AEROSPACE & OCEAN ENGINEERING
AT VIRGINIA TECH

Greenspan

Final Proposal

2008-2009 AIAA Undergraduate Design Competition

Submitted: June, 2009

Greenspan

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Mission Statement

To work cooperatively in completing the initial design of an efficient, compliant, and superior family of transport category aircraft that will win the 2008-2009 AIAA Undergraduate Design Competition.

Team Values

Honor
Collaboration
Efficiency
Preparedness
Innovation

Executive Summary

Greenspan is pleased to present the WB-1 concept, our selected design to compete in the 2008-2009 AIAA Undergraduate Design Competition. The Request for Proposal (RFP) requires teams present transcontinental transport category aircraft capable of carrying 150 passengers up to 2,800 nautical miles. Additional constraints include fuel burn, noise, emission, and cost requirements that current aircraft do not meet. Using innovative design and advanced technologies, Greenspan's proposed WB-1 concept will meet or exceed the requirements.

The proposed concept employs a design proven in lightweight general aviation aircraft – that of the strut-braced wing. Recent Multidisciplinary Design Optimization (MDO) studies performed at Virginia Tech show the strut can dramatically improve performance metrics in transport category aircraft by decreasing the required structure within the wing. Not only will this reduce wing weight, but the thinner wing will also reduce drag. The thinner wing delays transonic effects, allowing the wing to have less wing sweep than current generation airliners. This reduction in sweep allows for reduced chord length, lowering the Reynolds number and delaying the transition to turbulent flow over the wing.

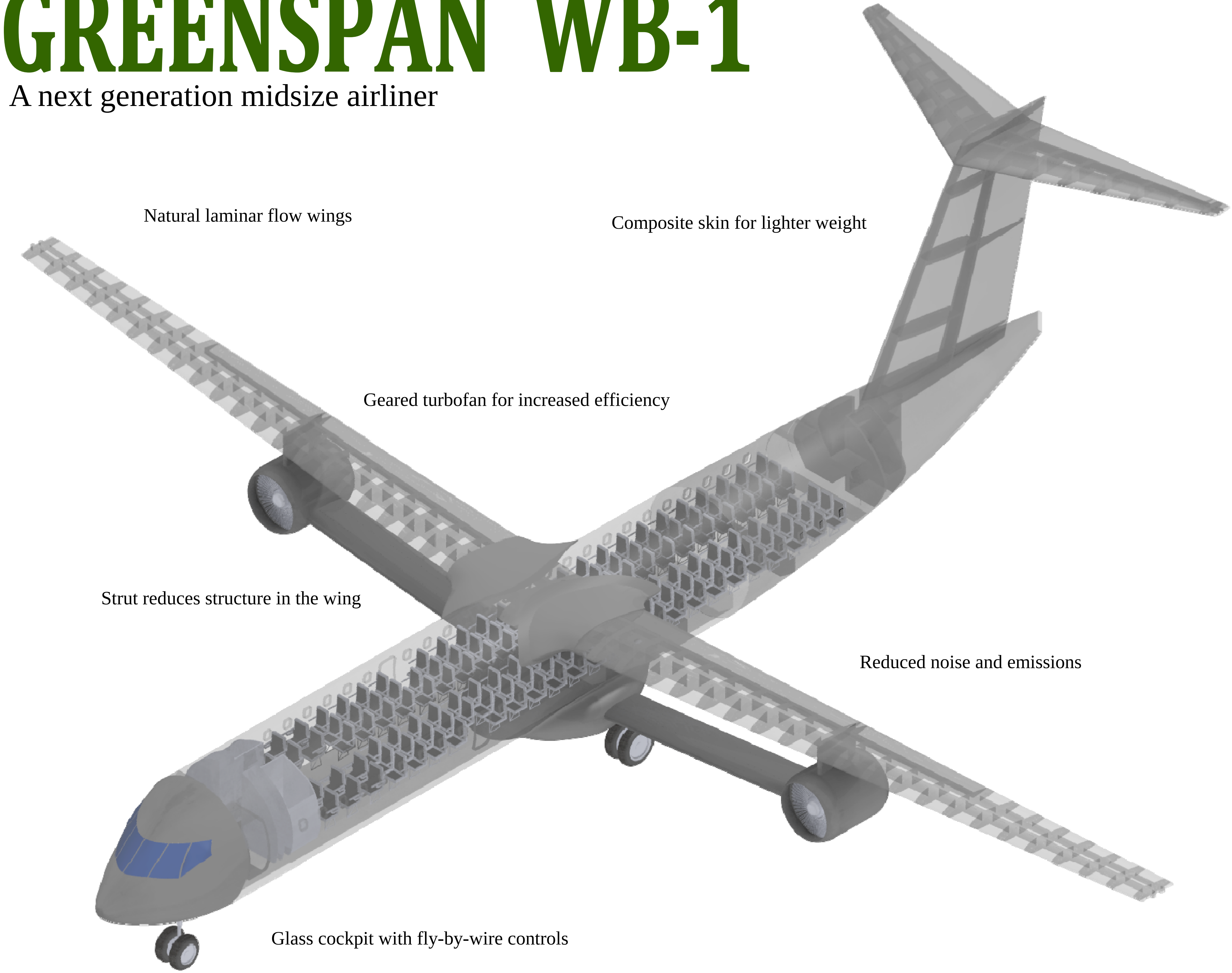
Greenspan designed the WB-1 to include the newest technologies, while maintaining low risk to achieve the fundamental design objective to transport passengers safely. The new technologies include a new engine, the use of reduced-bleed aircraft systems, and the aforementioned use of a high aspect ratio strut-braced wing. The resulting design promises efficiency, increased productivity, and reliability. Today's market is full of high quality aircraft that have been flying for decades. It is now time for the next generation of short to medium range transport aircraft. With the WB-1, Greenspan provides the solution for the next generation transport aircraft. The table below summarizes the request for proposal and locates explanations of how the various requirements are met throughout this proposal:

Request for Proposals Summary

Parameter	Requirement	Met?	Supporting Information
Passenger Capacity	150 Passengers	Yes	Page 27: Interior Layout
Cargo Capacity	7.5 ft^3/passenger	Yes	Page 27: Cargo Configuration
Maximum Range	2,800 nm	Yes	Page 49: Mission Performance
Cruise Speed	.78 Mach	Yes	Page 49: Mission Performance
Initial Cruise Altitude	> 35,000 ft	Yes	Page 49: Mission Performance
Maximum Operating Altitude	43,000 ft	Yes	Page 49: Mission Performance
Maximum Landing Speed	135 kts	Yes	Page 52: Field Performance
Takeoff Field Length	7,000 ft	Yes	Page 52: Field Performance
Community Noise Level	ICAO Ch. 4 -20 db	Yes	Page 86: Noise Comparison
Fuel Burn	≤41 lb/seat	Yes	Page 89: Results of Cost Analysis
Operating Cost	8% Reduction	Yes	Page 89: Results of Cost Analysis

