-40 vehicle has *M(L/D)* values of 20.1 and 18.8 at the beginning and end of cruise, respectively. Both of these values are higher than the *M(L/D)* requirement of 17.5 to meet the desired range. The SAI team recognized the limitations of the methodology and requested that Boeing perform Navier-Stokes (N-S) computations on the SAX-29 configuration. (The Boeing principal investigator thought that the configuration was that of the SAX-30, so this designation is used here for consistency with the Boeing references.) For this configuration, the *M(L/D)* value that was predicted by the CFD was 13 percent lower than the value that was calculated by the SAI team. Applying this same factor to the SAX-40 values reduced them to 17.5 and 16.4 for beginning and end of cruise, respectively, or an average of 16.9 or about 3.4 percent below the required value.

In the above calculations, both the quasi-3D and 3-D N-S computational models were for wing/body configurations with no propulsion system. For the Boeing 450-1L configuration, similar N-S computations were performed for the basic wing/body configuration with both pylon-mounted conventional nacelles and surface-mounted BLI nacelles. These computations (and subsequent high-Reynolds-number tests in the National Transonic Facility (NTF)) indicated that adding the BLI nacelles resulted in about a 4 percent drop in the *M(L/D)* relative to the baseline wing/body. Given the technical challenges that are associated with BLI nacelles, pylon-mounted nacelles may need to be used instead. This propulsion system integration approach is preferred by Boeing, and for their 450-1L vehicle the NTF tests indicated approximately a 7 percent penalty in *M(L/D)* relative to the BLI nacelles.

Note that the SAX-30 has TE closure angles that are at least twice as large as those for the 450-1L over the inner 40 percent of the span, even though the airfoil thicknesses are comparable in this region. Some of the original BWB configurations at Boeing (Douglas at that time) had large closure angles that led to flow separation when the nacelles were added. This effect contributed to the requirement for extending the central body region further aft to reduce the angles, even though it added wetted area. This extension appears to be one of the planform differences between the SAX-40 and 450-1L configurations that may need to be added into the SAX-40, regardless of which propulsion approach is used. The additional wetted area should increase the drag, but a quantitative estimate of the *M(L/D)* penalty was not attempted.

The final area of concern is the feasibility of using an elliptical spanload, especially because the outboard airfoils are approximately 10 percent thinner than those on the 450-1L. Several modern transports have a more triangular loading that increases the induced drag at cruise but is based on consideration of wing bending moment (and the resulting structural weight), as well as approach and high-speed buffet aerodynamic characteristics. The 450-1L design included a fairly detailed look at these areas and has the more typical triangular loading. Some of this difference is attributable to the undercut nose of the SAX-30 body, which provides a moment balance for greater aft and/or tip loading, but does not account for these other concerns. Note that the outer wing airfoils on the SAX-30 are strongly supercritical, with considerable aft loading. Achieving this loading requires a lower surface cove that results in reduced thickness near the aft end of the airfoil. For example, the thickness of the SAX-30 airfoil at 80 percent of the semispan and at an $x/c = 0.85$ is less than half of the thickness of the corresponding 450-1L airfoil at the same chordwise location. The high aft loading and thin airfoil section might prove unrealistic from a structural and control surface loading requirement. Although the Boeing studies did not individually address these items, some of the results inferred that shifting the spanload toward a triangular shape and using thicker airfoils with less aft-loading would reduce the *M(L/D)* by 5 to 10 percent. These results were obtained for the SAX-30 configuration, which appears to have the same basic airfoil and loading characteristics as the SAX-40.

The cumulative impact of these concerns suggests that a more reasonable estimate of the performance of the SAX-40 with the propulsion system installed, a more triangular spanload, and thicker outboard airfoils might fall 10 to 20 percent short of the desired *M(L/D)* of 17.5. Much of this deficit could potentially be recovered through the application of fully 3D, viscous design methods. Such methods could also be used to address the need to extend the body airfoils to reduce the aft closure angles to alleviate any flow separation that is related to propulsion/airframe integration.

Recommendation: Mitigate the risk.

Mitigation strategy:

1) Redesign the SAX-40 wing/body.
   a) Obtain the geometry for the current SAX-40 configuration and any design constraints, such as the cabin region and wing volume.
   b) Redesign the configuration using 3D CFD design methods.

2) Assess and redesign for aerodynamic/structural issues.
   a) Evaluate the off-design performance (e.g., buffet, approach) for the SAX-40 wing/body.
   b) Evaluate the impact of parametric variation in spanload, outboard airfoil thickness, and reduced airfoil aft loading on the performance of the SAX-40 wing/body.
   c) Perform detailed structural analysis to assess the adequacy of the current wing to handle the existing spanwise and chordwise loadings and make recommendations for loading and thickness changes.
   d) Redesign the configuration to meet these new constraints.

3) Assess and redesign for propulsion/airframe integration effects.
   a) Obtain the geometry for the SAX-40 with BLI and pylon-mounted (if available) nacelles installed. Integration of the pylon-mounted nacelles with 2D thrust-vectoring nozzles may be problematic.
   b) Assess the initial impact of the propulsion/airframe integration using 3D N-S analysis.
   c) Redesign the configuration by using 3D CFD design methods and the constraints from 2D body-extension airfoils, if necessary,

4) Perform wind-tunnel verification of the design.
   a) Fabricate the model from 3(c) for testing in the NTF.
   b) Conduct tests to evaluate cruise and off-design performance.

5.2.2 Risk #2, Deployable, drooped LE and continuous mold-line (CML) elevons

Likelihood = 2, Consequence = 4

Risk statement: If the deployable drooped LE and CML elevon performance is less than predicted, then attainment of the noise and operational performance requirements will be jeopardized.

The issues that are associated with the deployable drooped LE and CML elevons are:

1. Can these technologies provide the required high lift for takeoff and approach operations?
2. When deployed, will these technologies meet the noise requirements?
3. Will the skins, mechanics, and actuators required result in an effective and robust system?
4. Will the systems be able to meet weight constraints?
5. Can CML elevons, split elevons, and TE brushes be effectively integrated?

The "all lifting body" concept eliminates the need for TE flaps (refs. 4 and 8), which are a significant noise source, and results in a high approach angle of attack (refs. 11 and 22). A slow, steep aircraft approach profile is desirable for meeting noise-reduction goals (refs. 4, 19, and 23). A drooped LE is intended to enhance high-angle-of-attack performance (ref. 5) while providing reduced airframe noise characteristics. Although some efforts to fill a traditional slat cove have not resulted in the desired noise reductions (ref. 24), others have succeeded (ref. 25). Researchers are optimistic that further slat noise reductions are possible and that a drooped LE may not be required. Increased lift from the application of circulation control techniques can further decrease takeoff and touchdown speeds and increase departure and approach angles (ref. 9). Continuous mold-line technology (CMT) has been researched and developed for some time (ref. 26) and has been shown to effectively reduce high-lift system noise without compromising performance (ref. 25). Continuous mold-line link, a mechanically efficient, elastic structure that connects a deflected flap edge to the adjoining nondeflected wing, has been shown in wind tunnel testing to be a very effective technique for flap or slat edge noise reduction (ref. 25). Initial studies on TE brushes (ref. 27) have shown the potential for significant source noise reduction.

The ability to combine multiple quiet technologies and quiet operations provides an optimistic outlook for the success of attaining the quiet, high-lift operational goals.

Based on inputs from the noise research community, the indication is that the high-lift system noise goals should be able to be met for low-speed, high-lift takeoff and approach operations. Recent research on the noise that is generated from LE and TE high-lift systems has been promising. Drooped LE technology has already been developed and is currently being used on the Airbus A380. CMT and TE brushes are expected to satisfy the noise requirements. More of a challenge may exist in the development of the materials, structures, and mechanisms that are required for the CML high-lift systems. However, a CMT flight demonstration program has been completed for the Air Force (ref. 28), which has resulted in the maturation of a continuous control surface concept to a TRL of 5. The company Continuum Dynamics, Inc. (ref. 29), has demonstrated a continuously deformable shape-memory-alloy controlled airfoil section. Flexsys, Inc. (ref. 30), has successfully demonstrated flexible wing LEs and TEs in the wind tunnel environment. Some risk is associated with the ability to develop a complex split flap system that incorporates a CML capability and TE brushes. Several airframe manufacturers are working to further develop CMT, and meaningful progress is expected to continue to be made in these proprietary programs. The associated drag reduction that results from CML systems is another incentive for the continued development of this technology. The U.S. Air Force and the Defense Advanced Research Projects Agency (DARPA) are funding research on flexible material systems over the next few years; thus, further advancements are anticipated. Furthermore, stealth technology often has low noise attributes. Because of the military's ongoing interest in furthering the development of stealth technology, the evolution of additional acoustical benefits is likely to follow.

Recommendation: Two options deserve further consideration.

1. Transfer the risk: Because of the substantial ongoing efforts in the development of CMT in other research organizations, outside research programs may assume the risk in the development of a CML elevon. Similarly, efforts by military research programs to pursue improved stealth capabilities could lead to reduced risk in the achievement of the low noise requirements.

2. Mitigate the risk: A research plan that incorporates the coordinated assessment of aerodynamic high-lift performance, as well as the resulting acoustical performance, would be required. This assessment would involve the use of CFD to guide experimental wind tunnel verification testing. Iterations on the high-lift design would result, based on aerodynamic and acoustical performance results. Adequate trimmed lift also would be necessary for takeoff and approach. The design, fabrication, and demonstration of a split flap system that employs CML capabilities and TE brushes also would be necessary.

5.2.3 Risk #9, Transmission system

Likelihood = 3, Consequence = 3

Risk statement: If the engine transmission system performance is less than predicted, then attainment of the mission requirements will be jeopardized.

In general, the inclusion of a gearbox system on any aircraft engine increases the risk of system failure and overall engine maintenance and should be avoided whenever possible. An enlarged engine oil lubrication system and oil cooler are also necessary and will increase engine system weight. On the other hand, inclusion of a gear system can decrease overall system weight and improve performance and operability because of the improved speed matching of components. In some cases, the gear system can be used to reduce noise by reducing propulsor tip speeds. A number of aerospace vehicles, such as helicopters and turboprops, require the use of gearboxes. These systems have been in operation for many years, so the technologies involved are well understood.

The SAI transmission system is described in reference 6. While the design philosophy is outlined and the physical characteristics of the system are given, the actual results for efficiency are omitted, and the system weight is incomplete. Thus, evaluation of the design is difficult. Previous internal studies conducted at Glenn Research Center (GRC) (ref. 31) have shown that power loss can be considerable through multiple right-angle gearboxes. Subsequent discussions with Pratt & Whitney regarding gearbox efficiency calculations have shown that significantly different values can be obtained using different methods, creating uncertainty in the final results. Public references do not adequately demonstrate whether the SAI design is conservative or optimistic. However, a cursory analysis by Dr. Robert Handschuh indicates that some of the gear meshes in the selected SAI design may have been under-designed by as much as a factor of 2. Other poor design practices are also evident in the SAI report; however, with proper design this concept should be workable.

Recommendation: Mitigate the risk.

Mitigation strategy: Further design and analysis is needed to validate the proposed design options. Other design options are also available. The appropriateness of the design choices are not yet clear, as the analysis is incomplete. The following tasks should be undertaken:

1. Replicate the SAI designs using available NASA and American Gear Manufacturers Association (AGMA) design tools and determine their actual expected efficiency and weight.
2. Examine alternate engine layouts and power transmission options.

Because the overall design of the engine is highly dependent on the power transmission design, a feasible design must be used. The design trades made by the SAI team may be suspect as a result of this shortfall, leaving room for much more conceptual design work for ultra-high bypass ratio (UHB) configurations.

5.2.4 Risk #10, Single-core/multiple-fan concept

Likelihood = 3, Consequence = 3

Risk statement: If the single-core/three-fan concept performance is less than predicted, then attainment of the mission requirements will be jeopardized.

The SAI activity was a high-level conceptual study, that is, a point design look at what might be done to significantly reduce jet exit velocity. As in any conceptual design study, many design factors are reduced to simple correlations or models to assess the trend of the overall system. Because the configuration(s) under study are not well understood and differ considerably from a conventional architecture, these correlations/models may contain considerable unquantified error for this application. Additionally, some physical attributes of the system have been ignored for simplicity of analysis that may turn out to be significant in an eventual design. These are necessary risks that are associated with conceptual design.

Obviously, if the engine performance turns out to be significantly worse than predicted, the overall vehicle design could be compromised. A number of vehicle programs have been abandoned over the years when the propulsion system design did not meet the requirements.

Not all loss mechanisms have been accounted for in the SAI study. For example, nacelle/nacelle interactions, inlet corner flows, fan performance degradation due to distortion, and overall performance degradation due to the long noncircular inlet and nozzle duct. The sources and rationale for the engine weight analysis are unclear. Scaling effects are unknown. The capability of the primary performance degradation mitigation, which is the BLI installation, still needs to be tested in a practical design. Design changes will likely be required to meet operability requirements. Sufficient conservatism does not appear to have been used in the design process to account for all of the unknowns. Previous internal studies performed at GRC of similar configurations have shown relatively high performance penalties for such factors as inlet performance and gearbox efficiency.

The basic truth is that to reduce jet velocity a large volume of air will have to be moved, and a large amount of drag-inducing structure and weight will be required to move that large volume of air. The SAI is one of only a handful of studies that has looked at design options for UHB systems. Many more studies will be required to map the design space for these low noise aircraft. The SAI result represents only one of many possible design options. Research needs to be conducted to better understand whether the assumptions that have been made in this type of study are reasonable.

Recommendation: Mitigate the risk.

Mitigation Strategy: Key areas for further study include:

1. Distortion-tolerant turbomachinery, particularly the fans.
2. Increased pressure recovery S-duct inlets with distortion mitigation.
3. Power transmissions with improved performance and reliability.
4. Off-design component performance models.
5. Overall BLI performance.
6. Coupled vehicle/engine performance (needed for BLI).

All of these factors should also include scaling effects to better indicate where a given design characteristic fits in terms of the vehicle class.

5.2.5 Risk #12, Low flight idle thrust

Likelihood = 3, Consequence = 3

Risk statement: If the assumed low flight idle thrust is not feasible, then attainment of the noise and operational requirements will be jeopardized.

The source of engine noise during landing primarily results from the fan and the LPT. The use of a low idle thrust setting reduces the loading on the fan blades, thereby minimizing broadband and tonal noise. The airframe center body provides shielding of the forward-radiated engine noise; this noise is addressed through shielding and duct length. In addition, acoustic liners are used to attenuate rearward-propagating noise.

Engine design also reduces jet noise through two primary mechanisms. The first is to fully mix the core exhaust with a large amount of bypass flow from the primary fan, thereby lowering the jet temperature. The second mechanism is to minimize jet velocity through the engine thrust settings.

To produce the required thrust while keeping jet velocity low, the mass flow rate of each engine is increased by augmenting the flow with two additional fans. These auxiliary fans are driven by the LPT through a complex transmission with a gear ratio of 1. To maintain the operability of the fans over the entire mission profile, a continuously variable nozzle area is used. This variable-area nozzle allows the mass flow rate through the fan to change while keeping the fan pressure ratio within reasonable conditions.

In addition, the role of the engine is key during the landing approach; the engine works in conjunction with the airframe to provide stability and control. The nozzle provides thrust vectoring and is used to change the aerodynamic moment of the vehicle, which enables the aircraft trim settings that are described above.

During the entire landing profile, the engine speed is reduced to 45 percent to both lower noise and facilitate drag trim. This power setting is substantially lower than the conventional reduction to 60 to 70 percent of maximum engine speed for approach. An issue with the low spool speed occurs when a go-around maneuver is required or additional thrust is needed to compensate for weather. At 45 percent engine speed a significant lag occurs when engine power is increased, which could induce pilot error. A similar issue occurred during the initial years of the 727 aircraft (United flight 227), which was eventually alleviated by pilot training.

Several engine design issues are related to low flight idle thrust. First, the fan is the most critical component because it provides the majority of the thrust and affects other important engine performance parameters. In this configuration, with a variable nozzle in control of the fan conditions, the blading must be designed for off-design conditions. At low fan speed, this design may produce negative incidence on the outlet guide vane (OGV). Second, even though LPT blading is optimized to minimize noise, this source of noise is difficult to quantify and must be further evaluated. Third, the design of a transmission and cooling system for the multiple-fan configuration is challenging and must be assessed for its reliability.

The low spool speed is likely to be an issue for weather-related engine power needs and for go-around conditions. Training can alleviate the pilot error that can be associated with a late go-around call, but weather is more unpredictable. If weather causes pilots to manipulate engine power, the noise benefit will be reduced with no obvious substitutes. Weather is also a transitory event that may cause the noise target to be exceeded on relatively rare occasions.

Recommendation: Assume the risk.

Weather-related issues may cause problems, but these types of issues may not occur frequently enough to require mitigation.

5.2.6 Risk #16, TE brushes

Likelihood = 3, Consequence = 3

Risk statement: If the TE brush technology performance is less than predicted, then attainment of the noise requirements will be jeopardized.

Several concerns associated with TE brushes:

If the tips of the brushes are too thick, although the turbulent boundary layer (TBL) and TE noise would be reduced, TE bluntness noise could increase perhaps negating the benefit of the brushes.

TE brushes have been evaluated only in a laboratory environment. A number of concerns are associated with the TE brush buildability, maintainability, reliability, durability, and so on. At this point, TE brush technology will require significant maturation before implementation becomes feasible. Often during such a maturation process, benefits are lost to gain viability. TE brushes are currently at such a low state of maturity that it is unlikely that all of the benefit that has been demonstrated in the laboratory can be achieved on a real vehicle.

TE brushes only ameliorate one of the SAI noise sources, albeit an important one. The SAI assessments show that airfoil noise only dominates the overall aircraft noise levels well before the aircraft passes overhead; as such, the airfoil noise does not contribute to the highest EPNL levels that dominate computation of the certification noise level (ref. 4). Thus, much of the SAI noise benefits can be achieved even if the TE brushes do not perform as predicted as the technology matures.

Recommendation: Assume the risk.

Even if only some of the noise benefit of the TE brushes is achieved, the aircraft will still be a very quiet aircraft.

5.2.7 Risk #21, Thrust-managed takeoff

Likelihood = 2, Consequence = 5

Risk statement: If the thrust-managed takeoff is not viable, then attainment of the noise requirements will be jeopardized.

The departure profile is segmented into three parts—acceleration, roll, and climb—each with different conditions for engine control. During acceleration, thrust is maximized by controlling fan speed and nozzle area. The roll phase commences when the required velocity is achieved. At this point, engine control is based on maintaining constant velocity, which is a function of both thrust and drag. The third phase, climb, begins when sufficient lift is generated to exceed the takeoff weight. In this phase, control is based on constant velocity and maximum climb angle.

To meet the noise target, engine control alone is insufficient. Achieving the noise target will require coordinated control of both the airframe and the engine. Traditionally, engine control and airframe control are two separate entities that are governed by separate organizations. While this segregated condition is arbitrary, it is nevertheless a reality in present engine/airframe integration practices.

Although additional control law processing, sensing, and actuation will be required to implement thrust-managed takeoff, this implementation is not deemed to be beyond the capability of present control-system technology. However, a more holistic approach to control system architecture (e.g., the open systems approach that is advocated by distributed control methodologies) would be beneficial for both the airframe and engine systems.

For noise mitigation during vehicle takeoff, the entire approach to control is different than traditional practice. Noise performance requires integrated airframe and engine control but is not beyond the bounds of current technology.

Recommendation: Mitigate the risk.

Mitigation strategy: The recommendation for thrust-managed takeoff is to mitigate the risk by conducting the necessary additional research into integrated vehicle control. This additional research entails the development of new control architectures that reduce the impact of integrating the engine and airframe by creating functional elements with standardized interfaces for both hardware and software. Work that was performed for the

NASA F-15 Highly Integrated Digital Electronic Control (HIDEC) experiment should be reviewed for applicability to this risk.

5.2.8 Risk #26, Emissions

Likelihood = 2, Consequence = 4

Risk statement: If the emissions characteristics of the SAX-40 are undesirable, then attainment of the mission requirements will be jeopardized.

Based on the SAX-40 literature, the estimated emissions reductions for the silent aircraft concept were expected to result from decreased fuel burn. To improve efficiency and reduce fuel consumption, the overall pressure ratio of the SAX-40 engines is 48.8. This value is higher than that of current engines and will cause an increase in the combustor inlet temperature $T3$, which will increase the NO_x emissions index (i.e., grams of NO_x emitted per kg of fuel consumed). The combustion system was not addressed in the SAX-40 literature.

The assumption is made that the emissions were calculated using empirical correlations; however, no information on the calculations was provided. The lack of information makes it difficult to judge whether the calculations are reasonable and whether the increase in NO_x emissions that results from the increase in $T3$ is mitigated by the decrease in fuel burn.

The apparent use of a standard combustion system reduces the risk because an advanced low-emissions combustor does not need to be developed. However, we cannot assume that all of the emissions benefits can be realized through fuel savings alone. If the increased pressure ratio causes a substantial increase in the NO_x emissions index, then this effect may offset the reduced fuel consumption benefit.

Recommendation: Assume the risk.

5.2.9 Risk #27, Experimental

Likelihood = 3, Consequence = 4

Risk statement: If the attributes (e.g., assumptions, approximations, scaling) of any of the experimental investigations that were conducted in support of the SAX-40 concept are questionable, then attainment of the mission requirements will be jeopardized.

The phased microphone array work that was presented by the SAI team is reviewed in this section. The phased microphone array design is detailed in reference 32, which describes the design process and the initial testing. The microphone array design consists of prepolarized condenser microphones for which the protective grid over the diaphragm has been removed. These microphones are sensitive for a range of 10 Hz to 40 kHz with correction. Electronically, the array was designed to measure two frequency ranges (650-6500 Hz and 5-50 kHz) and was flush mounted to the tunnel floor. The array was designed specifically for the Markham Wind Tunnel at Cambridge University, which is a 5.5-ft by 4-ft closed-circuit subsonic tunnel with a maximum free-stream velocity of 60 m/s. Initial testing of the microphone array was conducted using various techniques (e.g., loudspeaker and thin cylinder); the vortex-shedding tonal noise that was generated by a NACA 0012 airfoil was measured as well. All of the measurements and beam-forming results agreed well with the predicted values. In addition, the data analysis methods (i.e., the CLEAN algorithm (ref. 33)) were developed to quantify the noise levels and eliminate the side lobe contributions.

This phased microphone array design was used to test various individual components of the SAX-type aircraft. Major tests included investigating the airfoil LE high-lift geometries and support (ref. 34), quantifying the noise components that are associated with landing gear (ref. 35), and determining the acoustic differences between rough and smooth surfaces (ref. 36). These results were used for a variety of design modifications. For example, the support brackets were the major source of noise for the LE geometries, and the slat was a significant source of noise overall. Experiments on the landing gear demonstrated a 12-dB reduction in noise when a simple landing gear that contained only main struts was used.

The design seems to be well-suited for the Markham tunnel and has been validated by using conventional measurement techniques. However, this design was customized for the Markham tunnel; thus, issues may arise if experiments are performed in another facility. Several of the numbers that were quoted by the SAI team appear to have come from these experiments using this phased microphone array, and without this array (or a comparable system), noise measurements would be suspect at best.

Recommendation: Assume the risk.

5.3 Low-risk items

5.3.1 Risk # 6, BWB configuration, internal layout

Likelihood = 1, Consequence = 3

Risk statement: If the SAX-40 configuration layout does not result in a feasible design, then attainment of the requirements will be jeopardized.

The internal layout of the SAX-40 concept is presented on page 10 of reference 5. The cabin, cargo bay, fuel tanks, and landing gear are placed within the SAX-40 OML in a 2D representation. The cabin density is 0.9 passengers/m^2, compared with 1.4 passengers/m^2 for the Boeing 767; thus, the available internal volume for the SAX-40 is more than adequate. In fact, 335 passengers could be carried by the SAX-40 if the density factor of the 767 was utilized (ref. 5). In addition, BWB configurations tend to have abundant volume; thus, internal layout and packaging requirements are not typically design drivers as they can be for a supersonic transport configuration, for example.

However, to provide a first-order assessment of this risk item, a 3D layout was developed utilizing Pro-Engineer.™ Starting with the initial graphics exchange specification (IGES) file provided by SAI, the cabin, cockpit, galleys, restrooms, fuel tanks, cargo bay, retracted landing gear, and major bulkheads and frames in these areas were sized and placed within the OML. A high-density seating arrangement of 335 passengers was used, which corresponds to the current seating density of the 767. Figure 5 shows that the SAX-40 can easily accommodate the design load of 215 passengers.

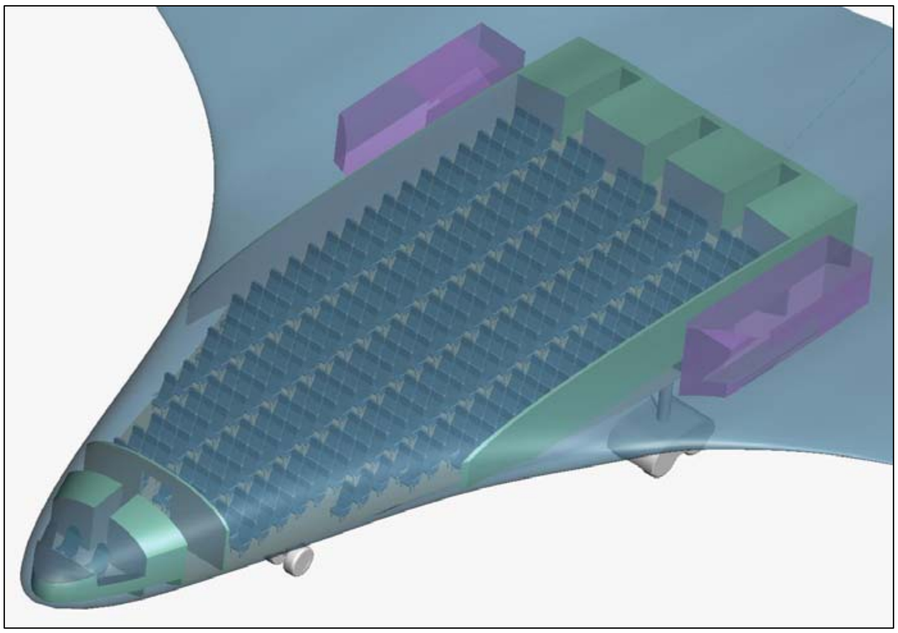

Figure 5. Sample 335-passenger layout for volumetric sanity check.

The large cubes that are situated in the rear of the passenger cabin represent the volume that is required for the galleys and restrooms. The rectangular volumes that are located outboard from the seating area show the required fuel tank size. A large volume clearly exists in the wings for additional fuel, as pointed out in reference 5. However, any additional fuel would increase both the weight empty and the gross weight of the vehicle, which would have a negative impact on the noise performance. Figure 6 shows the geometry of the landing gear retraction. Again, adequate volume is available.

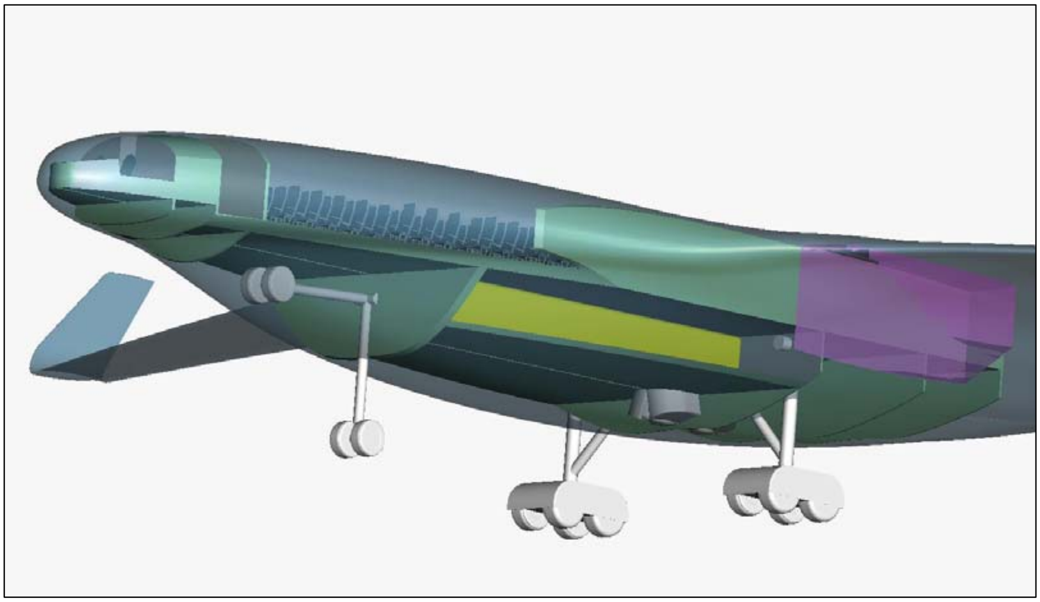

Figure 6. Landing gear retraction geometry.

Based on the 3D modeling, issues with the internal packaging of this design are not likely. The BWB configuration in general, and the SAX-40 concept in particular, have relatively large amounts of internal volume. Should a packaging issue arise, however, the consequences would not be minor. Major redesign of the components or OML changes would be required. These changes could easily compromise the attainment of the mission requirements by 10 percent or more.

Recommendation: Assume the risk.

5.3.2 Risk #11, Propulsion/airframe integration: buried engines

Likelihood = 2, Consequence = 3

Risk statement: If the buried-engine concept presents propulsion/airframe integration issues that cannot be resolved, then attainment of the mission requirements will be jeopardized.

This risk item is closely coupled with risk items #7, BLI /inlet design, and #10, Single-core/multiple-fan concept. Because these two risk assessments are dealt with separately, the current assessment of risk item #11 is addressed only from the propulsion/airframe integration point of view as it relates to burying or embedding engines within the airframe. Aside from the well-known problem of inlet distortion, which is covered in risk item #7, the following issues or concerns are identified:

1. Engine-out impact on overall vehicle aerodynamics and controllability: Critical engine failure effects were recognized in terms of thrust loss and increased drag (refs. 3 and 8). Because the three-fan/single-core propulsion system is closely coupled with external aerodynamics, an outboard or even a center engine failure may cause a reduction in airframe lift, especially near the vehicle aft area, and may interfere with the vehicle stability. In addition, the effect of flow disturbance from the failed engine on the other engines must be studied to minimize impact to overall vehicle performance. For the case of uncontained engine-blade failure, the likelihood of adjacent engine failure as a result of failed blades must be considered because of the proximity of these engines to one another.