GREENSPAN WB-1

A next generation midsize airliner



WB-1 Selected Details	
Maximum Takeoff Gross Weight	117,200 pounds
Maximum Landing Weight	99,620 pounds
Maximum Fuel	27,250 pounds
Maximum Payload	40,986 pounds
Passenger Capacity	150 in Two-Class Configuration 162 in High-Density Configuration
Wingspan	150 feet
Overall Length	126 feet
Overall Height	41 feet
Taper Ratio	0.40
Leading Edge Sweep	7.83°
Aspect Ratio	20.8
Reference Area	1083 square feet
Mean Aerodynamic Chord	7.67 feet
Cost per Seat Mile (500 nm mission)	$0.0804 per nautical seat mile
Fuel Efficiency (500 nm mission)	38.79 pounds per seat
Noise Emissions	ICAO Chapter 4 –20 EPNdB
FAA Airport Type Code	C-IV (C-III with folding wing option)
Thrust Loading	0.35
Wing Loading	120 pounds per square foot
L/D_{Max}	29.1
Balanced Field Length (Standard Day)	5620 feet
Landing Field Length (Standard Day)	3940 feet
Max Designed Range	2,800 nautical miles
Long Range Cruise Speed	Mach 0.80

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Nomenclature

a_0	Speed of Sound
AR	Aspect Ratio
b	Span
C_D	Coefficient of Drag
$C_{D,f}$	Friction Drag Coefficient
$C_{D,i}$	Induced Drag Coefficient
C_{D0}	Coefficient of Drag due to zero lift
C_g	Center of Gravity
CG	Total Aircraft Center of Gravity
C_L	Coefficient of Lift
$C_{L,Max}$	Maximum Coefficient of Lift
D	Drag
$D_{exhaust}$	Nozzle Exit Diameter
E	Aircraft Oswald Efficiency Factor
e	Wing Oswald Efficiency Factor
h_{TR}	Transition Height
k	$\frac{1}{ARe\pi}$
k_a	Technology factor
K_T	Thrust acceleration
L	Lift
L/D	Lift to Drag Ratio
M_{DD}	Drag Divergence Mach Number
R_e	Reynolds Number
S	Wing area
S_a	Object Clearance Distance
S_g	Ground Roll
S_{ldg}	Landing Field Length
S_T	Transition distance
t/c	Thickness to Chord Ratio
T/W	Thrust to Weight Ratio
V	Velocity
Λ	Leading Edge Sweep
V_c	Cruise Speed
V_D	Dive Speed
$V_{exhaust}$	Nozzle Exit Velocity
W	Weight
W/S	Wing loading
W_f	Final Weight
W_i	Initial Weight
M	Mach Number
ρ	Air density
$\rho_{exhaust}$	Nozzle Exit Density
σ	Density Ratio

Acronyms

ADS-B	Automatic Digital Surveillance-Broadcast
AIAA	American Institute of Aeronautics and Astronautics
APU	Auxiliary Power Unit
BFL	Balanced Field Length
CFRP	Carbon Fiber Reinforced Plastic
ECS	Environmental Control System
ELT	Emergency Locater Transmitter
ETOPS	Extended-range Twin-engine Operational Performance Standards
FAA	Federal Aviation Administration
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
MDO	Multi-disciplinary Optimization
MTOW	Maximum Takeoff Weight
NASA	National Aeronautical and Space Administration
OEI	One Engine Inoperative
RAT	Ram Air Turbine
RFP	Request For Proposal
TOGW	Takeoff Gross Weight
VLM	Vortex Lattice Method
WAAS	Wide Area Augmentation System

Introduction

Greenspan introduces the WB-1 to meet the need of the airlines to replace the aging fleet of mid-range transport-category aircraft. These aircraft are losing their respective battles against efficiency and are under environmental scrutiny. The Boeing 737 and the Airbus A320 constitute this market. The objective of the AIAA Undergraduate Design Competition RFP is to design a new airplane that will advance the current standards of transport aircraft. This proposal describes our understanding of the design objectives, conceptual development, and a detailed description of our solution to the design problem.

RFP Interpretation

The RFP details a variety of requirements that the design must meet. The requirements include a demand for a greener and leaner aircraft that is more environmentally friendly and efficient. The aircraft must operate in the same infrastructure as the aircraft it will replace, while having similar acquisition costs. A summary of technical requirements follows in Table 1.

Table 1: RFP Requirements

Parameter	Requirement	Considerations
Maximum Range	2,800 nm	40,986 lb payload
Capacity	150 2-Class Configuration with High Density Option	
Speed	Mach 0.78 (Objective Mach 0.80)	Long-Range Cruise Speed
Cost	8% Reduction per seat vs. similar in-service aircraft (Objective 10%)	Acquisition Cost Commiserate with Current Products
Noise	ICAO Chapter 4 minus 20db Cumulative	
Climb	43,000 Ft Max Altitude at ISA +15˚C	35,000 Initial Cruise Altitude Capability
Fuel Efficiency	Fuel Burn <41 lbs/seat (Objective <38 lbs/seat)	500 nm Mission
Landing Speed	< 135 knots	Landing at Maximum Landing Weight
Takeoff Field Length	< 7,000 feet	Sea Level at 86°F

Further, additional requirements exist. For instance, the aircraft must be certifiable according to today's regulations and be ready for delivery in less than 10 years (by 2018).

General Aircraft Design Drivers

In general, a common set of drivers control all aircraft design. These drivers include increasing range while decreasing fuel burn. The Breguet Range Equation relates range to specific fuel consumption, velocity, lift-to-drag ratio, and weight:

$$Range = \frac{V}{SFC}\frac{L}{D} ln\left(\frac{W_i}{W_f}\right)$$

While not drivers directly, the drag coefficient and the maximum lift-to-drag ratio are both examples of ways to quantify the efficiency of the aircraft. If the drag is reduced, less thrust is needed and it is possible the engine size could be reduced, which may reduce noise and improve fuel economy.

$$C_D = C_{D,0} + \frac{C_L^2}{\pi\ AR\ e}$$

$$\left(\frac{L}{D}\right)_{max} = \frac{1}{2}\sqrt{\frac{\pi\ AR\ e}{C_{D,0}}}$$

What do all of these equations effectively imply? Primarily that low weight and low specific fuel consumption are critical for efficient cruise. Additionally, a high aspect ratio improves the lift-to-drag ratio, thereby improving efficiency. The performance section of this report discusses the missions the WB-1 will fly.

Comparator Aircraft

Before any concepts were proposed, Greenspan gathered information about aircraft that the concept would replace. The comparator aircraft examined were the McDonnell Douglas MD-88, the Boeing 737-800, and the A320-200. Table 2 shows some of the performance characteristics of these aircraft.

Table 2: Aircraft Comparison[1,2]

	Airbus A320-200	Boeing 737-800	MD-88
Long Range Cruise Mach Number	0.76	0.785	0.76
Ceiling (ft)	39,000	41,000	
Range (nm)	3,000	3,060	2,052
Takeoff Field Length (ft)	6,430	6,890	8,735
Capacity	150 (12/138)	162 (12/150)	142 (14/128)
Max TOGW (lbs)	162,040	174,200	149,500
Wing Span (ft)	111' 10.25"	112' 7"	107' 8"
Wing Area (ft^2)	1,319.7	1,345.5	1,239
Aspect Ratio	9.5	9.4	9.62
Sweep (degrees at c/4)	25	25.02	24.5
Thrust Loading (lbs/ft^2)	0.33	0.31	0.27
Wing Loading (lbs/ft^2)	122.79	129.5	117.7
High Lift Device LE	3-position slats	3-position slats	3-position slats
High Lift Device TE	Single-slotted flaps	Main /aft double-slotted flaps	Fixed vane / main double-slotted flaps

These in-service aircraft meet many of the RFP carriage requirements, and serve as good starting points for many considerations during design. However, they do not meet the noise and efficiency requirements, the primary considerations in this design competition.