2. Engine maintenance: The installation and removal of a three-fan/single-core engine may be difficult and time consuming because of the interconnected fan gearing system; the long and shape-changing (axisymmetric to 2D) nozzle duct; and the relatively high location of the engines with respect to the ground (ref. 37). For example, on the Lockheed L-1011, the center-engine installation and removal from the rear fuselage was known to be problematic.

3. Possible interruption of rear structural spars as a result of the embedded engines: Embedding engines within an airframe has not been a major obstacle, based on historical vehicle configurations such as the Northrop YB-49, B-2, and small fighters. However, applying the concept in commercial vehicles may introduce additional difficulties in terms of vehicle operations and support.

4. Engine noise propagation to the passenger compartment: As a result of the engine casing contact with the airframe structure, noise propagation to the payload area, as well as acoustically induced structural fatigue, are expected. The engine-fan gearing system will further increase the likelihood of both noise propagation and structural fatigue. The problem can be mitigated through the use of both sound insulating material and a heavier structure.

5. Variable nozzle strike at takeoff: For conventional vehicles, a number of tail strikes result from pilot over-rotation. In operational situations such as vehicle payload loading, incidents of tail strikes have resulted from imbalanced payload loading. In the case of the SAX-40, variable nozzles are extended beyond the vehicle tail area, making damage to flight-critical and expensive variable-nozzle hardware a possibility.

6. Integration of active/passive/hybrid flow-control devices with inlet duct: As a result of the extended acoustic liners along the long inlet duct, the integration of active or hybrid flow-control devices may not be trivial.

7. Passenger egress with embedded engines: This issue is not seen as a major problem; the structure can be designed to accommodate passenger egress between and under the engines.

8. Insufficient control surfaces as a result of the unusually wide propulsion system: If thrust vectoring is employed to augment control surfaces, this problem may not be critical.

9. Thrust reverser: The three-fan/single-core combination thrust reverser may be mechanically complex and may exhibit unusual pitching moment if the thrust is directed upward.

10. Long, acoustically treated inlet and nozzle ducts: These components will reduce the overall propulsion system performance.

11. Water, snow, and ice ingestion.

12. Pre-flight inspection requirements.

The major issues and concerns are related primarily to vehicle operation rather than the technical aspects of the aircraft. From the technical point of view, no major problems prevent development of such a propulsion/airframe integration concept. Maintenance and operational issues are somewhat more complex than for conventional aircraft, but these could be considered as the “price to pay” for an extremely low noise aircraft. In regard to the vehicle safety issues that are associated with an uncontained engine blade burst, this risk could be minimized with newly developed technology and the use of redundant structure (e.g., extra containment material near the engine core).

Recommendation: Mitigate the risk with typical developmental activities that are performed in support of the detailed design.

5.3.3 Risk #13, Low-speed fan with forward swept blades

Likelihood = 3, Consequence = 2

Risk statement: If the fan performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.

The embedded-engine configuration places the fan into a highly distorted inlet flow condition during the entire operating envelope. The highly distorted flow in the circumferential direction at the fan face can have a detrimental effect on fan efficiency and surge margin (i.e., operability). If the fan performance predictions and tolerance to distortions are not as predicted by the analyses, the engine thrust and specific fuel consumption may be detrimentally affected.

We already know that an embedded fan experiences circumferential flow distortion at the fan face. We also know that this distortion reduces the aerodynamic efficiency of the fan and also can have a negative impact on its stall margin. We need to determine the magnitude of reduction in efficiency and operability that results from inlet distortion and the effect that this has on the overall engine cycle. High incidence on the OGV's is an additional factor that can reduce overall fan performance at several engine operating conditions.

Because most of the engine thrust is dependent on the performance level of the fan, fan performance has a significant effect on meeting the overall engine requirements. The expected outcome of the inlet distortion could possibly result in reduced overall engine performance between 1 and 10 percent. However, this reduction in performance can be minimized by the development of inlet-flow-distortion mitigation technology. The incidence on the OGV may be mitigated with the use of flow control with plasma or flow injection techniques that would need development.

Recommendation: Mitigate the risk.

Mitigation strategy: The inlet distortion issue can be mitigated by executing a technology development plan that includes the following necessary events:

1. Conduct analysis of specific engine configurations with thermodynamic engine cycle studies.
2. Create a conceptual design of the embedded engine, including the inlet and fan design. This task should include input from engine manufacturers.
3. Perform CFD analyses of the inlet and fan at several operating points to determine quantitatively the effects of distortion on fan efficiency and operability, as well as incidence effects on the OGV.
4. Determine analytically (CFD) whether flow distortion mitigation techniques, such as flow control, could be effective at reducing the fan face distortion with minimal negative impact on the engine cycle. The same techniques need to be applied to the OGV to reduce separation as a result of high levels of incidence.
5. Validate the analytical results by rig testing the embedded fan and OGV at several engine operating conditions.

5.3.4 Risk #14, High-pressure compressor (HPC) design

Likelihood = 3, Consequence = 2

Risk Statement: If the HPC performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.

The circumferential flow distortion that is experienced by the embedded fan does not in most cases completely mix out and; thus, this distortion propagates through the fan and results in some flow distortion into the core compressor. In addition, the static pressure at the fan exit is not uniform, which may cause additional unknown effects on compressor performance. The magnitude of the distortion at the compressor inlet is not constant and can change significantly depending on aircraft maneuvers during the flight envelope, crosswinds, and engine-out conditions. Varying levels of boundary-layer thickness at the fan face can result in large swings in the corrected mass flow rate into the core compressor and can cause a compressor surge. The reduced-pressure-ratio fan places an additional burden on the core compressor to provide an even higher pressure ratio to compensate for the reduced-pressure fan. A highly loaded high-pressure compressor is likely to be more sensitive to small levels of inlet distortion and will have reduced operability compared with one that has an undistorted inlet flow. Compressor inlet flow distortion and increased pressure-ratio requirements will reduce compressor operability, while anticipated swings in the corrected flow rate will require increased levels of compressor operability. The compressor will likely experience stability issues.

The expected outcome of the inlet distortion at the compressor face could result in reduced overall engine performance and operability. Even a low level of distortion into the high-pressure multistage compressor can negatively impact the aerodynamic efficiency and stall margin, or the operability. This places an additional requirement on the compressor to have even higher margins of operability than those in traditional engines.

Recommendation: Mitigate the risk.

Mitigation strategy: The compressor inlet distortion issue can be mitigated by a technology development plan that includes the following necessary events:

1. Conduct analysis of the specific SAX-40 engine configuration with thermodynamic engine cycle studies.
2. Create a conceptual design of the embedded engine, including fan and multistage compressor. This task should include input from engine manufacturers.
3. Perform CFD analyses of the multistage compressor at several vehicle/engine operating points throughout the flight envelope. The varying magnitude of the boundary layer into the engine/fan and the resulting swings in corrected mass flow rate at the core compressor inlet must be determined.
4. Determine analytically (CFD) whether flow distortion mitigation techniques, such as flow control and non-axisymmetric design of the compressor inlet, could be effective at reducing compressor face distortion with minimal negative impact on the engine cycle.
5. Determine analytically whether variable-geometry compressor inlet guide vanes and stators can be effective at mitigating the swings in the compressor inlet corrected flow that are caused by the boundary-layer thickness variations encountered in the flight envelope.
6. Identify a test facility with an adequate flow rate capacity and drive power

that can be used to verify core multistage compressor aerodynamic performance. If the drive power is excessive, then the multistage axial and the centrifugal compressors can be tested separately.

5.3.5 Risk #15, Low-noise, LPT design

Likelihood = 3, Consequence = 2

Risk statement: If the LPT performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.

The LPT is one of the major contributors to engine noise in the SAX-40. One way to minimize tonal noise from the LPT is to design a large number of rotor blades. The interaction between the LPT blades and vanes can generate noise in the audible frequency range. During the design process, the number of LPT rotor blades and vanes can be increased to generate higher frequencies that are less audible. The higher frequencies are more easily attenuated by the atmosphere. However, the maximum number of blades is limited by structural, mechanical, and manufacturing considerations, as well as by the aerodynamic performance consideration of minimum Reynolds number. As the blade number is increased the chord is reduced, thereby reducing the Reynolds number, especially at cruise operating conditions. The reduced Reynolds number has a high risk of increasing the LPT boundary-layer profile losses. If the boundary-layer separation bubble on the blade surface becomes excessively large, it may not collapse back onto the blade surface before the TE, which can result in even higher losses and underturning in the last few blade rows of the LPT, causing a reduction in power generated by the LPT.

Recommendation: Mitigate the risk

Mitigation strategy: The LPT boundary-layer loss profile can be mitigated by a technology development plan that includes the following necessary events:

1. Perform analysis of the specific SAX-40 engine configuration with thermodynamic engine cycle studies.
2. Create a conceptual design of an embedded engine including the LPT. This task should include input from engine manufacturers.
3. Perform CFD analyses of the LPT at several vehicle/engine operating points throughout the flight envelope. Determine the varying magnitude of the boundary layer in the blade rows of the LPT and assess the profile losses.
4. Identify technologies that could reduce the boundary-layer growth that results from low Reynolds number. Test candidate technologies such as flow control and plasma control in a turbine cascade.
5. Identify a rotating test facility that can be used to verify LPT aerodynamic performance at the low-Reynolds-number operating conditions. The facility should also enable measurement of LPT acoustic performance.
6. Validate LPT performance and acoustics by rig testing.

5.3.6 Risk #17, Low noise undercarriage

Likelihood = 2, Consequence = 3

Risk statement: If the low noise undercarriage performance is less than predicted, then attainment of the noise requirements will be jeopardized.

Landing-gear systems are complex mechanical devices, which require robust but efficient design, frequent inspection and maintenance, and high reliability with respect to mechanical actuation and motion. Additionally, landing gear operate in severe environments of heat, dust, foreign-object impact, and forceful water/snow/ice spray, and mishaps that involve tire failures are not uncommon. These conditions would likely make the operational life of fairing structures very short or else require the fairings to be quite robust, thereby adding both weight and complexity in maintenance. In addition, a maximum-energy aborted-takeoff incident usually results in a fire that involves the tires, wheels, and hydraulics, so unhindered fire-suppression access to these systems is paramount. In normal service, heat buildup in the brakes during taxi to the takeoff location must dissipate quickly so that the brakes are ready for a potential aborted-takeoff operation, and the heat buildup during landing and taxi to the gate must also dissipate quickly for ground safety. The fairing system that is proposed for noise reduction must not significantly impact these issues because they are safety related. Also, landing gear are geometrically complex with many adjacent components, so the sources of noise are surmised to be large-scale interacting turbulent wakes and their impingement on various surfaces. Thus, the selection of which components to fair and the manner in which to do so is not obvious because the flowfield around the undercarriage can change dramatically with aircraft attitude in the various stages of approach.

While both U.S. and European wind-tunnel tests appear to have demonstrated landing-gear noise reduction through the use of fairings and shielding, flight tests have yielded disappointing results at best. Depending on the longitudinal location of the undercarriage, the noise created by the wake interaction with the TE flaps may be an unaddressed noise source; on the Boeing 777, phased-array tests suggest that this component can contribute as much as 25 percent of the total undercarriage-related noise. Noise that is generated through interactions with the SAX-40 TE brushes (instead of flaps) is unknown. Additionally, none of the demonstrated fairings are even remotely acceptable in regard to integration issues, based on extensive discussions with Boeing and Goodrich undercarriage designers during certain NASA programs (e.g., the Advanced Subsonic Technology (AST) and Quiet Aircraft Technology (QAT) programs).

Undercarriage-related noise is frequently the largest component of airframe noise during approach and often accounts for more than 50 percent of the total approach noise. A mitigating factor related to the BWB configuration is the relatively short undercarriage length (i.e., compared with a configuration with a high-bypass-ratio engine mounted in an underwing nacelle).

Recommendation: Avoid the risk. Concentrate on the development of systems to enable the delay of undercarriage deployment until late in the approach timeline. The focus would need to include increased deployment reliability although these systems are already considered quite reliable, quiet air-brake devices, and automated fast-response go-around controls.

5.3.7 Risk #18, Quiet drag

Likelihood = 2, Consequence = 2

Risk statement: If sufficient quiet drag cannot be generated, then attainment of the noise requirements will be jeopardized.

An adequate amount of drag must be generated. The necessary drag is produced by inducing additional drag via an inefficient lift distribution over the all-lifting airframe during approach. This inefficient lift distribution is created through a combination of upward-deflected elevons and vectored thrust. For the purposes of this assessment, we assume that this is feasible. The risk that is inherent in the vectored-thrust system and the high-lift system has been addressed separately.

Assuming that the amount of drag is adequate, we must determine whether the drag is generated in an adequately quiet manner.

In the SAX-40 design (ref. 4), the required drag for a low approach speed would be achieved through the use of a large wing area at a high angle of attack and through the use of elevons and thrust vectoring. Aside from the engine noise (thrust vectoring), the drag noise is inherent airfoil noise (i.e., the noise generated by the air flowing along the surface of the wing and elevon).

The likelihood is high that the drag noise (inherent airfoil noise) for the SAX-40 in an approach configuration would be much less than that generated from an aircraft with traditional slat and flap high-lift systems. This assumption is true because the dominant noise sources that are typically located in the slat and flap cove/gap regions and along the flap side edges are eliminated in the SAX-40 wing configuration at approach. The remaining noise is the noise that radiates from the TE of the elevons and wing tips; this noise can be controlled via the use of TE brushes. See risk #16 regarding the performance of the TE brushes.

Prediction methods (well-established empirical and semi-empirical models) were used to estimate the noise that is generated by the SAX-40 wing in an approach configuration. However, accurate measurements of the overall resulting noise level (which would need to be performed in a facility that is designed for aeroacoustic testing) of the complete SAX-40 wing airfoil profile (including drooped LE, deflected CML elevons, approach speed, and angle of attack) were not obtained. Noise measurements were only performed to evaluate the benefit of using a drooped LE versus a slat (ref. 34). These measurements were acquired at a lower speed (40 m/s) than the target approach speed (60.8 m/s) and in a facility that has not been designed for aeroacoustic testing (i.e., an untreated, closed wind tunnel with relatively higher background noise). Nevertheless, these acoustic measurements did indicate that the drooped LE would be significantly quieter than a traditional slat, but quantitative measurements of the actual noise level and spectra were hindered by the high background noise, the proximity of the microphone array to the test model, and so on.

No prediction or experimental measurements of the noise that is generated in the region where the side edges of the deflected elevon are linked to the main wing have been performed. The CML technology has previously been tested as a means to reduce flap side edge noise (ref. 26). The flow in the side edge region of the elevon would differ from that in the side edge region of a deployed flap. Nevertheless, because of the absence of the side edge, we can reasonably assume that no significant noise source would form in that region, but the TE may need to be treated differently along the CML link than along the rest of the elevon TE.

In summary, the noise that is generated from the selected airfoil configuration (e.g., drooped leading edge, CML elevons, main-element high angle of attack) should be mostly TE noise. The TE does not generate as much noise as the other noise sources that were eliminated. The geometry of the TE plays an important role in the level of noise that radiates from that edge.

For a single-airfoil-wing configuration, where the LE airfoil (slat), main airfoil, and TE airfoil (elevon or flap) are molded into a single airfoil, the TE noise is the only noise source that is left to control. This noise source is not typically important (compared with slat noise or flap side edge noise); however, the level of noise that radiates from the TE will greatly depend on the TE geometry.

In summary, if sufficient drag can be generated without having to depart from this single-airfoil configuration, then the noise requirements could likely be met. If the necessary drag cannot be generates without having to revert back to the use of slats and flaps, then the noise requirements would most likely not be met (but the flap side edge noise could at least be mitigated via the use of a CML to eliminate the flap edges).

Recommendation: Assume the risk.

5.3.8 Risk #19, Long ducts with acoustic liners

Likelihood = 2, Consequence = 3

Risk statement: If the integration of long ducts with acoustic liners results in acoustic penalties, then attainment of the noise and mission requirements will be jeopardized.

Based on the SAX-40 literature, the integration of long ducts with liners involves the following assumptions:

1. The length-to-height ratio of the acoustically lined section of the exhaust fan duct will be greater than the ratio that can be achieved with conventional engines. The amount of attenuation in the duct will increase as the length-to-height ratio is increased; thus, this effect is clearly positive.
2. Reduced fan diameters with higher rotational speeds will result in increased attenuation (ref. 6). As the blade passage frequency is increased, the effectiveness of the conventional acoustic liners increases. This effect is clearly positive.
3. The complex propagation path will require an increase in the number or the width of the splices (ref. 6). The interaction of the rotor-stator noise with the splices causes the sound field to be scattered into higher order modes, in particular when the splices are close to the fan (refs. 38 and 39). This effect is enhanced as the width of the splices is increased. The amount of attenuation that is achieved by the acoustic liner depends on whether the liner is properly designed to match the resultant scattered modes. One way to mitigate this concern is to develop methods for the fabrication of liners that are acoustically smooth (i.e., the effects of the splices are virtually eliminated). Recent tests conducted by industry (ref. 40) demonstrated that an acoustically smooth inlet on a Boeing 777 aircraft with GE90-115B engines could be used to achieve excellent attenuation. Thus, although these splice effects can be important, they are reasonably well understood.
4. The complex propagation path will result in a reduced “line of sight” from the fan to the exhaust plane (ref. 6). For this condition, the sound field will interact with the acoustically treated wall at oblique angles of incidence; thus, the absorptive capability of the liner will be enhanced. Although this shape is expected to have a negative impact on the performance of the engine, it will result in increased noise attenuation. The NASA Langley Curved Duct Test Rig has recently been developed to study the effects of S-shaped wall curvature on the sound field (ref. 41).
5. Multilayer and or multisegment liners will be installed in these long ducts (ref. 42). As these liner types are designed to achieve broadband attenuation, the noise spectrum of concern is assumed to be predominately broadband. The inclusion of multilayer liners will increase the frequency range over which significant sound absorption can be achieved but will do so at the cost of reduced peak tonal attenuation (ref. 39). However, the added length of the duct provides multiple options for overcoming this reduction in tonal attenuation. As indicated in reference 42, multisegment liners may result in preferential scattering into higher order modes. However, the work of Zlavog et al. (ref. 43) indicates that the mode scattering that occurs at the interfaces between each liner segment can cause the sound absorption to either increase or decrease (relative to uniform liners), depending on the relative phases of the multiple modes that interact with these liner segments. Thus, the modal content of the fan noise must be known to achieve the benefit of segmented liners.

Recommendation: Assume the risk.

5.3.9 Risk #20, Airframe shielding

Likelihood = 1, Consequence = 2

Risk statement: If the airframe shielding benefits are less than predicted, then attainment of the noise requirements will be jeopardized.

The SAX-40 configuration provides shielding for the propulsive noise that is radiated from the engine inlets, including broadband and tone noise from the fan and the compressor. The amount of tone noise may be greater than it would be for podded engines because of nonuniform inflow, and broadband noise may be greater as a result of ingestion of boundary-layer turbulence. Therefore, shielding may be important to compensate for the increase in the noise that is radiated from the inlet. Nevertheless, the SAI team demonstrated (ref. 44) that even conservative estimates of the effects of shielding predict a reduction in noise in the direction of primary inlet radiation to the ground (i.e., 60 to 100 degrees with respect to the inlet axis) of approximately 30 dBA. These predictions are consistent with previous studies of similar configurations (ref. 45).

Estimates were based on wave calculations at low frequency and were projected to high frequency. Ray calculations at a high frequency should predict even greater effects of shielding in the shadow zone than are predicted from the low-frequency wave calculations. Inlet noise will need to be controlled by making the inflow as uniform as possible and by maximizing noise absorption by the duct liners because of the proximity to the passenger compartment. Therefore, even only moderately shielded inlet noise is unlikely to be a major contributor to total aircraft noise.

Recommendation: Assume the risk.

6.0 ATB Comparison

Throughout the various SAI-related publications, comparisons have been made between the SAX-40 and various existing or near-term aircraft, such as the Boeing 767-300, 777, and 787-3. A more enlightening comparison would involve an ATB (i.e., a conventional “tube with wings”) concept that has been sized for the SAX-40 design mission and that utilizes similar levels of technology. Such a comparison would address the overall SAX-40 feasibility and the risk level relative to the conventional baseline, thereby highlighting the cost of optimization solely for low noise.

Standard analysis practice begins with the identification of a starting point from which to create the baseline design. The starting point should be an existing aircraft with a range and payload performance that is consistent with the SAX-40 design mission and for which adequate data are available to calibrate the analytical model. Once calibrated, the analytical model can then be adjusted with technology and mission performance assumptions that match the SAX-40 design to result in a resized ATB design.

The SAX-40 design mission is to carry 215 passengers for 5000 nm. This passenger load is slightly larger than the largest existing single-aisle transport (i.e., the Boeing 757-300) yet not quite in the range of most wide-body, twin-aisle transports. Therefore, two starting points were used: a single-aisle Boeing 757-300 and a twin-aisle Boeing 767-200ER. The 757 was modeled, calibrated, and then resized to result in a design that is termed the “Single-Aisle–Advanced-Technology Baseline” (SA-ATB); likewise, the 767 was modeled, calibrated, and resized to result in a design that is termed the “Twin-Aisle–Advanced-Technology Baseline” (TA-ATB).

The primary aircraft level sizing and analysis tool that was used was the Flight Optimization System (FLOPS) computer code. A baseline model of a 757-200 (186-passenger, mixed-class configuration) was developed using a combination of publicly available data for geometry, weight, and performance characteristics (ref. 46) and a PW2040-like engine model that was developed at NASA. In addition, a Boeing-generated 757-200 group weight statement was utilized. The FLOPS weight predictions were calibrated by setting the maximum ramp weight and landing weight to the values that were reported by Boeing (221,000 lb and 198,000 lb, respectively) and comparing the FLOPS-predicted operating empty weight (OEW) with the Boeing data. To match the OEW from the Boeing group weight statement, calibration adjustments were made to the individual component weights in the FLOPS model. Next, the model was modified by applying the 757-300 geometric and design mission parameters, and the OEW was recalibrated by adjusting the predicted weights for two operating items (passenger service and cargo containers). The maximum ramp weight for the 757-300 is 271,000 lb, and the OEW is 141,800 lb. The calibrated FLOPS model predicted an OEW of 141,807 lb.

The FLOPS-predicted mission performance was then calibrated to a specific point on the 757-300 payload-range diagram that is provided in reference 46. Assuming a payload of 58,200 lb (243 passengers at ~240 lb per passenger), the OEW plus payload is 200,000 lb. At a fuel load of 60,000 lb, the ramp weight for the calibrated mission is 260,000 lb. According to the payload-range diagram, at this operating point the range is 2500 nm. This mission performance was used as a calibration point for the FLOPS model. The FLOPS-predicted fuel capacity (which is based on wing geometry) was calibrated to match the published capacity for the 757-300. Assuming that the weight characteristics are accurate based on the previously described weight calibration process, range performance is impacted most directly by the mission profile, engine-thrust-specific fuel consumption (TSFC), and the aircraft lift-to-drag ratio (L/D). Although a detailed mission profile is not provided in reference 46, some parameters are specified in the payload-range diagram, such as cruise Mach number, typical mission reserves, and a 200-nm alternate airport. The step cruise that is specified (31,000-35,000-39,000 ft) was approximated in FLOPS by cruising at optimum altitude (i.e., “cruise climb”). The internally computed FLOPS aerodynamic performance was adjusted to achieve a range of 2500 nm. The impacts of engine specific fuel consumption and aircraft L/D cannot be separated when matching range performance. The accuracy of the PW2040-like engine model thus impacts the accuracy of the calibrated FLOPS aerodynamic performance. For example, if the actual engine TSFC is higher than that in the model, then the range-calibrated aerodynamic efficiency will be lower than the actual efficiency.

The final step in the development of a baseline model that was representative of the Boeng 757-300 aircraft was to ensure that the FLOPS sizing was consistent with that of the actual aircraft. For basic FLOPS sizing, the varied parameters are engine thrust and wing area, with an objective to minimize the gross weight that is required to meet the mission. One of the difficulties in sizing for this case is that the design mission that is described above is at a gross weight that is below the maximum gross weight. Performance constraints, such as initial cruise altitude capability and takeoff field length, need to be met when the mission start weight is at the maximum weight. A more significant issue is that the wing area and the thrust of the actual aircraft can be sized by additional considerations that are outside the scope of FLOPS. For example, the wing or engine may be oversized for a future "growth version" of the aircraft. Without any adjustments to the weight and the aerodynamic calibrations that are described above, the FLOPS-sized vehicle for the selected mission resulted in a gross weight of 262,157 lb (261,000 lb actual from Boeing data), an OEW of 142,857 lb (141,800 lb actual), and wing area of 1963 ft^2 (1994 ft^2 actual).

A similar procedure was utilized to model the 767-200ER, minus the use of an actual group weight statement. The calibration design point selected from the Boeing data (ref. 47) was for a 388,000-lb maximum design ramp weight, a 181,610-lb OEW, and a range of 6600 nm with 216 passengers in mixed-class seating. The FLOPS-sized vehicle for the selected mission, which utilizes a NASA developed PW4056-like engine model, resulted in a gross weight of 381,309 lb (388,000 lb actual), OEW of 178,290 lb (181,610 lb actual), and wing area of 3117 ft^2 (3050 ft^2 actual).

The SA-ATB and TA-ATB airframe models were then created as derivatives of the baseline models that are described above. The primary technological advance that was assumed for the airframe was the extensive use of composite materials for the airframe structure. For the Boeing 787 that is currently in development, as much as 50 percent of the primary structure is made of composite materials (ref. 48). This composite construction was assumed to result in a 15 percent reduction in the weight of the wing, fuselage, and empennage compared with that of traditional metal construction. Several other minor technological improvements were assumed, based on the 787 development, including an increased hydraulic pressure of 5000 psi and a 1 percent reduction in drag. Changes were also made to the mission and payload parameters that are described above to match the SAX-40 design mission (i.e., 215 passengers in a mixed-class configuration and a 5000-nm range).

The results are presented in Table 2. The 757-300 and 767-200ER data are included for completeness. The SA-ATB and TA-ATB gross weights are within approximately 1 percent of each other, with the twin-aisle option having a slightly better efficiency than the single-aisle design (7000 lb or approximately 7 percent less fuel burn).

Table 2. ATB Comparisons

	767-200ER	757-300	SA-ATB	TA-ATB	SAX-40
In-service date	1984	1998	~2010	~2010	~2030
Engine architecture	Twin podded	Twin podded	Twin podded	Twin podded	Embedded, three cores driving nine fans
Range, nm	6600	2500	5000	5000	5000
No. of passengers	216	243	215	215	215
TOGW, lb	387,000	260,000	284,650	281,110	332,560
OEW, lb	181,610	141,800	138,700	142,140	207,660
Fuel, lb	159,000	60,000	94,350	87,370	73,310
Payload, lb	45,100	58,200	51,600	51,600	51,600
Span, ft	156.0	124.8	134.1	136.9	221.6
Wing area, ft^2	3050	1994	2264	2343	-
Length, ft	159.0	177.4	177.4	159.0	144.3

Using the TA-ATB as a basis for comparison, the SAX-40 is significantly heavier: 46 percent heavier in OEW and 18 percent heavier in TOGW. The fuel burn for the SAX-40 is 16 percent less than the TA-ATB design. These comparisons indicate that either the SAI team's weight estimates were extremely conservative or that the SAX-40 would be significantly more costly to design and produce (however, the fuel burn savings would result in a lower fuel costs). SAI selected the BWB configuration because of its inherent airframe noise shielding benefit; therefore, the increased design and acquisition costs can be roughly viewed as the cost of obtaining the extremely low noise benefit offered by the SAX-40 concept. The technology assumptions that are applied to the ATB designs were based on advertised Boeing 787 levels; therefore, the in-service date was given as approximately 2010. The assumed in-service date for the SAX-40 is approximately 20 years later. This 20-year period makes the ATB estimates conservative; that is, the actual weights and fuel burn of an ATB design with comparable technologies to the SAX-40 will be lower than those shown in Table 2.

7.0 Conclusions and Recommendations

The SAX-40 risk assessment identified high-risk items in three primary areas: BWB configuration (structures and weights, human factors), propulsion (BLI/inlet and nozzle/thrust-vectoring design), and operations (displaced threshold, CDA). In addition, the overall noise estimates and the cost of the concept are high-risk items. The following is a summary of the challenges that are associated with the high-risk items and the recommended risk management strategy:

1. The challenge of building a relatively lightweight, noncircular pressure vessel must be

overcome prior to committing to the full-scale development of a BWB concept. Focused research efforts should be undertaken to design, build, and test several structural concepts, culminating in the construction and testing of a full-scale structural article that represents the preferred approach. In addition to the verification of the preferred structural concept, this effort should result in an empirical database for noncircular pressure vessels and the associated tools and methods for incorporating this data into the design process for BWB configurations.

Recommended risk management strategy: Mitigate.

2. The challenge of designing and integrating the BLI inlet design and the variable-area nozzle with thrust vectoring is not trivial. Both the inlet and nozzle represent highly complex mechanical and fluidic design challenges, which if not met can prevent the attainment of the SAX-40 requirements. Efforts to design, build, and test both components would be necessary to reduce the risk prior to full-scale development.

Recommended risk management strategy: Mitigate.

3. The challenge of integrating the SAX-40 into the airspace represents a serious issue. The significantly slower approach speed relative to the other traffic in the pattern will necessitate increased spacing, thus reducing airport capacity. Most projections forecast a large increase in demand over the next 20 years, and increasing capacity is a high priority; therefore, introducing a system that has the opposite effect will not be acceptable. Likewise, utilizing a displaced threshold may not be acceptable in all situations. A detailed study of airport operations and infrastructure would be required before a determination of the feasibility of low speed CDA's with displaced thresholds could be made. One option would be to operate the SAX-40 in a conventional mode during peak hours (sacrificing some noise performance) and utilize the slow CDA and displaced threshold during off-peak hours to attain the full noise benefit.

Recommended risk management strategy: Avoid.