Advanced Technology

Greenspan firmly believes that the use of advanced technology is critical to providing marketable products. However, we will be prudent by considering reliability issues and our ability to limit risk. Greenspan will limit the use of unproven technologies to enhance the marketability of the WB-1.

Propulsion

Pratt and Whitney is currently developing a new high bypass ratio turbofan that features a gearbox behind the fan.[3] This gearbox allows the fan and turbine to turn at their optimum rates. In current turbofans, a single shaft connects the fan and turbine. By integrating a reduction gearbox into the system, the fan turns slower, while the turbine can spin faster. This improves the engine fuel economy because when all of the parts turn and work at their optimum rates, they are more efficient. This gearbox may improve fuel efficiency by up to 12% over the current generation of turbofans.[3]

Enhanced Laminar Flow

While the idea of using laminar flow to decrease drag is not new, the method by which our concept will attempt to achieve it is an integration of many technologies. We consider this integration to be a new technology in itself. The WB-1 wing consists of an advanced supercritical airfoil with a low-sweep, high aspect ratio wing planform. To support the high aspect ratio wing, a strut augments the wing's structure. The reduced sweep angle decreases the airfoil thickness-to-chord ratio and allows a reduction of the chord length, effectively reducing the Reynolds number and delaying transition.

Further, the struts will help reduce the amount of internal structure required in the wing, decreasing the total wing weight. Composite construction produces smooth surfaces with shapes required to maintain laminar flow over the wing and fuselage. The HondaJet is currently using natural laminar flow shaping; therefore, we fully expect to be able to account for the benefits provided by the integration of the various technologies.[4]

Reduced-bleed Systems

Greenspan will implement reduced-bleed systems in the WB-1. The Boeing 787 is going to be the first aircraft of its kind to implement such advanced systems.[5] Boeing has eliminated all of the bleed air on the 787, except for the amount required for engine cowl de-icing. Shaft driven generators connected to a gearbox on the engine generate electricity to power all of the other aircraft systems. By reducing the bleed air removed from the compressor, the hot air remains in the engine's gas generator to generate additional thrust. Greenspan expects weight reduction and improved powerplant efficiency due to reduced-bleed system integration.[5] The major difficulty with implementing such systems is sizing the electrical system properly. The Systems section of this proposal provides additional detail regarding reduced-bleed systems.

Risk Awareness

The high level of efficiency that the RFP requires forced Greenspan to integrate several advanced technologies. Greenspan is more than certain that they can achieve the design requirements by utilizing the advanced technologies. However, in the event that the integration of one or more of the advanced technologies fails, Greenspan has considered the risk involved. Through analysis, Greenspan determined the effects of removing the advanced technologies, and whether or not the aircraft performance, still achieved the RFP requirements.

The geared turbo fan is critical for meeting the noise requirement. Although, other noise reducing properties are implemented all throughout the aircraft, meeting the noise requirement ultimately depends on the geared turbofan. The engine is projected to be released in 2013, and the WB-1 does not need to be in service until 2018. This leaves ample time to work out any issues that may arise with the integration of the geared turbofan.

Enhanced laminar flow is the primary reason for achieving nearly all of the RFP requirements, especially fuel burn and operating cost. With the amount of research put into laminar flow, the high aspect ratio, the low wing sweep, the small thickness to chord ratio, among others, Greenspan feels that enhanced laminar flow is at a low risk for failure.

Lastly, the ability for the WB-1 to meet the RFP requirements does not depend at all on the reduced-bleed system. The low bleed system aids in efficiency and weight reduction, but a failure to integrate the system into the aircraft would not hinder the WB-1 from being a green and efficient replacement for the Boeing 737-800 and Airbus A320.

Greenspan tackled several advanced technologies that pose some threat to design feasibility; however, the WB-1 was designed cautiously considering these risks.

Concept Selection

Initially, the Greenspan design team considered many concepts as possible solutions to the design problem. Initial concepts included a traditional low-wing configuration, an over-the-wing engine-mount, a strut-braced high-wing design, an integrated wing body, and a joined-wing design. Greenspan ruled out the integrated wing body design due to concerns regarding the packaging of the payload and passengers. Unproven structural complexities removed the joined–wing design from contention. Greenspan also disregarded innovations requiring drastic changes affecting the current infrastructure, such as the utilization of non carbon-based fuels. Therefore, Greenspan examined the traditional low-wing configuration, the over-the-wing engine-mount design, and the strut-braced high-wing as possible concepts.

Concept Descriptions

Each configuration is a variation of the basic tube and wing design. The "tube" generally remains the same among each configuration, as the payload is also the same. The shape and size of the wing planform varies with the designs. For example, the low-wing designs require a thicker wing with greater chord lengths than the strut-braced concept because they do not have the support of the strut that would allow a decrease in thickness and sweep.

Greenspan considered the traditional low-wing configuration because of its past success. The concept included the fuselage mounted atop the wings. Under-wing engine mounts and a T-tail were initially considered for the empennage. However, this design raised concerns among Greenspan team members because some believed that the technological advances in this configuration may already be exhausted. Aircraft currently in development, such as the Bombardier C-Series aircraft and Mitsubishi Regional Jet, will likely be similar to this concept. Figure 1 displays an initial three-view drawing of this concept.