4. The challenge of producing an economically viable concept must be met for any new design and for the SAX-40 in particular because it represents such a large departure from convention. The ATB comparison indicated that the SAX-40 would be significantly heavier than a conventional design (comparable in all categories except noise and fuel burn); therefore, RDT&E and production costs would be greater. A detailed life-cycle cost estimate should be performed to quantify these costs, including the costs of operations and support. The benefit of extremely low noise must be worth any additional costs that are incurred, otherwise, the concept will not be viable.

Recommended risk management strategy: Further study is needed prior to selecting a strategy.

5. The primary motivation for the SAX-40 is low noise. Therefore, attainment of the

overall noise requirement is a crucial requirement. Concerns that have been raised during this risk assessment include a reliance on operational techniques that may not be acceptable in all places at all times. In addition, many high-risk items, for example, landing gear, are designed for low noise but will require new, unconventional, and complex approaches.

Recommended risk management strategy: Assume the risk. (Even if only two-thirds of the predicted noise benefits are feasible, the SAX-40 still represents a very quiet aircraft).

6. The challenge of correctly assessing the public's reaction to an unconventional configuration such as the BWB is critical. This issue cannot be understated given the fact that public perception (even if the perception is incorrect) can be a showstopper for commercial viability. The BWB represents a radical departure from the traditional tube-with-wings design, and the human-factors issues must be addressed. Simply identifying the issues is a challenge. For example, the BWB may be perceived as less safe than the tube-with-wings configuration because it looks different. Public assessment through surveys, interaction with full-scale mock-ups, and flight simulators must be performed to address this risk.

Recommended risk management strategy: Mitigate.

In addition to these high-risk items, the ATB comparisons should be considered as well. The results show that a significant weight penalty is associated with the SAX-40 concept when compared with the baseline. This weight penalty will translate into higher RDT&E and production costs and can be roughly viewed as the cost of achieving the extremely low noise performance promised by the SAX-40. Although the SAX-40 serves as an example of what a commercial transport concept might look like when optimized solely for low noise, the commercial viability of such a design is questionable. The types of commercial transports that are viable are those that maximize operator profits. These aircraft are specifically targeted at reducing acquisition and operations costs and increasing revenue. Therefore, the following design drivers should be utilized:

1. Minimize labor costs (e.g., maintenance, crew, servicing)
2. Minimize fuel burn
3. Maximize availability
4. Minimize emissions
5. Minimize noise
6. Minimize structural weight

The challenge is to develop a design that achieves the proper balance among these cost drivers. Optimizing only one driver, such as noise, will not achieve this balance. Optimizing singularly for low noise will, however, highlight technology areas and new concepts for noise reduction; thus, given that perspective the SAX-40 design was successful.

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APPENDIX B: BWB Literature Survey

- May 1984

  Douglas Aircraft input to the NRC Vehicle Applications Panel Group E.

  Desirable features of future commercial aircraft are low cost, noise, and emissions. BWB mentioned in context of long-haul military airlifters only, not commercial transports. No data.

- October 1990

  Callaghan, J. T. and Liebeck, R. H.: "Some Thoughts on the Design of Subsonic Transport Aircraft for the 21st Century," SAE Paper No. 901987, October 1990.

  This paper was a response to Dennis Bushnell's challenge to industry to develop innovative concepts and is cited in NASA-CR-4624 below. Contains a nice introduction showing technology and cost trades with return on investment crossover based on fuel price. This paper compares the derivative/evolutionary path for improvements with a revolutionary path (BWB). Interesting progression from DC-10 to MD-11 to MD-11-Advanced to a year 2000 synergistic technology transport. Then a MD-BWB is compared with the synergistic technology transport; the BWB offered a 50 percent increase in L/D and a 25 percent reduction in fuel burn.

- September 1994

  Liebeck, R. H.; Page, M.A.; and Rawdon, B. K.: "Concepts for Advanced Subsonic Transports," NASA CR-4624, September 1994.

  The relatively crude initial study in SAE Paper 901987 above provided the incentive for this study. Purpose was to develop and compare a conventional tube with wings (baseline), a BWB, and a pure spanloader, all utilizing the same technology levels. Requirements envisioned for a 2020 entry into service (EIS) were 800 passengers, 7000-nm range, 11,000-ft takeoff length, 155 knots V_{ap}, 0.85 cruise Mach, and 35,000-ft initial cruise altitude. The structural problem of pressurizing a noncircular passenger cabin was assumed to be solved efficiently. Given this, the BWB fuselage weight was 6,000 lb higher than the conventional baseline. BWB cruise L/D of 27.2 resulted in 105,000 lb fuel load savings (27 percent less) versus conventional (cruise L/D = 20.6). The TOGW was 14 percent less than the conventional baseline, OEW was 10 percent less. NASA analysis showed a much better conventional baseline, reducing the BWB benefits to 6 percent on TOGW and 2 percent on OEW, and 17 percent on fuel.

- January 1996

  Liebeck, R. H.; Page, M.A.; Rawdon, B. K.; Potsdam, M. A.; Wakayama, S.; and Girvin, R.: "BWB Configuration Control Document, CCD-2," NAS1-20275 Deliverable, January 1996.

  Update of CCD-1, published 12-9-94. Preliminary design of BWB-1-1 continues to offer benefits over conventional baseline: 15 percent lower TOGW, 28 percent lower fuel burn. Update has yielded a preferred engine arrangement (three engines with BLI inlets), a pressure vessel concept (5.5-in thick composite sandwich with aluminum honeycomb core), a new cabin arrangement, and slats on the outer wing. 800 passenger BWB with 7000-nm range. 2020 EIS with 2015 technology; however, 2012 EIS is possible.

- October 1996

  Mukhopadhyay, V.: "Structural Concepts Study of Non-circular Fuselage Configurations," AIAA/SAE WAC-67, October 1996.

  Analysis of several noncircular fuselage concepts, including flat and vaulted shell, deep honeycomb sandwich shell, and ribbed double-wall shell. Flat sandwich shell found to be preferable to the vaulted shell because of its superior buckling stiffness. Vaulted double-skin ribbed shell configurations were superior because of weight savings, load diffusion, and fail-safe features.

- June 1997

  Potsdam, M. A.; Page, M.A.; and Liebeck, R. H.: "BWB Analysis and Design," AIAA-97-2317, June 1997.

  Focus on CFD methodologies for BWB wing aerodynamic design. No validation data available. Configuration was 800 passenger, three-engine design with *t*/*c* of approximately 18 percent. Claim 28 percent fuel-burn reduction versus conventional, but no baseline given, no backup to support performance claims.

- October 1997

  Liebeck, R. H.; Page, M.A.; Rawdon, B. K.; Potsdam, M. A.; Wakayama, S.; and Girvin, R.: "BWB Configuration Control Document 3, CCD-3," NAS1-20275, October 1997.

  This update to CCD-2 focuses on the test phase results from the contract, including Langley's 14-ft by 22-ft low-speed test of a 4 percent model, global finite-element method (FEM) analysis, Stanford 6-percent-scale flying model, BWB-17, and University of Southern California's inlet testing with vortex generators.

- January 1998

  Liebeck, R. H.; Page, M.A.; and Rawdon, B. K.: "Blended-Wing-Body Subsonic Commercial Transport," AIAA-98-0438, January 1998.

  Summary of three-year NASA-sponsored feasibility study. 800 passenger 7000-nm-range BWB compared with conventional design, both with 2020 EIS. Reduction of 27 percent in fuel burn for BWB. Engine installation trade study, mid-bifurcated BLI was lightest but impractical, so upper S-duct BLI was utilized. Five inch thick structural shell concept for fuselage. Tests:

  - Low-speed powered 4 percent model, Langley's 14-ft by 22-ft tunnel
  - NTF test in spring 1997
  - Six-percent flight-test model (BWB-17, Stanford)

- January 1998

  Anabtawi, A. J.; Blackwelder, R.; Liebeck, R. H.; and Lissaman, P.: "Experimental Investigation of Boundary Layer Ingesting Diffusers of a Semi-Circular Cross Section," AIAA-98-0945, January 1998.

  Baseline (no vortex generators) total pressure loss coefficient = 19 percent, and distortion coefficient = 63 percent. With vortex generators, these numbers were 17 to 21 percent and 24 to 54 percent. Boundary-layer diversion yielded 9.6 percent and 10.5 percent for these coefficients.

- September 1998

  Wakayama, S. and Kroo, I.: "The Challenge and Promise of BWB Optimization," AIAA-98-4736, September 1998.

  Used NASA's Advanced Subsonic Technology (AST) Task 18 BWB concept as baseline (855 passengers, 7500-nm range); applied an updated WingMOD tailored for BWB. Used 134 design variables and 705 constraints (90 active) to show design improvement due to MDO.

- September 1998

  Wakayama, S.: "Multidisciplinary Design Optimization of the Blended-Wing-Body," AIAA-98-4938, September 1998.

  Write-up of same work from previous citation, 4736, with more information on actual updates made to WingMOD to handle BWBs. Aerodynamics updates to handle 3D effects calibrated with CFD results.

- August 1998

  Pelkman, R.A.: "Key Findings and Conclusions from an NTF Wind Tunnel Test of an Initial Blended-Wing-Body Concept," Boeing Report No. CRAD-9402-TR-3985, August 1998.

  Wing/body model for high-Reynolds-number (*Re*) testing for cruise Mach ranging from 0.5 to 0.88, and low speed at Mach = 0.25. *Re* = 3.5 million (to assess viability of transonic test), 12.3 million (to assess one-fourth scale model) and 25 million (max for NTF safety, close to cruise *Re* of full-scale vehicle) and low-speed (Re = 20.5 million) points were tested. Main purpose was to verify CFD predictions. Good matches at 0.85, poorer at 0.5. Predicted *L*/*D* at 0.85 cruise was 20.5 (with no engines, but *Re* will be higher at full scale).

- January 1999

  Anabtawi, A. J.; Blackwelder, R. F.; Lissaman, P.; and Liebeck, R. H.: "An Experimental Investigation of Boundary Layer Iingestion in Diffusing S-Duct With and Without Passive Flow Control," AIAA-99-0739, January 1999.

  Follow-up investigation from AIAA-98-0945, compared straight duct diffusers with S-duct diffusers both with and without vortex generators. Ducts had thinner entrance lips and were shorter. Pressure recovery was 93 percent for straight duct, 90 percent for S-duct. Distortion in S-duct was 14 percent, vortex generators decreased this to 3.4 to 6 percent. The distortion numbers have been corrected from the low Mach number test condition to *M* = 0.85. This correction was not done in the previous work.

- May 1999

  Clark, L. R. and Gerhold, C. H.: "Inlet Noise Reduction by Shielding for the Blended Wing Body Airplane," AIAA-99-1937, May 1999.

  BWB provided significant inlet noise shielding. Noise radiating downward into the forward sector below the model was reduced by 20–25 dB due the presence of the BWB model. Tests:

  - 4-percent scale fiberglass three-engine nacelle BWB

- June 1999

  Anabtawi, A. J.; Blackwelder, R. F.; Lissaman, P.; and Liebeck, R. H.: "An Experimental Study of Vortex Generators in Boundary Layer Ingesting Diffusers with Centerline Offest," AIAA-99-2110, June 1999.

  The S-duct total pressure recovery was 90 percent with and without vortex generators; total pressure distortion was 77 percent without vortex generators (normalized to dynamic pressure) and 11 percent in some cases with vortex generators that were the same height as the boundary-layer thickness (30–40 percent of inlet height as calculated by CFD). Description of Mach number effects and corrections appears to be inconsistent with January paper. "Generally speaking, a typically acceptable distortion level (normalized to *q*) would be no more than 20 percent."

- July 1999

  Anabtawi, A. J.; Blackwelder, R. F.; Lissaman, P.; and Liebeck, R. H.: "An Experimental Study of the Effect of Offset on Thick Boundary Layers Flowing Inside Diffusing Ducts," AIAA-99-3590, July 1999.

  Boundary layers measured to be on the order of one-third of the inlet height, confirming previous CFD estimates. The S-duct geometry caused boundary-layer separation.

- August 2000

  Roman, D.; Allen, J. B.; and Liebeck, R. H.: "Aerodynamic Design Challenges of the Blended Wing Body Subsonic Transport," AIAA-2000-4335, August 2000.

Challenges include: volume requirements (led to center wing t/c of approximately 17 percent); deck angle versus cruise trim trade study; secondary power requirements for control surfaces; lower wing loading required for acceptable approach speeds; buffet and stall characteristics driven by outboard airfoils; high alpha during approach; propulsion airframe integration; and manufacturing issues of complex 3D shapes. Other proprietary constraints hinted at but not detailed. CFL3D utilized for clean wing CFD calculations, compared with NTF data (1998 test). OVERFLOW utilized for PAI. First generation BWB was 800 passenger, second generation was 450 passengers (referred to as current generation in paper). New class of transonic airfoils were designed to reduce t/c and improve manufacturability. Longitudinal trim problem solved using TE camber and wing twist. Problems remain with deck angle, secondary power, and PAI. Mail slot BLI, isolated submerged BLI, isolated with boundary-layer diffusion (BLD) have all been deemed unacceptable. Current concept is strut-mounted engines.

- September 2000

  Wakayama, S.: "Blended-Wing-Body Optimization Problem Setup," AIAA-2000-4740, September 2000.

  WingMOD applied to next iteration of BWB, focusing on cabin geometry, balance, and stability and control issues. Detailed description of how WingMOD is used to model and design a BWB. Optimization added wing sweep (35.7 to 42.8 deg) to balance the aircraft.

- January 2001

  Pambagjo, T. E.; Nakahashi, K.; Obayashi, S.; and Matsushima, K.: "Aerodynamic Design of a Medium Size Blended-Wing-Body Airplane," AIAA-2001-0129, January 2001.

  200-passenger, 2000-nm-range BWB studied for aerodynamic feasibility. Minimum cabin height of 2 m (78 in.) resulted in maximum of 15 percent t/c. Results indicate that this size BWB may have greater wetted area than conventional counterpart. Inverse design process and new smoothing algorithms applied. L/D = 18.9.

- January 2002

  Liebeck, R. H.: "Design of the BWB Subsonic Transport," AIAA-2002-0002, January 2002.

  2002 Wright Brothers Lecture Paper. Gives background of BWB formulation (CR 4624, Sep. 1994) and initial development (1994–1997 NAS1-20275, CRAD-9405-TR-3780, and AIAA-98-0438). After this, in-house preliminary design study initiated on BWB-450 concept (468? 478? passenger, 7750 nm? 9000 nm? range). WingMOD used to size this concept. Podded engines and BLD embedded engines studied; podded engines selected, nose-down thrust moment deemed acceptable. Center-body structural concept skin/stringer outer surface with 5- to 6-in. deep stringers, internal Y-braced ribs. Claims this weighs little more than a conventional fuselage, but table shows 21 percent heavier than A380 fuselage?

- February 2002

  Green, J. E.: "Greener by Design – The Technology Challenge," *The Aeronautical Journal*, Vol. 106, No. 1056, February 2002, pp. 57–113.

  Simplistic parametric sizing studies, no numerical analysis. Proposes multiple segments of shorter range aircraft instead of single segment of a long range aircraft. BWB one of eleven concepts studied, recommended as a key area of future research.

- April 2002

  Willcox, K. and Wakayama, S.: "Simultaneous Optimization of a Multiple-Aircraft Family," AIAA-2002-1423, April 2002.

Presents development of framework to simultaneously optimize two common aircraft in a family, a 475-passenger and a 272-passenger BWB, both with 8550-nm range. Weight savings were in the tenths of a percent of TOGW. Focus on MDO formulation.

- September 2002

  Laban, M.; Arendsen, P.; Rouwhorst, W.; and Vankan, W.: "A Computational Design Engine for Multi-Disciplinary Optimisation with Application to a Blended Wing Body Configuration," AIAA-2002-5446, September 2002.

  Computational Design Engine (CDE) for multidisciplinary, multifidelity, multilevel, multisite design and analysis is presented, with sample application of BWB in aero (panel codes to Euler to full Navier-Stokes), structures (bending-beam theory to full blown FEM), and flight mechanics (low-fidelity stability and control to a full handling qualities analysis of closed-loop aircraft system). "CDE system applied to the Breguet range optimization of the BWB for constant MTOW." Focuses on CDE process more than BWB design.

- September 2002

  Qin, N.; Vavalle, A.; Le Moigne, A.; Laban, M.; Hackett, K.; and Weinerfelt, P.: "Aero Studies for Blended Wing Body Aircraft," AIAA-2002-5448, September 2002.

  European BWB concept used for CFD studies; 80-m span, propulsion system not included. On baseline, outer wing stalls at cruise $M = 0.85$ and $\alpha = 4$ deg (cruise $\alpha = 3$ deg). Twist distribution redesigned to alleviate high outboard loading.

- September 2002

  Mukhopadhyay, V.; Sobieszczanski-Sobieski, J.; Kosaka, I.; Quinn, G.; and Charpentier, C.: "Analysis Design and Optimization of Non-cylindrical Fuselage for Blended-Wing-Body Vehicle," AIAA-2002-5664, September 2002.

  Deep sandwich panel and ribbed shell concepts shown to be structurally inefficient. These flat panel concepts weighed 25–38 kg/m^2. Alternative approach using multibubble fuselage with outer ribbed shell was more promising (20–30 percent lower weight than flat-panel concepts); however, still twice as inefficient as a cylindrical fuselage.

- September 2002

  Rodriguez, D. L.: "A Multidisciplinary Optimization Method for Designing Boundary Layer Ingesting Inlets," AIAA-2002-5665, September 2002.

  CFL3D, NEPP (engine analysis code) are linked, and NPSOL (gradient-based nonlinear optimizer) is used for optimization. Fuel burn was minimized while maintaining cruise lift. Emphasis of paper on MDO method, not BWB design results.

- September 2002

  Gilmore, R.; Wakayama, S.; and Roman, D.: "Optimization of High-Subsonic Blended-Wing-Body Configurations," AIAA-2002-5666, September 2002.

  BWB cruise speed pushed from $M = 0.85$ to 0.95; $M = 0.93$ configuration was studied in more detail. Best option was $M = 0.90$, but propulsion airframe interference was not assessed. "BWB sonic cruiser" study.

- January 2003

  Gilmore, R.; Wakayama, S.; and Roman, D.: "Aerodynamics of High-Subsonic Blended-Wing-Body Configurations," AIAA-2003-0554, January 2003.

Similar to September 2002 paper. CFL3D N-S CFD results used to calibrate WingMOD. The M = 0.93 BWB-6-250B configuration optimized (propulsion not modeled).

- June 2003

  Pilczer, D.: "Noise Reduction Assessments and Preliminary Design Implications for a Functionally-Silent Aircraft", Massachusetts Institute of Technology, M.S. Thesis, June 2003.

  Introduces "silent" aircraft concept utilizing "quiet lift" using clean BWB wing and seamless TE, "silent thrust" using embedded propulsion (nine engines) with high-aspect-ratio nozzles and low jet velocities, and a "hidden TE" by ingesting the boundary layer avoiding the scattering of turbulent boundary-layer flow across the TE. BLI improves range by 5.4 percent assuming 60 percent of engine mass flow stems from the boundary layer. Concept predicted to reduce approach and takeoff EPNL by 30 dB and 22.5 dB, respectively. "Silent drag" requirements quantified, but no solutions proposed.

- July 2003

  Wakayama, S.; Gilmore, R.; and Brown, D.: "Design Trades for a Large BWB Freighter," AIAA-2003-2503, July 2003.

  Design BWB to carry smaller sized versions of standard shipping containers (intermodal containers). 5000-nm range. Measuring efficiency as (Wpayload*range*cruise Mach)/TOGW, the "BWB-8-1000" offers significant improvement (44 percent) over baseline (current freighters).
- July 2003

  Liebeck, R. H.: "BWB Design Challenges," AIAA-2003-2659, July 2003.

  Proposes common airframe for both military (tanker, cargo, bomber) and commercial application to make development viable. States "BWB must exceed performance of existing airplanes." Challenges are commonality, speed and flight mechanics. Breguet range equation used for performance estimates, BWB compared with A380F, C-5A, KC-10A, B-52, and B-2.

- July/August 2003

  Willcox, K. and Wakayama, S.: "Simultaneous Optimization of a Multiple-Aircraft Family," *Journal of Aircraft*, Vol. 40, No. 4, July/August 2003, pp. 616–622.

  Journal article of AIAA-2002-1423, April 2002. See above for summary.

- November 2003

  Ko, A.; Leifsson, L. T.; Mason, W. H.; Schetz, J. A.; Grossman, B.; and Haftka, R. T.: "MDO of a Blended-Wing-Body Transport Aircraft with Distributed Propulsion," AIAA-2003-6732, November 2003.

  Examines effect of distributed propulsion using eight embedded engines and a hybrid jet flap/jet wing/conventional exhaust approach. Shows 5.4-percent TOGW improvement compared with conventional BWB (four embedded engines). Effect of jet wing on pressure distribution of body not included. The jet is expected to entrain the flow over the body and increase drag. Breguet range equation used for performance estimates. Refreshingly good paper relative to many others mentioned above (acknowledgements to Kimmel and Guynn).

- December 2003

  Daggett, D. L.; Kawai, R.; and Friedman, D.: "Blended Wing Body Systems Studies: Boundary Layer Ingestion Inlets with Active Flow Control," NASA CR-2003-212670, December 2003.

  Sponsored by the Ultra Efficient Engine Technology (UEET) project, Karl Geiselhart was NASA technical monitor. Utilized BWB 450-1U design as baseline. Overall performance compared with 747-400. Study concluded BLI with active flow control (pulsating air jets) showed 5.5 percent fuel efficiency benefit compared with conventional pylon-mounted engine. Assumes active flow control technology works and requires negligible power.

- January/February 2004

  Liebeck, R. H.: "Design of the Blended Wing Body Subsonic Transport," *Journal of Aircraft*, Vol. 41, No. 1, January/February 2004, pp. 10–25.

  Journal article version of 2002 Wright Brothers lecture and paper. Good summary of concept development. BWB-450 (primary structure assumed to be mostly composite) compared with Airbus A380-700 (primary structure assumed to be mostly aluminum), BWB showed 32-percent lower fuel burn per seat.

- May 2004

  Manneville, A.; Pilczer, D.; and Spakovszky, Z. S.: "Noise Reduction Assessments and Preliminary Design Implications for a Functionally Silent Aircraft," AIAA-2004-2925, May 2004.

  Study funded by Russ Thomas, NASA Langley Research Center. Explores the technological barriers to silent aircraft and assesses potential noise-reduction concepts and technologies. Aerodynamically smooth lifting surfaces (no flaps or slats), hidden TE, BLI, UHB engines (BPR = 40), distributed propulsion/high-aspect-ratio nozzles, and silent drag with engine air brakes were the main ideas proposed. Gear noise was neglected by assuming gear deployment very close to the ground. Idea for common core that drives multiple fans proposed. Concludes BWB-type aircraft with embedded propulsion can yield large noise reductions.

- July/August 2004

  Mukhopadhyay, V.; Sobieszczanski-Sobieski, J.; Kosaka, I.; Quinn, G.; and Vanderplaats, G. N.: "Analysis, Design and Optimization of Noncylindrical Fuselage for BWB Vehicle," *Journal of Aircraft*, Vol. 41, No. 4, July/August 2004, pp. 925–930.

  Journal article version of AIAA-2002-5664. See summary above.

- September 2004

  Hill, G. A.; Brown, S. A.; Geiselhart, K. A.; and Burg, C. M.: "Integration of Propulsion-Airframe-Aeroacoustic Technologies and Design Concepts for a Quiet Blended-Wing-Body Transport," AIAA-2004-6403,September 2004.

  Range of noise reduction technologies as applied to a 300-passenger, GE90-powered BWB configuration were studied using two evaluation frameworks. These evaluation frameworks were applied to rank PAA (Propulsion Airframe Aeroacoustics) technologies. Results show all technologies have performance penalties that become tolerable only if noise requirements are design drivers. Second, the concept was sized and analyzed using NPSS/WATE, FLOPS, and ANOPP assuming BLI inlets with AFC. Various nozzle and PAA technologies examined and several recommended for further study.

- November 2004

  Hill, G. A. and Thomas, R. H.: "Challenges and Opportunities for Noise Reduction Through Advanced Aircraft Propulsion Airframe Integration and Configurations," 8th CEAS Workshop Paper, November 2004.

  General PAA discussion with focus on airframe shielding. The forward shielding of the BWB concept was highlighted; however, aft shielding remains a challenge.

- January 2005

Campbell, R. L.; Carter, M. B.; Pendergraft, O, C.; Friedman, D. M.; and Serrano, L.: "Design and Testing of a Blended Wing Body with Boundary Layer Ingestion Nacelles at High Reynolds Numbers," AIAA-2005-0459, January 2005.

A knowledge-based aerodynamic design method (CDISC), coupled with an unstructured-grid N-S flow solver (USM3D), was used to improve PAI for a BWB with BLI nacelles. An NTF model was built and tested to validate predictions. Sponsored by UEET in 2004 timeframe.

- February 2005

  Diedrich, A. J.: "The Multidisciplinary Design and Optimization of an Unconventional, Extremely Quiet Transport Aircraft," Massachusetts Institute of Technology, M.S. Thesis, February 2005.

  In-house tools and the Boeing WingMOD program was used to design a silent BWB. Results showed direct operating costs equal to that of B-747-400. Assumed technology levels for 2030 EIS. BWB configuration appears to be selected *a priori*. Design mission is 250-passenger, 4000-nm range. In-house model utilized Breguet range equation for cruise performance. Various parametric studies performed using in-house model and WingMOD. Early SAX-10 configuration proposed here. Specific fuel consumption was 0.54 lbm/lbf-hr.

- April 2005

  Beran, P. S.; Snyder, R. D.; Strong, D.; Bryson, D.; Hur, J.; and Strganac, T.: "Static Nonlinear Aeroelastic Analysis of a Blended Wing Body," AIAA-2005-1944, April 2005.

  Static aeroelastic analysis of BWB for Sensorcraft application performed using NASTRAN to obtain deflections caused by linearly computed airloads. These deflections were then transferred to high-fidelity methodology (Air Force Air Vehicles Unstructured Solver (AVUS)) to compute nonlinear aerodynamics. Computational framework is MDICE (Multidisciplinary Computing Environment), which is designed to link high-fidelity tools, in this case aerodynamics and structures. Paper focuses on geometry representation for BWB and grid generation and deformation.

- April 2005

  Mukhopadhyay, V.: "Blended Wing Body Fuselage Structural Design for Weight Reduction," AIAA-2005-2349, April, 2005.

  Lessons learned from earlier 800-passenger BWB studies, and current efforts on 480-passenger version described. Use of rapid FEM tools to design and analyze Y-braced fuselage derivatives were presented. Double-bubble, triple-bubble, and four- and five-bubble design concepts were presented and shown to be superior to the vaulted-shell concepts of the earlier generation. Finally, a Y-braced box-type fuselage concept using stitched resin-film-injected (RFI) composites with foam cores was presented as a practical alternative to ease manufacturing concerns.

- May 2005

  Reimann, C. A.; Tinetti, A. F.; and Dunn, M. H.: "Noise Prediction Studies for the Blended Wing Body Using the Fast Scattering Code," AIAA-2005-2980, May 2005.

  Fast Scattering Code (FSC) validated by comparisons of predicted values with measured values from 3 percent scale model acoustic tests performed at NASA Langley Research Center. Results show that FSC can successfully predict measured acoustic behavior.

- September 2005

  Green, J. E.: "Air Travel—Greener by Design," *The Aeronautical Journal*, September 2005.

  Update on the 2002 publication. Mentions BWB and SAI concept in areas of noise reduction and increased *L*/*D* for reduced fuel burn. Recommends further study of BWB concept.

- January 2006

  Hileman, J. I.; Spakovszky, Z. S.; Drela, M.; and Sargeant, M. A.: "Aerodynamic and Aeroacoustic Three-Dimensional Design for a 'Silent' Aircraft," AIAA-2006-0241, January 2006.

  Presents design methodology for BWB airframe shape. States, "To be viable, the aircraft [SAI concept] requires a fuel burn comparable to modern conventional aircraft." Mission is 215 passengers and 5000-nm range. Paper addresses problem of obtaining low noise approach with minimal impact to cruise *L*/*D*. Suggested approaches are to increase centerbody LE camber, utilize thrust vectoring for pitch trim on approach, use quiet LE high-lift devices such as drooped LE, use quiet perforated spoilers to produce drag on approach, and use landing-gear fairings.

- January 2006

  Diedrich, A.; Hileman, J.; Tan, D.; Willcox, K.; and Spakovszky, Z: "Multidisciplinary Design and Optimization of the Silent Aircraft," AIAA-2006-1323, January 2006.

  MDO design tool development and application for BWB is described. 2030 EIS date postulated, but baseline is the Boeing 787. 215 passengers, 5000-nm range. Tool combines a modified version of WingMOD with acoustics models and semi-empirical propulsion, aero, weights, and mission modules. WingMOD provides an initial input to the other modules, which then iterate on thrust and fuel needed to complete the mission. Acoustic modules presented. Cruise module uses Breguet range equation. SAX-12 design presented here. SFC is 0.50 lbm/lbf-hr. Noise performance compared with 767-300.

- January 2006

  Wakayama, S.: "Subsonic Multi-Role Aircraft," AIAA-2006-1513, January 2006.

  Paper examines a conceptual tanker/bomber aircraft (BWB configuration), describes compromises needed for commonality, and explores potential capabilities. Performance of BWB concepts compared with existing aircraft (i.e., B-52, KC-10). BWB tanker/bomber concept of operations developed. Results show 60 percent fuel-burn savings over current aircraft, plus a 40 percent reduction in development cost compared with two independent development efforts.

- July 2006

  Stone, J. R.; Krejsa, E. A.; Berton, J. A.; and Kim, H. D.: "Initial Noise Assessment of an Embedded-Wing-Propulsion Concept Vehicle," AIAA-2006-4979, July 2006.

  Cruise efficient short takeoff and landing (CESTOL) vehicle concept with embedded-wing-propulsion utilized by consultants to Diversitech for NASA GRC. The study concept is a product of a Boeing configuration definition study by Kawai for a 170-passenger, 180,000-lb TOGW, twelve-engine BWB design with internally blown flaps for STOL performance. Noise-prediction capability for this concept was developed based largely on NASA's FOOTPR code. Significant noise reduction relative to current state of the art is predicted.

- September 2006

  Kim, H. D.; Berton, J. J.; and Jones, S. M.: "Low Noise Cruise Efficient Short Take-Off and Landing Transport Vehicle Study," AIAA-2006-7738, September 2006.