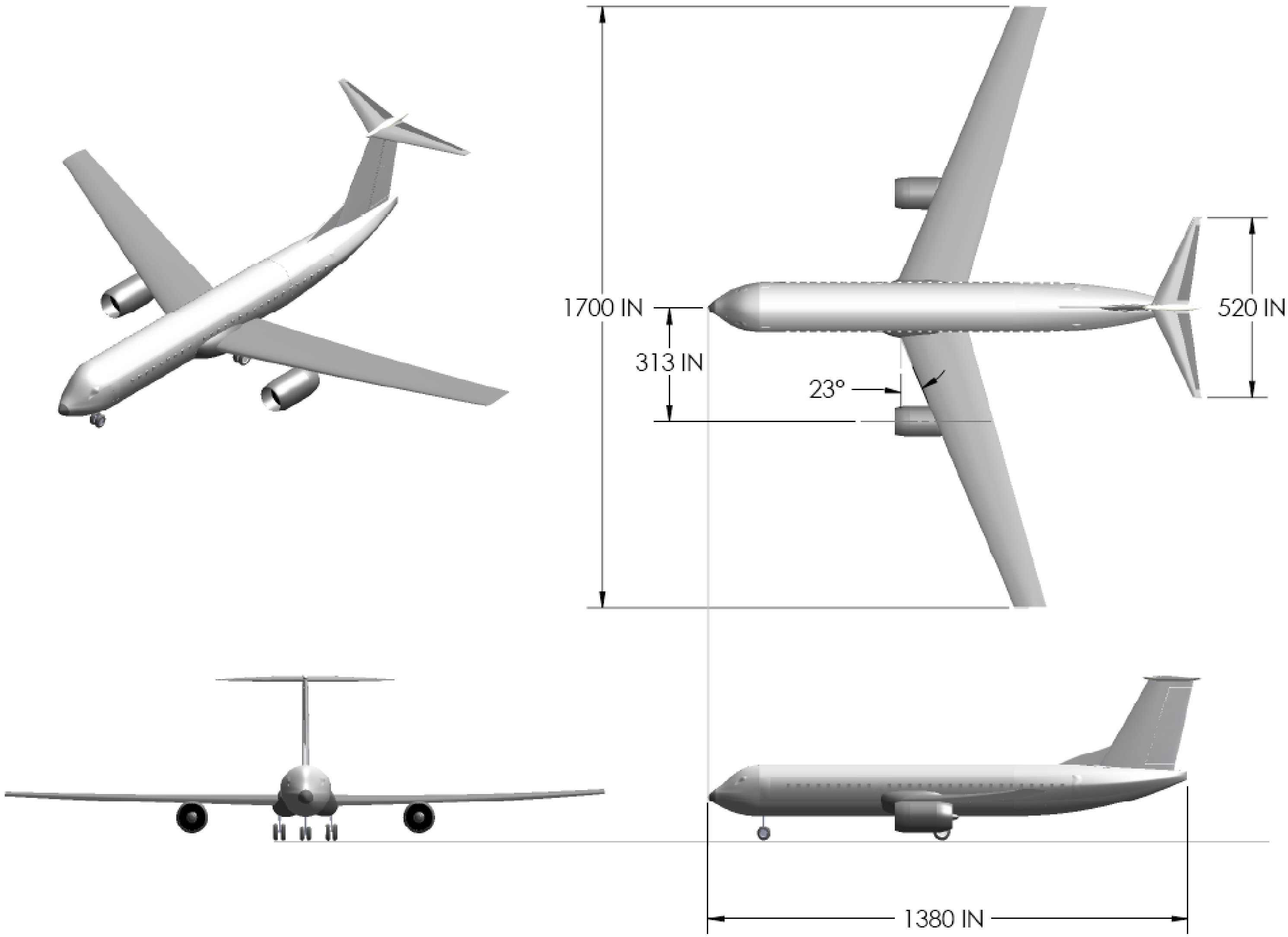


Figure 1: Traditional Low-wing Concept

Another concept examined was an over-the-wing engine-mount. The HondaJet uses an over-the-wing engine-mount to reduce vibration, noise, and drag.[4] The largest concerns with this design were maintenance, accessibility, and vibration. The relatively large size of the aircraft may amplify the vibrations, as compared to the HondaJet. Figure 2 shows the initial three-view drawing for this concept. The sizing for this concept is remarkably similar to that of the traditional low-wing concept.

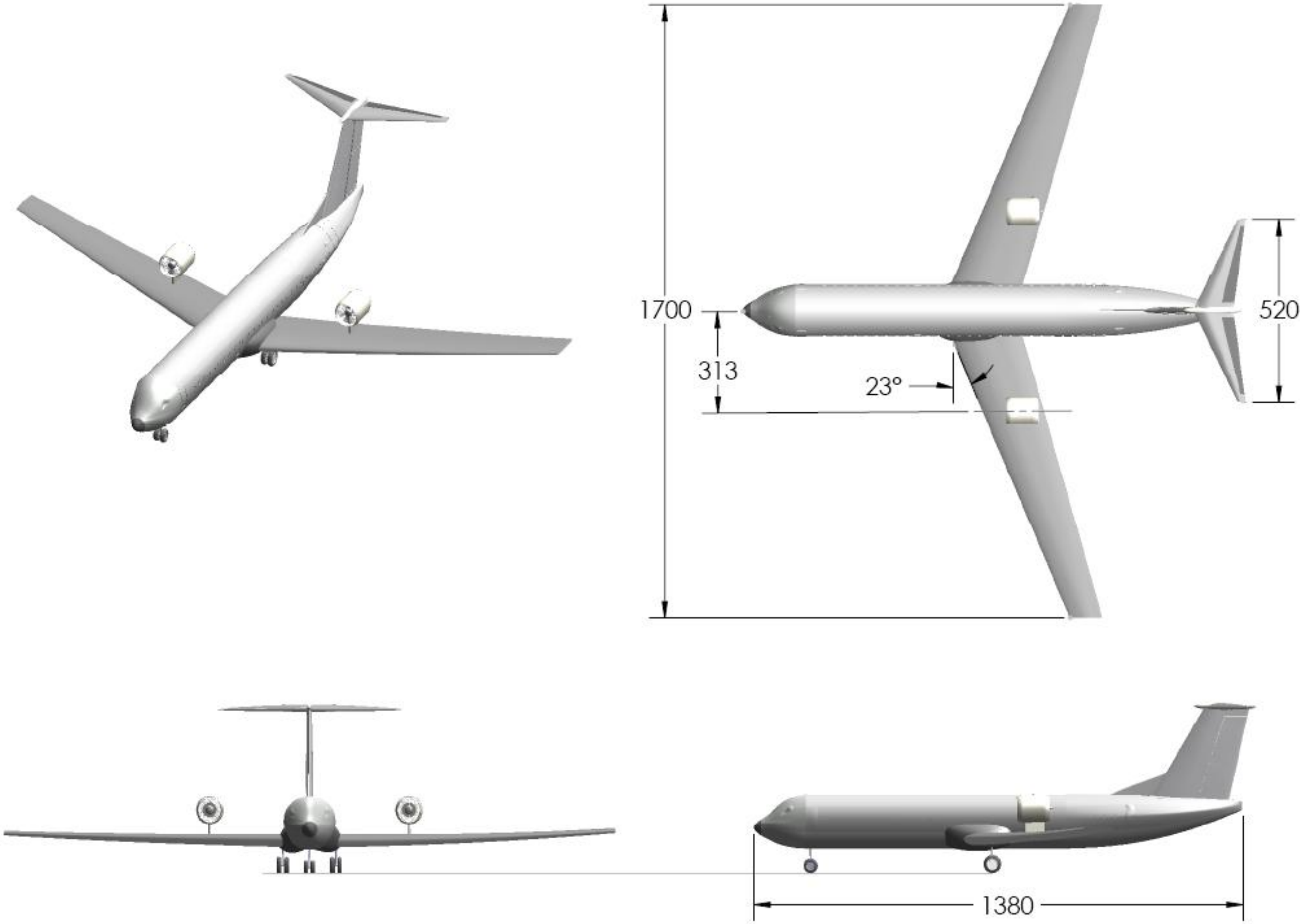


Figure 2: Over-the-wing Engine-mount Concept

The third concept that we considered was the strut-braced wing. This concept evolved to integrating the strut, pylon, and nacelle structures. This concept is necessarily a high-wing design. Virginia Tech has already completed a great deal of MDO work on the strut-braced wing design.[6] However, the requirements of the previous work at Virginia Tech focused on larger aircraft than those required by the RFP. Figure 3 shows the initial strut-braced wing concept.

In order to achieve all benefits of the strut, the design has a higher wingspan than the other designs. This causes an issue with the aircraft's ability to integrate smoothly into today's infrastructure. Specifically, there is concern that the aircraft may not fit within the gates of the aircraft it will replace. This matter is discussed further in the Operational Considerations section.