  Presents overall CESTOL concept from NASA-sponsored study. Twelve-engine, 170 passenger, 3000-nm range BWB from Boeing WingMOD folks (Kawai, Wakayama).

- September/October 2006

Campbell, R. L.; Carter, M. B.; Pendergraft, O, C.; Friedman, D. M.; and Serrano, L.: "Design and Testing a Blended Wing Body with Boundary-Layer Ingestion Nacelles," *Journal of Aircraft*, Vol. 43, No.5, September-October 2006, pp. 1479–1489.

Journal version of AIAA-2005-459. (See notes above.)

- November 2006

  Peigin, S. and Epstein, B.: "CFD Driven Optimization of BWB Aircraft," *AIAA Journal*, Vol. 44, No.11, November 2006, pp. 2736–2745.

  Multipoint, multiconstrained optimization of BWB for minimum drag using genetic algorithms and a combination of full N-S computations and reduced-order methods. Large drag reductions shown.

- December 2006

  Kawai, R. T.; Friedman, D. M.; and Serrano, L.: "Blended Wing Body (BWB) Boundary Layer Ingestion (BLI) Inlet Configuration and System Studies," NASA CR-2006-214534, December 2006.

  More detailed follow-on from 2003 study (see NASA CR-2003-212670 above). Previous study predicted 5.5-percent fuel efficiency benefit for BLI with AFC, but utilized simplified method to account for first-order airframe integration effects. This study utilized fully viscous N-S analysis. The BWB 450-1U configuration is utilized (three UEET direct-drive fan engines in podded nacelles). Results show a 10-percent fuel efficiency benefit. Details (and potential installation penalties) of AFC system not presented.

- January 2007

  Staelens, Y. D.; Blackwelder, R. F.; and Page, M. A.: "Novel Pitch Control Effectors for a Blended Wing Body Airplane in Takeoff and Landing Configuration," AIAA-2007-0068, January 2007.

  Introduces the concept of belly flaps to enhance the lift and pitching moment of a BWB during takeoff and landing. Wind-tunnel tests of a model patterned after the BWB-450 concept show an increase of 35 percent for takeoff C_L and an increase of 10 percent for pitching moment with the belly flap deployed to 90 deg.

- January 2007

  Plas, A. P.; Sargeant, M. A.; Madani, V.; Crichton, D.; Greitzer, E. M.; Hynes, T. P.; and Hall, C. A.: "Performance of a Boundary Layer Ingesting (BLI) Propulsion System," AIAA 2007-0450, January 2007.

  Utilized a power-saving coefficient (PSC), which is the difference in power required between traditional non-BLI podded engines (P_{ref}) and BLI engines (P_{bli}), divided by P_{ref}. Three models of increasing fidelity were used to examine the distortion transfer and propulsion system performance. Low distortion transfer through the fan will lead to higher PSC values. Results indicate BLI will decrease fuel burn up to 3.8 percent. Engine aeromechanical response issue noted briefly, no solutions proposed. More research needed.

- January 2007

  Hileman, J. I.; Reynolds, T. G.; de la Rosa Blanco, E. R.; Law, T. R.; and Thomas, S.: "Development of Approach Procedures for Silent Aircraft," AIAA-2007-0451, January 2007.

  Approach trajectory optimized for low noise to include a flight path angle of 3.9 deg, velocity of 60.8 m/s (118 knots), and a threshold displacement of 1.2 km (3937 ft). Noise footprint was then calculated given these assumptions, resulting in 61 dBA at the airport perimeter; EPNL was 71.9 EPNdB. Trim and drag production on approach (α = 15.6 deg) are accomplished by a combination of elevon deflection (18.5 deg up) and thrust vectoring (30 deg down). Approach high-lift configuration includes a 27-deg drooped LE, elevator deflection of –16 degrees and α of 21.9 deg (not sure how this relates to trim conditions listed above).

- January 2007
  Hileman, J. I.; Spakovszky, Z. S.; Drela, M.; and Sargeant, M. A.: "Airframe Design for 'Silent Aircraft,'" AIAA-2007-0453, January 2007.
  Main focus of this paper is the aerodynamic shaping of the airframe centerbody, but also includes a summary of the evolution of the SAX concepts and various design assumptions, such as 10-percent structural weight reduction as a result of advanced composites (2025), and fuel burned during climb was 2 percent of maximum takeoff weight.

- January 2007
  de la Rosa Blanco, E. R.; Hall, C. A.; and Crichton, D.: "Challenges in the Silent Aircraft Engine Design," AIAA-2007-0454, January 2007.
  Several potential engine concepts studied. References to previous work published in Europe in 2005 result in selection an of embedded engine with a single core driving three fans. Three engines were needed, resulting in nine fans, each 1.2 m in diameter. Variable-area 2D nozzles utilized, exit area is 45 percent larger at takeoff than top of climb. Engine component design described (good reference for GRC evaluation). Engine weight table not complete.

- January 2007
  Tam, R.; Belobaba, P.; Polenske, K. R.; and Waitz, I.: "Assessment of Silent Aircraft-Enabled Regional Development and Airline Economics in the UK," AIAA-2007-0455, January 2007.
  London Heathrow and East Midlands airport are used to analyze relationships among airline operations, noise, local housing prices, and regional economic growth. Assumed purchase price of SAX-40 was $161M. Several regulatory scenarios studied, including "light green" and "dark green," providing progressively greater operational and financial penalties for noisier aircraft. SAX-40 is the only profitable aircraft in the "dark green" scenario, assuming that purchase price and maintenance costs are no more than conventional alternatives (in 2020).

- January 2007
  Crichton, D.; de la Rosa Blanco, E. R.; Law, T. R.; and Hileman, J. I.: "Design and Operation for Ultra Low Noise Take-off," AIAA-2007-0456, January 2007.
  SAI target noise level was 60 dBA for 2025 aircraft technology (at the airport perimeter). Details given on takeoff profile design and performance. Analysis here indicates nozzle area should be 35 percent larger at takeoff than top of climb to achieve noise goal. Cumulative noise estimated to be 210 EPNdB, 75 dB below Chapter 4 requirements.

APPENDIX C : SAI Requirements

Noise

"Aircraft must be inaudible outside of a typical airport boundary."
Goal is 60 dBA.

Airport assumptions:

- 3000-m runway
- 450 m from the side of the runway to the airport perimeter
- 1000 m from both ends of the runway to the perimeter
- 2200 m from perimeter (on the approach end of the runway) to the touchdown point

Rationale: Aircraft noise is costly to society. Limiting aircraft noise to the airport boundary would result in significant benefits. The noise requirement is used to drive all aspects of the design to achieve the best possible result without unduly compromising performance. The goal of 60 dBA is equal to background noise inside an office or restaurant.

Comments: The Effective Perceived Noise in Decibels (EPNdB) certification points are not located at the airport perimeter, so the SAI team estimated the certification cumulative noise to be 209.4 EPNdB, which is 75 dB below Chapter 4 noise requirements. This certification noise level can be considered an SAI requirement, along with the 60 dBA goal.

Technology Risk Assumption

In general, a 2025 technology level (~TRL = 6) was assumed (e.g., for propulsion, materials).

Rationale: To meet the requirements, low TRL technologies and aggressive technology assumptions are utilized.

Mission

Mission performance paramters:

- 215 passengers in three-class configuration (assume 240 lb per passenger)
- 5000 nm range
- Cruise altitude of 40,000-45,000 ft
- Cruise speed = 0.8 M
- Reserve fuel for a 200-nm divert and a 45-minute loiter

Rationale: The target is a midsize aircraft that best meets the noise goals. The cruise speed was selected to be similar to existing aircraft (737, 757, 767), and initially the worry about inlet design held the speed to 0.8 M. Subsequent work showed that the inlet could handle a higher cruise speed.

Emissions

Competitive with existing or next-generation aircraft.

Rationale: Emissions characteristics are likely to be equal to or possibly greater in importance than noise for future air transports.

Comments: No explicit emissions requirements were found; however, the general theme would be that emissions should be no worse than conventional transport aircraft in the same timeframe.

Operations

Airports: Heathrow and East Midlands

Operational assumptions and characteristics that flow down from the noise requirement:

- Thrust-managed takeoff
- Approach speed of 60.8 m/s
- CDA on a 3.9-deg glide slope
- Displaced threshold of 1.2 km
- FAR requirements met for go-around, engine-out, gusts, and so on

Rationale: Low approach speeds (to enable displaced threshold landings), CDA on a glide slope that is slightly steeper than normal, and thrust-managed takeoff profiles all provide significant benefits for noise reduction.

Cost

No explicit cost requirements. Economics paper shows parametric sensitivity studies. Costs are extrapolated from existing aircraft cost data.

Rationale: No explicit cost requirements were found; however, the general theme would be that Life Cycle Cost (LCC) should not be a showstopper.

APPENDIX D: Risk Item List

Risk ID	Risk Title	Risk Statement	Complete?	Likelihood	Consequence
1	Cruise aero performance	If the actual SAX-40 cruise aerodynamic performance is less than predicted, then attainment of the mission requirements will be jeopardized.	Y	4	3
2	Deployable drooped leading-edge and continuous mold line elevons	If the deployable drooped LE and CML elevon performance is less than predicted, then attainment of the noise and operational performance requirements will be jeopardized.	Y	2	4
3	Stability and control	If the SAX-40 stability and control characteristics differ from the predictions, then attainment of the mission and operational requirements will be jeopardized.	N	-	-
4	BWB configuration: structures, weight	If the SAX-40 structural and subsystems weights are greater than predicted, then attainment of the mission requirements will be jeopardized.	Y	4	4
5	BWB configuration: human factors	If the SAX-40 human-factors characteristics negatively impact the concept feasibility, then attainment of the requirements will be jeopardized.	Y	3	5
6	BWB configuration: internal layout.	If the SAX-40 configuration layout does not result in a feasible design, then attainment of the requirements will be jeopardized.	Y	1	3
7	Boundary-layer ingestion/inlet design	If the SAX-40 inlet design and use of BLI does not result in the predicted performance, then attainment of the mission and noise requirements will be jeopardized.	Y	4	4
8	Variable-area exhaust thrust-vectoring nozzle	If the variable-area/thrust-vectoring nozzle performance is less than predicted, then attainment of the mission and noise requirements will be jeopardized.	Y	5	5
9	Transmission system	If the engine transmission system performance is less than predicted, then attainment of the mission requirements will be jeopardized.	Y	3	3

Risk ID	Risk Title	Risk Statement	Complete?	Likelihood	Consequence
10	Single-core/multiple-fan concept	If the singe-core/three-fan concept performance is less than predicted, then attainment of the mission requirements will be jeopardized.	**Y**	**3**	**3**
11	Propulsion-airframe integration/buried engines	If the buried-engine concept presents propulsion/airframe integration issues that cannot be resolved, then attainment of the mission requirements will be jeopardized.	**Y**	**2**	**3**
12	Low flight idle thrust	If the assumed low flight idle thrust is not feasible, then attainment of the noise and operational requirements will be jeopardized.	**Y**	**3**	**3**
13	Low-speed fan with forward swept blades	If the fan performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.	**Y**	**3**	**2**
14	High-pressure compressor design	If the HPC performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.	**Y**	**3**	**2**
15	Low noise low-pressure turbine design	If the LPT performance is less than predicted, then attainment of the noise and mission requirements will be jeopardized.	**Y**	**3**	**2**
16	Trailing-edge brushes	If the TE brush technology performance is less than predicted, then attainment of the noise requirements will be jeopardized.	**Y**	**3**	**3**
17	Low noise undercarriage	If the low noise undercarriage performance is less than predicted, then attainment of the noise requirements will be jeopardized.	**Y**	**2**	**3**
18	Quiet drag	If sufficient quiet drag cannot be generated, then attainment of the noise requirements will be jeopardized.	**Y**	**2**	**2**

Risk ID	Risk Title	Risk Statement	Complete?	Likelihood	Consequence
19	Long ducts with acoustic liners	If the integration of long ducts with acoustic liners results in acoustic penalties, then attainment of the noise and mission requirements will be jeopardized.	**Y**	**2**	**3**
20	Airframe shielding	If the airframe shielding benefits are less than predicted, then attainment of the noise requirements will be jeopardized.	**Y**	**1**	**2**
21	Thrust managed takeoff	If the thrust-managed takeoff is not viable, then attainment of the noise requirements will be jeopardized.	**Y**	**2**	**5**
22	Displaced threshold and continuous descent approach with increased approach angle	If the use of a displaced threshold and continuous descent approach with an increased approach angle have penalties, then attainment of the noise and operations requirements will be jeopardized.	**Y**	**5**	**4**
23	Cost	If the costs of developing, producing, and operating the SAX-40 outweigh the benefits, then attainment of the mission requirements will be jeopardized.	**Y**	**4**	**4**
24	Overall noise estimates	If the overall noise performance is worse than predicted, then attainment of the noise requirements will be jeopardized.	**Y**	**4**	**4**
25	Aeroelasticity	If the aeroelastic characteristics of the SAX-40 result in penalties, then attainment of the mission requirements will be jeopardized.	**N**	**-**	**-**
26	Emissions	If the emissions characteristics of the SAX-40 are undesirable, then attainment of the mission requirements will be jeopardized.	**Y**	**2**	**4**
27	Experimental	If the attributes (e.g., assumptions, approximations, scaling) of any of the experimental investigations that were conducted in support of the SAX-40 concept are questionable, then attainment of the mission requirements will be jeopardized.	**Y**	**3**	**4**

APPENDIX E: Additional Data Required to Support Further Analysis

As part of the risk-assessment process, the following list of questions was developed by the NASA risk-assessment team and provided to SAI. Because of resource limitations, SAI was unable to respond other than to provide previously published references.

Weights:

[Unless otherwise designated, all of the questions in this section pertain directly to Risk ID #4 and indirectly to many other items that apply to weights, such as Risk ID #'s 1, 2, 8, 9, 10, 16, 17, and 19.]

1. Do you have a short group weight statement for the SAX-40? The standard format is the Society of Allied Weights Engineers Recommended Practice No. 8A (SAWE RP #8A). Part I is relevant; Part II is too detailed for this application. This format is generally used to show a build-up to weight empty, then useful load, and then gross weight. If you don't have this type of breakdown, can you provide component weight estimates or assumptions (e.g., inlet and nozzle duct weights, nozzle variable geometry and thrust-vectoring mechanism weight, transmission-system gear and shaft weight)?

2. What database or methods were used for the WingMod response-surface-based weight estimation?

3. If any empirical weight estimation data exists, are these data available and how do they compare with this data?

4. What are the load cases that were used for the structural design?

5. Is a finite-element model (FEM) available for the SAX-40 internal structural layout? Is a FEM under development? What is the priority for such an effort compared with the noise reduction efforts?

6. Has any work has been done in the area of aeroelasticity, such as free-body flutter, tumbling, wing-flutter margins, and so on? [Risk ID #25]

7. What are the perceived risks that are associated with the weight escalation in the absence of a detailed FEM analysis design?

8. How did you determine the assumed 10-percent reduction in weight with application of advanced composite materials?

Aerodynamic Performance:

[All questions in this section pertain to Risk ID #1.]

1. What is your minimum allowable *L*/*D* to meet your mission goals?

2. In view of the lower performance that was predicted by viscous CFD, have you done anything to improve the performance following the SAX-30 iteration?