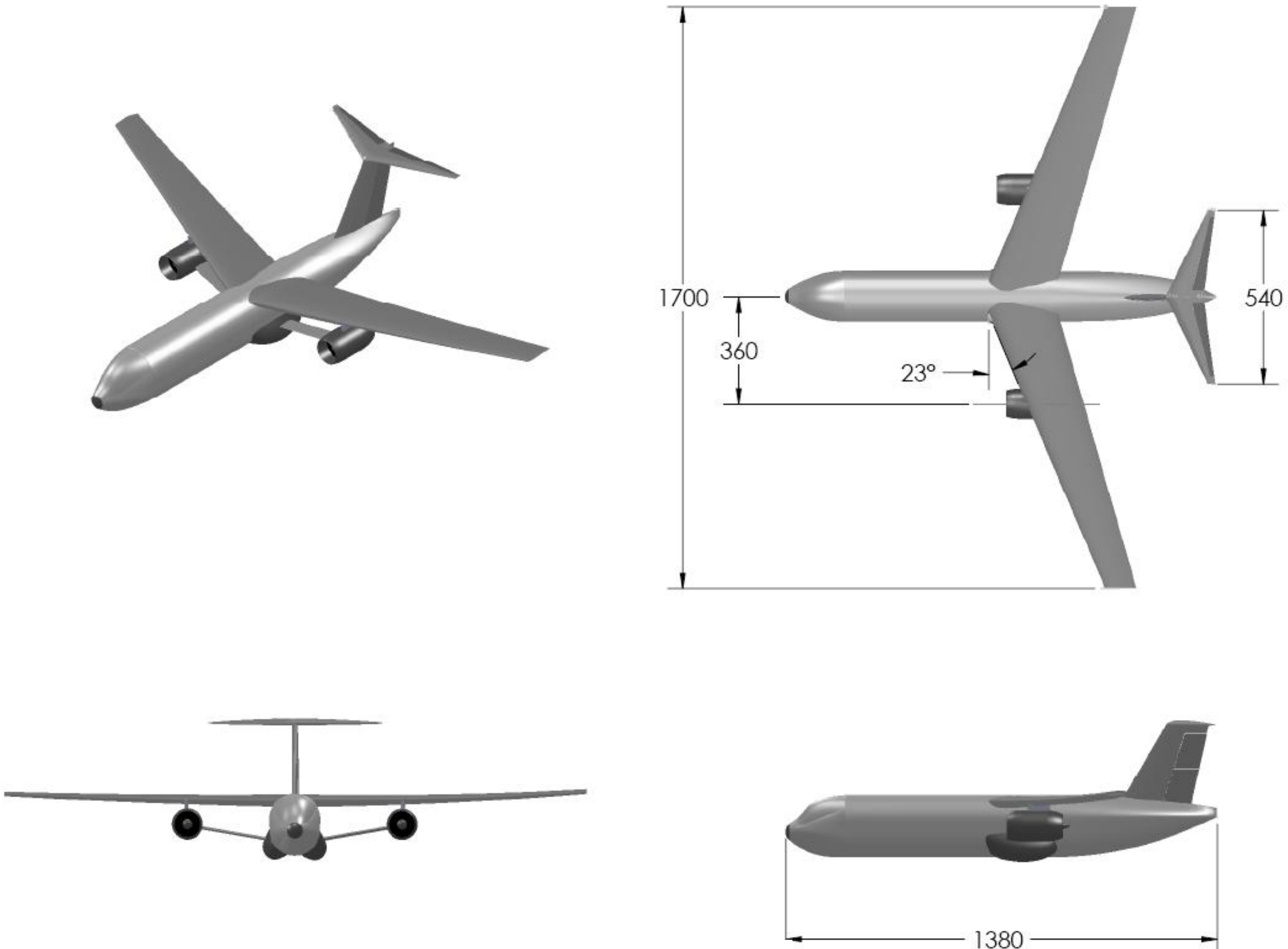


Figure 3: Strut-braced Wing Concept

Iterative Sizing Process

To size the WB-1 properly, Greenspan utilized an iterative design process. Many publications and texts contain details regarding iterative design methodology. For example, Laurence K. Loftin, Jr. provides a detailed analysis of how to design aircraft to meet specific performance objectives in NASA Research Publication 1060.[7] Chapter 3 of the publication is specifically devoted to the topic of sizing a jet-powered aircraft. Greenspan developed a unique method described by the flowchart in Figure 4. This process can be improved and extended to handle additional variables in future investigations.

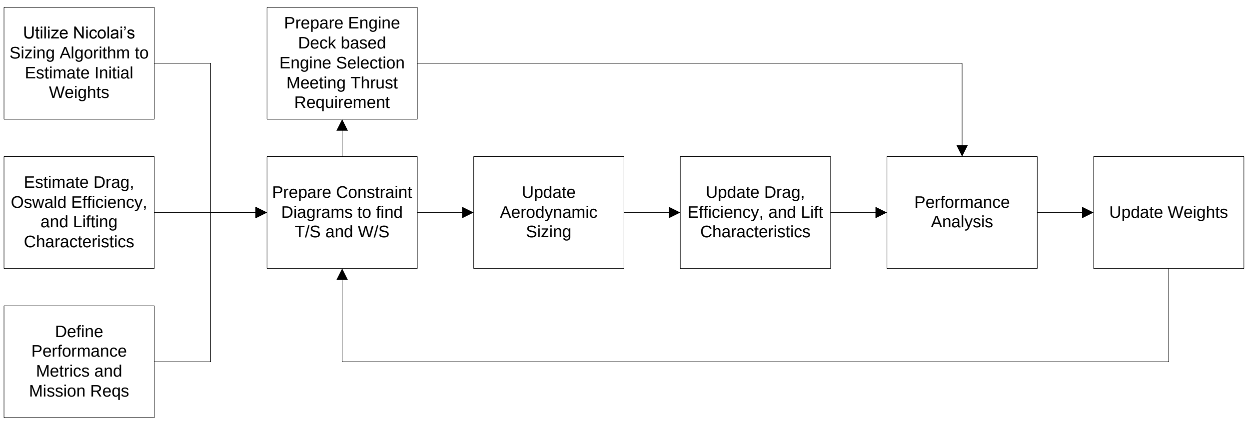


Figure 4: Iterative Sizing Method Flowchart

The circular method demonstrated in the flowchart indicates a coupled optimization problem covering areas including structure, cost, aerodynamics, and materials. To address all issues, designers use MDO. Some codes exist to help with MDO, and after establishing our concept, our design may be able to utilize these codes to optimize the final design. Table 3 shows the results from the initial sizing iteration. Greenspan refined the sizing of the WB-1, after the selection of the preferred concept.

Table 3: Initial Concept Sizing

	Strut-Braced Wing Concept	**Low-Wing Concepts** (Traditional and Over-the-wing Engine-mount)
Long Range Cruise Mach Number	0.80	0.80
¼ Chord Sweep Angle	15°	25°
Aspect Ratio	17.5	10
Takeoff Gross Weight	168,600 pounds	175,500 pounds
Wing Loading	120 pounds per square foot	120 pounds per square foot
Wing Reference Area	1405	1462.5
Thrust Loading	0.273	0.262
Taper Ratio	0.40	0.40
Wing Span	158.34 feet	119.74 feet
L/D	19.8	15.0
Fuel Burn (Long Range Mission)	46,000 pounds	58,000 pounds

Figure 5 is the constraint diagram for the last iteration of the iterative sizing method. Takeoff and second-segment climb requirements posed the greatest restrictions. Second segment climb requires a minimum climb gradient at low airspeeds, with one engine inoperative, without high lift devices. Earlier iterations sized the engine by setting the thrust loading at 0.273 and sized the wing by setting the wing loading at 120 pounds per square foot. Reductions in weight during later iterations caused the thrust loading to become greater than the design requirement and resulted in an increase in thrust loading. Further structural and configuration improvements allowed for a reduction in wing area and a reduction in overall weight. These modifications moved the design point to its current position on Figure 5. The design point is now located at a thrust loading of 0.392 and a wing loading of 108.2 pounds per square foot. Greenspan decided that the increased thrust loading and wing loading were acceptable, as they would allow the WB-1 to grow into a full family of aircraft without requiring major alterations to the planform or powerplant.

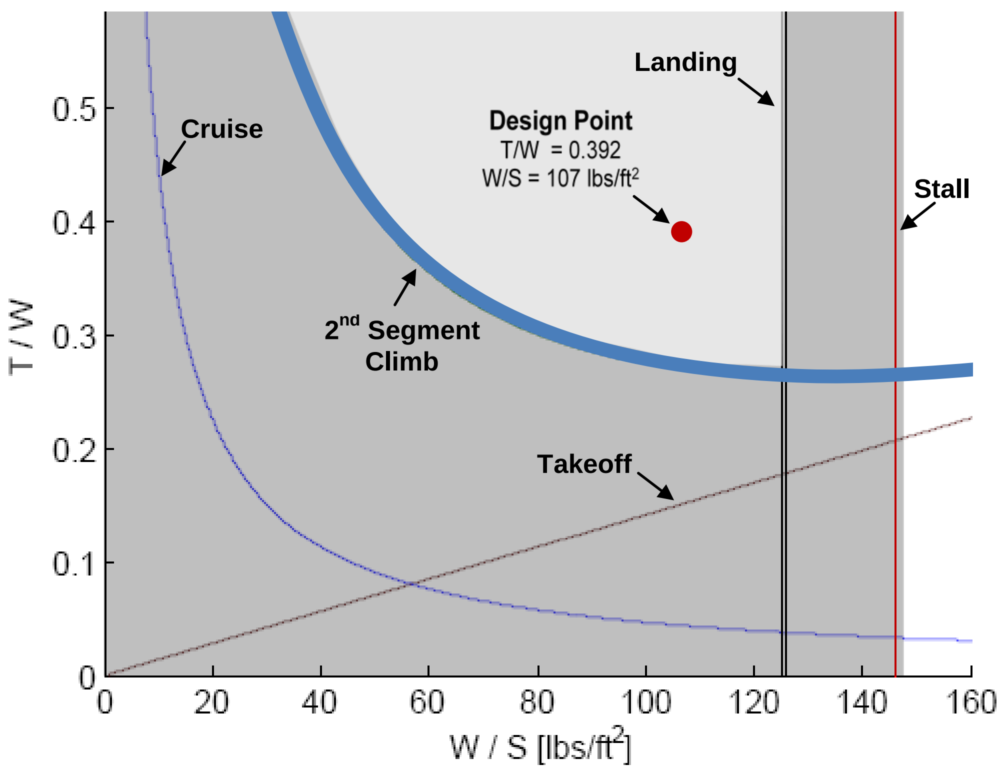


Figure 5: Final Constraint Diagram for WB-1

Concept Comparison

The RFP requirement is an 8% reduction in operating cost from current industry operating costs. Greenspan identified Southwest Airlines as an airline that consistently operates with high profit margins. Therefore, Greenspan used the published Southwest operating cost of 8.78 cents per nautical seat mile to determine the operating cost requirement.[8] This yielded a required operating cost no higher than 8.08 cents per nautical seat mile.

A detailed algorithm, which includes inputs for fuel prices, crew costs, maintenance costs, mission profile statistics, aircraft geometry, aircraft weights, and more, calculated the operating costs for the various concepts. Using inputs that correspond to a Boeing 737-800, the calculated operating cost is 8.69 cents per nautical seat mile. This result falls very close to the published 8.78 cents per nautical seat mile, validating the cost algorithm. More details concerning the algorithm are in the Cost Analysis section of this report. Figure 6 below shows the results of several calculations. "Strut" refers to the strut-braced configuration, while "Low Wing" refers to both the conventional configuration and the over-the-wing engine-mount configuration. The comparison includes operating costs, which correspond to the use of conventional aluminum structure, as well as the use of advanced composite structures.

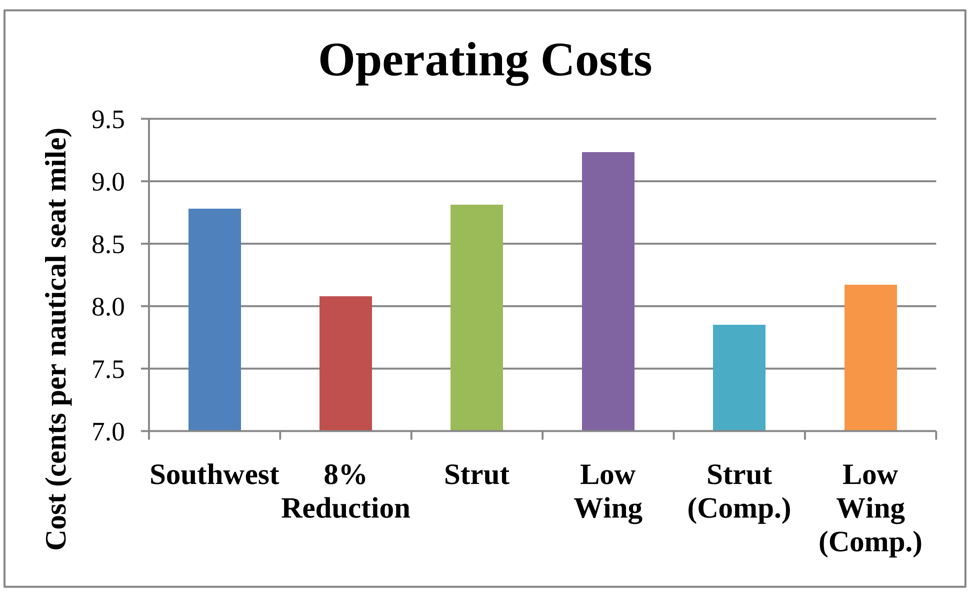


Figure 6: Operating Cost Comparison[8]

From the figure above, it appears the required operating cost is a lofty goal that conventional aircraft will have difficulty achieving. Second, the strut-braced configuration has a clear advantage over the more conventional low-wing configurations. Third, the use of composites has a staggering advantage over conventional aluminum structures. In terms of meeting the RFP operating cost requirement, composite integration is essential, and from the analysis, the composite strut-braced design is the only design that meets the requirement. Please note that acquisition costs varied minimally between concepts, and therefore carried little to zero weight in concept selection.

Greenspan constructed a decision matrix to compare the initial concepts' merits and faults, as shown in Table 4. Concentrations influencing the design were examined and then given a weight related to their perceived importance to the overall success of the design, with 5 being the most important and 1 being the least. Each configuration was given a ranking of 1 (worst) to 3 (best) for every concentration. The sum of the products of the weights and the rank for each parameter gives each configuration the overall score, with the best-perceived configuration receiving the highest score.