3. Your span loading is much more elliptical than typical transports or the Boeing BWB. Has this been evaluated for loads, weights, off-design (e.g., approach, buffet)?

4. Your airfoils are fairly aft-loaded. Have they been assessed for control deflection performance and actuator loads/sizing?

5. Do you have any predictions/estimates of the impact of adding the winglets and nacelles, and, if so, what method was used to generate the estimates?

6. Have you considered the additional performance losses that a real airplane might have?

Stability and Control:

[All questions pertain to Risk ID #3.]

1. For ramp and taxi operations, did you estimate stability during ground maneuvering in terms of tip-back, roll-over, and so on?

2. For takeoff, what is the predicted trim control setting and control flap deflection margin (i.e., degrees of deflection remaining) for longitudinal stability? What roll and yaw rates can be sustained? What is the predicted rotation speed? What is the predicted control setting to cause rotation?

3. For engine-out takeoff, what is the predicted minimum control speed (V_{mc})? What is the predicted control setting to trim one-engine-inoperative (OEI) takeoff? Did you account for second-segment climb gradient regulation?

4. For climb, what is the predicted trim control setting and control flap deflection margin (i.e., degrees of deflection remaining) for longitudinal stability? What roll and yaw rates can be sustained?

5. For cruise, what is the predicted trim control setting and control flap deflection margin (i.e., degrees deflection remaining) for longitudinal stability? What roll and yaw rates can be sustained? Have you identified a Mach buffet margin?

6. For descent and landing, what is the predicted trim control setting and control flap deflection margin (degrees deflection remaining) for longitudinal stability? What roll and yaw rates can be sustained? Do you have both an equilibrium configuration at the nominal operating point and a margin to allow off-nominal operation (e.g., higher descent angles and different speeds)?

7. Does the design have a tendency to pitch up on stall? If so, is the control power sufficient to recover?

8. Have you accounted for the “jet-flap” effect of the vectored thrust?

General Airframe:

1. Please provide any drawings or assumptions on the internal layout of the SAX-40. The economics paper states that the passenger compartment was designed for 215 passengers in a “two-class international configuration.” Can you provide more details? Are the two classes business and economy? How many seats of each? What about windows, aisles, doors, galleys, lavatories, and so on? How much cargo volume was assumed? What is the fuel tank layout, and how much fuel volume was assumed? Avionics bays? APU? Landing gear stowage? We’re in the process of creating an internal layout using ProE, so any insight you can give us per your assumptions in this area would be helpful. [Risk ID #5, 6]

2. Did you make any assumptions for the cabin/center-body/pressure-vessel materials/layers so that we can make an internal noise assessment? Were acoustic liners assumed for this area? [Risk ID #5]

3. Can you provide us full configuration drag polars for up-and-away cruise and low-speed takeoff and approach configurations? Can you provide a breakdown of these polars into zero-lift drag and induced-drag components? For the zero-lift drag, can you provide a further breakdown of each contributor to CD_0, including any estimates or assumptions for interference drag, excrescence and protuberance drag, and so on? [Risk ID #1]

High Lift System:

[All questions in this section support Risk ID #2.]

1. Where on the vehicle LE will the droop capability exist?

2. How will the droop mechanism work? Do you have a diagram of the mechanism?

3. If the droop capability exists inboard of the straight LE section, how will the droop mechanism work in this curved, concave area?

4. What demonstrated concept indicates that LE droop will be attainable on a BWB type configuration? Where are CML LE flaps being developed or used? You mentioned the A380? Can you provide more details on that research, development, and integration effort to show applicability to the SAX-40 concept? Are you familiar with any other applications, particularly with composite materials?

5. What CL_{max} and α are needed for takeoff? For approach? What data support this?

6. How much LE droop is needed?

7. How do you know that a drooped LE and CML elevons with brushes will be able to provide the lift levels required?

8. Will CML capability allow elevon deflections to large enough angles?

9. How will flutter or skin-rippling difficulties be avoided on the CML elevons?

10. How will fatigue fracture of CML elevon skins be avoided?

11. How will adequate frequency response of the elevons be ensured?

12. How do you ensure that deflected CML elevons will return to the correct undeflected external shape?

13. How do you ensure that maximum deflected CML elevons will still produce the required low noise levels?

14. How will an elastic flap, split flap, and TE brushes all work together effectively at the same time?

15. Where are drooped LEs, CML elevons, and TE brushes being developed? How was the weight estimated for these items?

Propulsion:

1. Please provide a full set of the efficiencies that were used in the engine-cycle analysis. Was a chart was shown during the March 2007 workshop at MIT with this type of data? [Risk ID #10]

2. Please discuss the assumption that the distortion produced by the BLI inlets can be tolerated by the fans. High-cycle fatigue caused by inlet dynamic distortion is an issue, and the assumption that it can be tolerated by the three-fan system downstream seems very optimistic. Did the engine companies express concern about this? Has active and/or passive flow control been considered as a means for reducing inlet distortion? [Risk ID #7]

3. How did you handle having three fans share a common inlet duct? Were any losses or inefficiencies assumed to result from interference, or were the three fan inlets somehow segregated inside the inlet? Were any other issues considered given this unconventional design? [Risk ID #7]

4. How finely were you able to design the inlet (i.e., were elements like the fineness of lip, the lip contraction ratio, and external forebody shaping factored into the design)? [Risk ID #7]

5. If flow control is required to achieve acceptable levels of dynamic distortion, do you have any concerns that the flow control devices will perform/behave differently in the presence of the liners? [Risk ID #7]

6. In the cruise condition, is a normal shock generated upstream of the inlet? If so, how is it addressed? [Risk ID #7]

7. Low noise LPT design: The low Reynolds number in the LPT can result in separation bubbles on the airfoils as a result of the boundary-layer profile growth, which results in losses. How much efficiency was traded off for the benefit of reduced noise? Do you have a flow analysis for the LPT conceptual design that can be made available to us? [Risk ID #15]

8. Low-speed fan: How large are the incidence swings that are experienced by the OGV during the flight envelope? In addition to the variable fan nozzle, is a variable OGV being considered? What about flow control on the guide vane surfaces and end walls? Do you have a flow analysis for the fan and an OGV conceptual design that can be made available to us? [Risk ID #13]

9. High-pressure compressor: During vehicle maneuvers, do large variations occur in the boundary-layer thickness on the wing surface in comparison with some nominal boundary layer thickness? If so, could the fan and the HPC be subject to large swings in corrected mass flow rate? What is the variable-geometry schedule for the compressor inlet guide vanes and stators along the operating line? Does the centrifugal compressor require variable geometry to match the axial compressor at all operating conditions? What are the design-point pressure-ratio requirements for the HPC? What are the loading levels per blade row? Do you have a flow analysis for the HPC conceptual design that can be made available to us? [Risk ID #14]

10. AIAA-2007-450 quotes a 3.8-percent fuel burn reduction and a 16.6-percent airframe drag reduction as a result of BLI (~25.1 cruise *L*/*D*). The paper also states that "the installation downstream of the fan was assessed using loss estimates based on clean flow." [Risk ID #7]

- Were friction losses in the acoustically lined S-duct accounted for in the inlet pressure recovery?

- Were aerodynamic and friction losses in the acoustically lined duct that leads to the nozzle accounted for?

- Were aerodynamic, leakage, and friction losses in the variable-area, thrust-vectoring nozzle accounted for?
- Was the external (boat-tail) drag of the variable-area, thrust-vectoring nozzle accounted for?
- Was the gear-box cooling system drag accounted for?

If the answer to any of the above questions is *yes*, please quantify.

11. During thrust reversal, how is the flow directed: up, down, or both? [Risk ID #8]

12. Were any weight penalties assessed for acoustic treatment of the passenger compartment or acoustically induced structural fatigue and vibration? [Risk ID #11]

13. In AIAA-2007-450, you recognize distortion as a high-risk area and you account for it by designing the fan to transfer/attenuate it downstream. Do any penalties result in the fan efficiency (for increasing the required surge margin) or weight (due to high-cycle fatigue) as a result of the circumferential distortion that enters the fan? If yes, please quantify. Do you believe a fan can even be designed to tolerate that level of distortion for 30,000 hours? [Risk ID #7]

14. Did you resize the engine for different levels of BLI in your studies? Increased BLI would decrease the engine mass flow for a given inlet size, as well as cause a drop in the mass-averaged pressure recovery of the inlet flow. This result should lead to a change (loss) in overall engine thrust. This loss is somewhat offset by the decrease in ram drag, but it is unlikely that these two values match. [Risk ID #10]

15. The CFD of the flow through the inlet ducts looks very symmetric within the duct, albeit with circumferential distortion. I would expect to see more asymmetry because the inlets are not symmetric. A lack of any vortical structures that might be expected is also noted. Is the CFD of the actual configuration or a surrogate? [Risk ID #10]

16. Can you provide additional information (e.g., efficiencies, pressure ratios, geometry, weight, performance) on the alternate lower risk propulsion system design (three podded engines). This would aid in our assessment of the SAX-40 system. [Risk ID #10]

17. Do you have a design or assumption for the mechanism that controls the variable-area nozzle and/or the thrust-vectoring system? Have you accounted for any power requirements to operate these systems? [Risk ID #8]

18. Can you provide more details on the engine transmission system design, such as gear and shaft weights, reliability, horsepower ratings, lubrication and cooling requirements, vibration, noise, and so on? [Risk ID #9]

19. Can you provide the engine deck (thrust and fuel flow as a function of Mach, altitude, and power setting) that you utilized for your performance estimates? [Risk ID #1]

Operations:

1. Can the SAX-40 use a conventional approach speed of 140 knots to 145 knots? [Risk ID #22]

2. Quantify both separately and cumulatively the loss of the noise benefit that results from not using CDA, from not using a displaced threshold, and from not using a lower speed approach. Can the SAX-40 still provide a useful reduction in noise even if it is flown with conventional approaches and departures at speeds that are compatible with existing large aircraft? [Risk ID #22]

3. Does any wake benefit result from this design—is the wake likely to be classified as "small" or "large"? [Risk ID #22]

4. A 45-percent engine design speed is required during landing approach. Have the engine resonance issues been considered? (Normally you accelerate quickly through any resonant point and maintain an operational speed well away from resonance.) [Risk ID #12]

5. What consideration has been given to stage matching in the compressor during extended operation at 45-percent speed? Do the stators have to be rotated so far as to cause a wide clearance issue during cruise? [Risk ID #12]

6. Has engine response time during landing been considered? This could be an issue as a result of the low spool speed. [Risk ID #12]

Noise:

[Questions 1-5 pertain to Risk ID #19.]

1. According to AIAA-2007-454, the current SAX-40 design allows for a fan diameter of 1.2 m and an engine length of 2.46 m.
   - What is the axial length of the lined region in the engine nacelle?
   - What is the duct height (inner to outer wall) of this lined section of the engine nacelle?

2. The exhaust duct is a complex propagation path (S-shaped). How does this complexity affect the requirement for splices for the liners? Will they be wider or will there be more of them? If this has been considered, what are the predicted effects?

3. According to AIAA-2006-2525, numerical optimization of the liner parameters was accomplished by developing and solving the appropriate eigenvalue problems based on in-house routines. The paper also states that single-layer liners were used in an optimization study and that any scattering effects that were caused by impedance changes at the interfaces were neglected. Also, the optimization used liners with depths up to 8 in.
   - Have any estimates been made regarding the positive and negative effects of scattering on the far-field attenuation?
   - Has any consideration been given to mode interaction effects (that result from modes of different phases that are encountering the LE of the liner)?
   - Because the fans will be smaller and the noise spectrum will shift upward in frequency, what is the purpose of including frequencies as low as 50 Hz in the optimization? Also, conventional aircraft typically only allow liner depths of up to ~3 in. Will the SAX-40 be able to relax this constraint to allow for significantly deeper liners? What are the impacts if this constraint is relaxed?

4. According to AIAA-2007-453, improved increases in attenuation will be possible with more advanced liners.
   - Have any of these advanced liners already been used for attenuations predictions, or is this just a plan for the future?

5. Can you provide any further details on your decisions related to the application of TE brushes beyond what is in AIAA-2007-451? Have you looked at any potential challenges that are associated with the use of TE brushes (e.g., material, reliability, maintainability)? Do you have a drawing or concept of the installation and mechanisms utilized for TE brush deployment? Did you account for the power that will be required to operate this system?

[Risk ID #16]

6. How much drag is required for landing (both nominal and off-design)? [Risk ID #18]

7. What is the noise benefit that is estimated for the CML surfaces? [Risk ID #18]

8. What is your assumed noise contribution for induced drag? Is induced drag truly quiet? [Risk ID #18]

9. What is the noise budget for the quiet drag? [Risk ID #18]

10. Do you have a baseline quiet drag device in mind? If it is an engine air brake, do you have an estimate of the noise impact during operation? What are the possible noise sources (mechanisms)? How well will the swirl tube work with BLI? If using engine braking, how does this work with thrust vectoring for trim? [Risk ID #18]

11. If you are using perforated drag plates, what is the expected noise impact and why? [Risk ID #18]

Emissions:

1. Can you provide an explanation for how you estimated your emissions performance? Numbers for CO_2 and NO_x were quoted in the slide presentation. What correlations were utilized? [Risk ID #26]

Cost:

[All questions in ths section pertain to risk ID #23.]

1. In the economics paper (AIAA-2007-455), under Section V, Airline Business Case Analysis, on page 9, you mention comparisons with “competitors in the same seat class.” Could you provide more information on these competitor concepts, that is, which ones (if any others besides the 767-300ER), what range/payload was assumed, fuel burn, and so on. How did you define the current technology (2006) midsize international aircraft? Can you provide more details on that aircraft as well?

2. Can you provide a copy of Ref. 26 in the economics paper (AIAA-2007-455), by Belobaba, P., “Airline Fleet Planning Overview,” Lecture Notes, *The Airline Industry* (MIT 16.71J), October 10, 2001.

3. Can you provide the data and process/assumptions used in the extrapolation of “average price per seat” information to estimate purchase prices (page 10 of the economics paper, AIAA-2007-455)? What year dollars are these estimates?

Experimental:

1. Is any information available on the design of the phased microphone arrays that were used for component testing, as well as a description of the experiments and results? A list of references would be fine. [Risk ID #27]

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14. ABSTRACT
A risk assessment of the Silent Aircraft Initiative's SAX-40 concept design for extremely low noise has been performed. A NASA team developed a list of 27 risk items, and evaluated the level of risk for each item in terms of the likelihood that the risk would occur and the consequences of the occurrence. The following risk items were identified as "high risk," meaning that the combination of likelihood and consequence put them into the top one-fourth of the risk matrix: structures and weight prediction; boundary-layer ingestion (BLI) and inlet design; variable- area exhaust and thrust vectoring; displaced-threshold and continuous descent approach (CDA) operational concepts; cost; human factors; and overall noise performance. Several advanced-technology baseline concepts were created to serve as a basis for comparison to the SAX-40 concept. These comparisons indicate that the SAX-40 would have significantly greater research, development, test, and engineering (RDT&E) and production costs than a conventional aircraft with similar technology levels. Therefore, the cost of obtaining the extremely low noise capability that has been estimated for the SAX-40 is significant. The SAX-40 concept design proved successful in focusing attention toward low noise technologies and in raising public awareness of the issue.

15. SUBJECT TERMS
BLI; BWB; Embedded; Noise; Silent; Transport

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