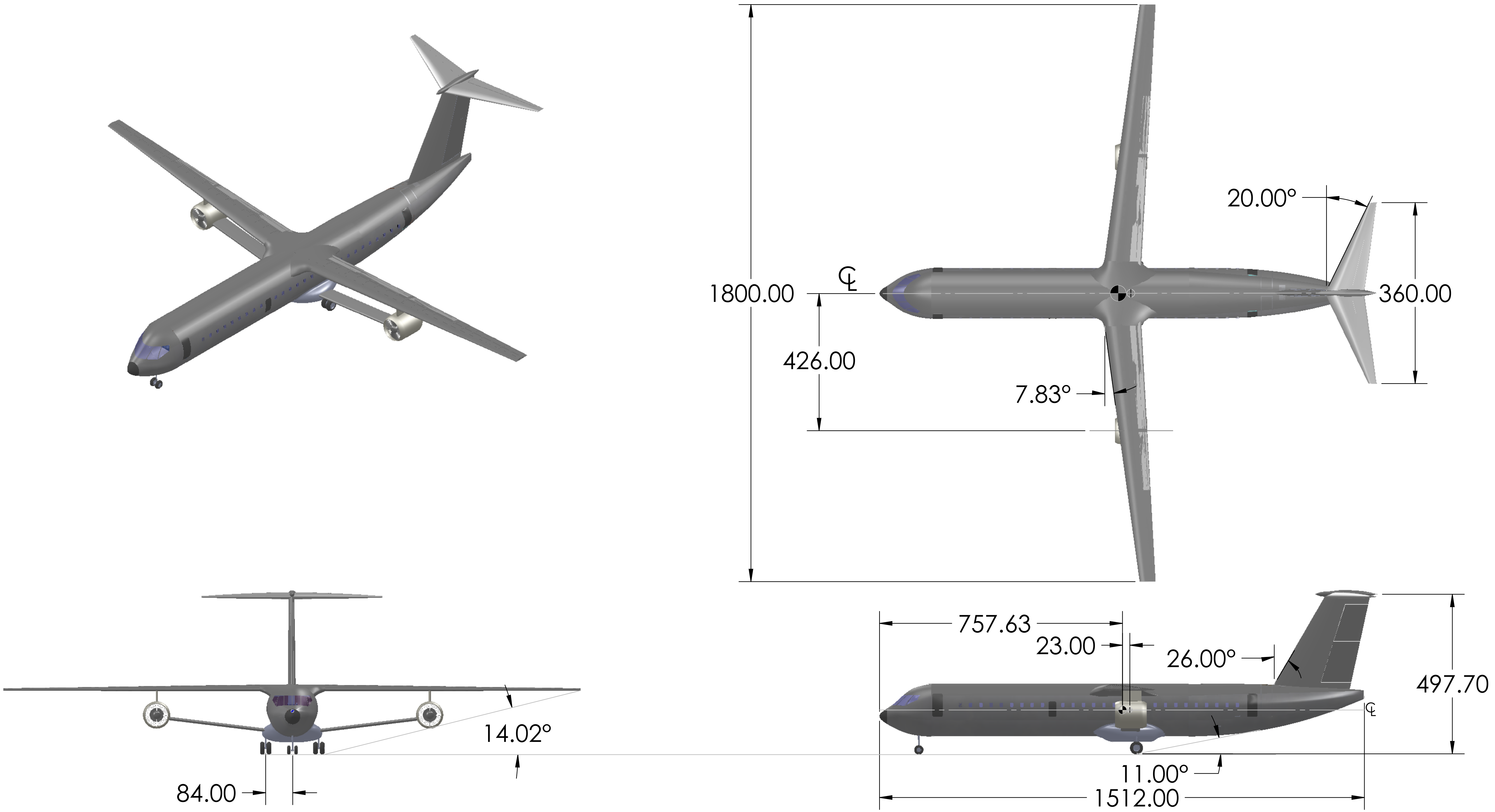
Table 4: Conceptual Decision Matrix

	Weight	Conventional Low-Wing Design	Over-the-wing Engine-Mount	Strut-Braced High-Wing
Aerodynamics/Drag	4	2	2	3
Cost	5	1	2	3
Noise	5	1	3	2
Weights	5	2	2	3
Fuel Burn	4	2	2	3
Loads/Structures	4	1	2	3
Stability and Control	4	3	1	2
Maintenance and Manufacturing	4	3	2	1
Totals		64	71	88

Preferred Concept Selection

From the decision matrix, it was clear that Greenspan should pursue the strut-braced wing design. The strut allowed a lower wing weight by supplementing the structure within the wing. By reducing the weight of the wing, Greenspan fully expected that the overall weight of the aircraft would be less than the other concepts. Mounting the engines at the junction between the strut and wing will also relieve the stresses carried by the wing. Generally, lower weight results in lower cost, emissions, and noise.

Additionally, the strut allows the wing to have a reduced sweep angle. Because of the reduced sweep, the thickness and chord of the wing decrease. As previously discussed, this will lower the Reynolds number. Since lower Reynolds numbers indicate an increased probability of laminar flow, the concept will experience a reduction in skin-friction drag. Overall, the strut-braced wing concept that Greenspan is presenting has superior aerodynamic and weight characteristics relative to current in-service aircraft and alternative concepts.



	NAME	DATE
DRAWN	SWF	5/5/09
CHECKED	SCB	5/6/09
MGT APPR.	JRR	5/6/09

COMMENTS:

DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED.

GREENSPAN

TITLE:

WB-1 FINAL CONCEPT

SIZE	DWG. NO.	REV
B	FOLDOUT 1	3

SCALE: 1:384 WEIGHT: SHEET 1 OF 1

Configuration and Layout

Passenger Compartment

The overall objective is to carry humans as safely, efficiently, and comfortably as possible. To accomplish this task, the WB-1 can incorporate either a low-density layout or a high-density layout. The RFP defined the low-density layout as being able to hold 150 dual-class passengers with 12 first class seats and 138 economy class seats. The first class cabin featured a 36-inch pitch and the economy class featured a 32-inch pitch. For the purposes of passenger comfort, the dimension of the inside width of the fuselage was set at 150 inches embedded in a 159 inch external surface cross-sectional diameter. This gave a wall thickness of 4.5 inches and allowed 6 passengers abreast to have 20 inches of shoulder space each and 20 inches for the aisle. This is wider than most current configurations, exceeding the 737-800 by 6 inches and the A320-200 by 5 inches.[2] Figure 7 shows a cross section comparison of the WB-1 and the Boeing 737-800. A cabin length of 85 feet gave each economy seat 1 foot of legroom between the consecutive rows with an extra three inches of legroom for the first class passengers.

The RFP specifies a 30-inch pitch for the high-density layout, leading to a maximum of 162 single-class passengers. This reduced the legroom distance between each consecutive row of seats to 9.5 inches. The cabin comprises of one galley in the front area to serve the front seated passengers and one in the central part of the aft fuselage, behind the two lavatories.

Cargo Hold

Figure 7 shows the inboard profile of the WB-1. The WB-1 provides 8.5 cubic feet per each of the 162 passengers, easily exceeding the cargo RFP requirement of 7.5 cubic feet per passenger. The cargo bay occupies approximately 75% of the cabin length plus bulk load space in the tail cone. The extra thick cross-sectional surface on the bottom deck of the cargo section is used to carry system lines and fuel. One of the benefits of the high-wing configuration is that it allows better accessibility for the service trucks during loading and unloading. The cargo bay is accessible from two doors, located 335 inches and 975 inches from the nose on the port side of WB-1. The forward door is 45.5 inches tall and 28.6 inches wide, while the rear door is 30.5 inches tall and 23.9 inches wide.

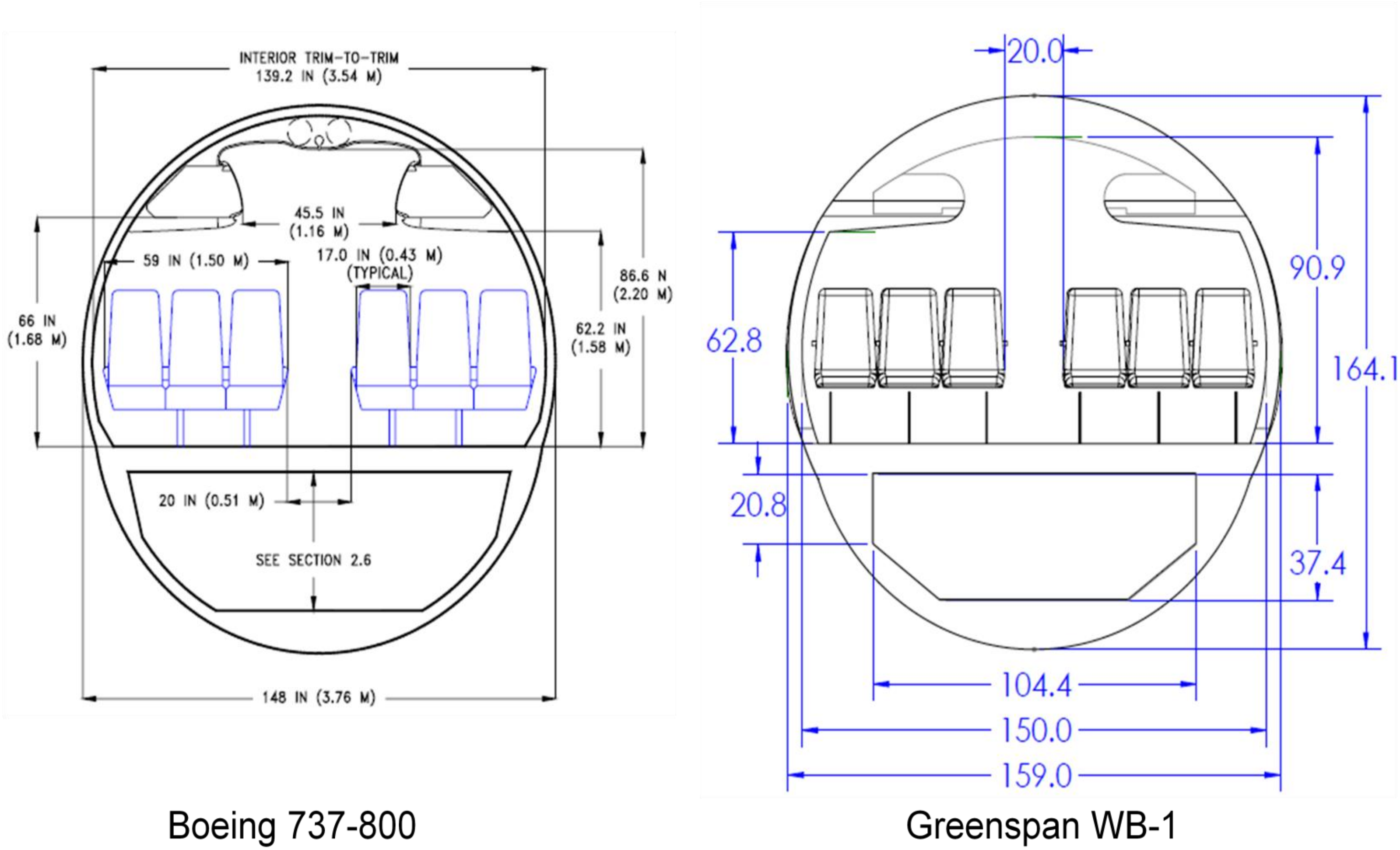


Figure 7: Cross-section Comparison [9]

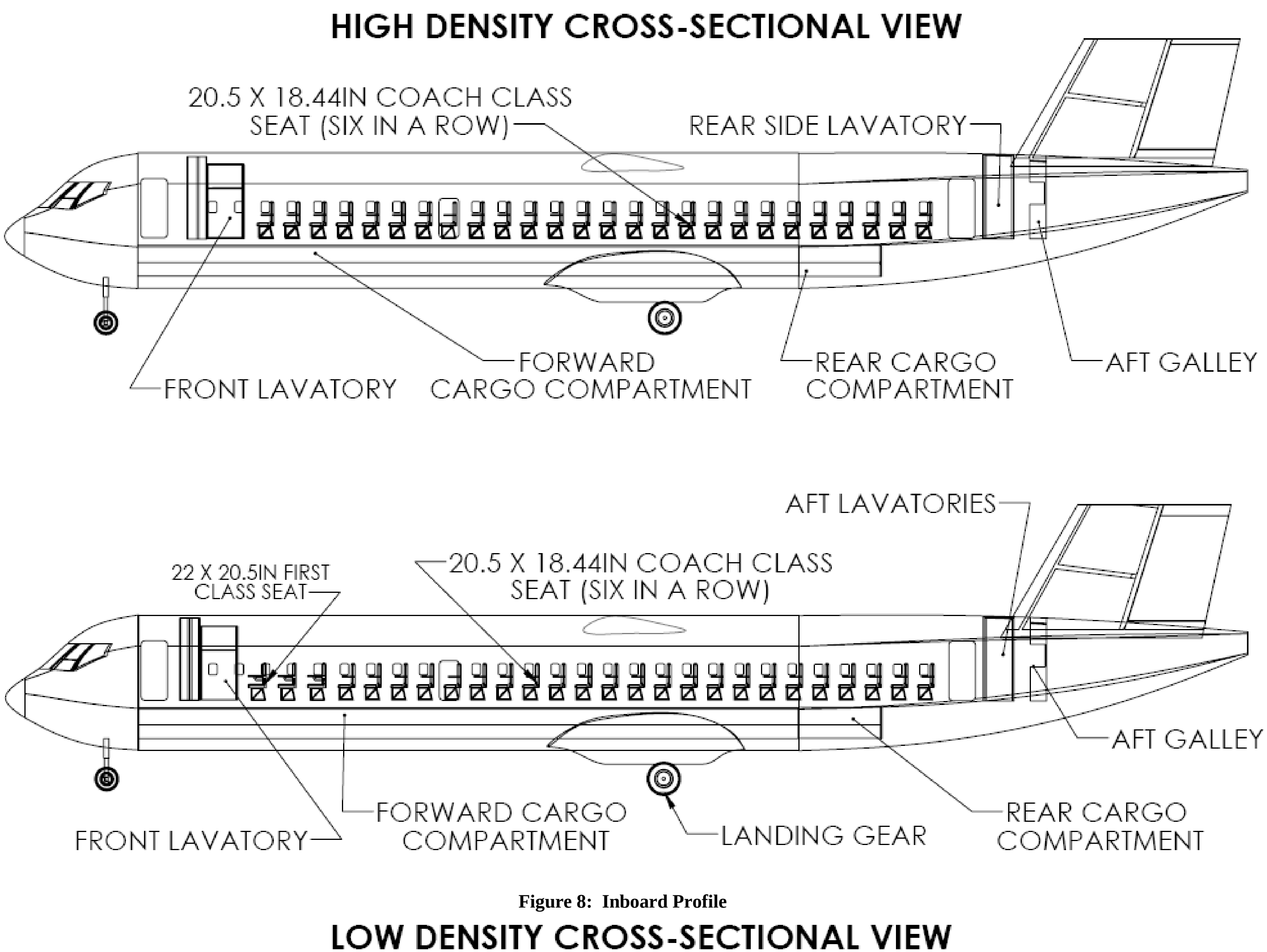
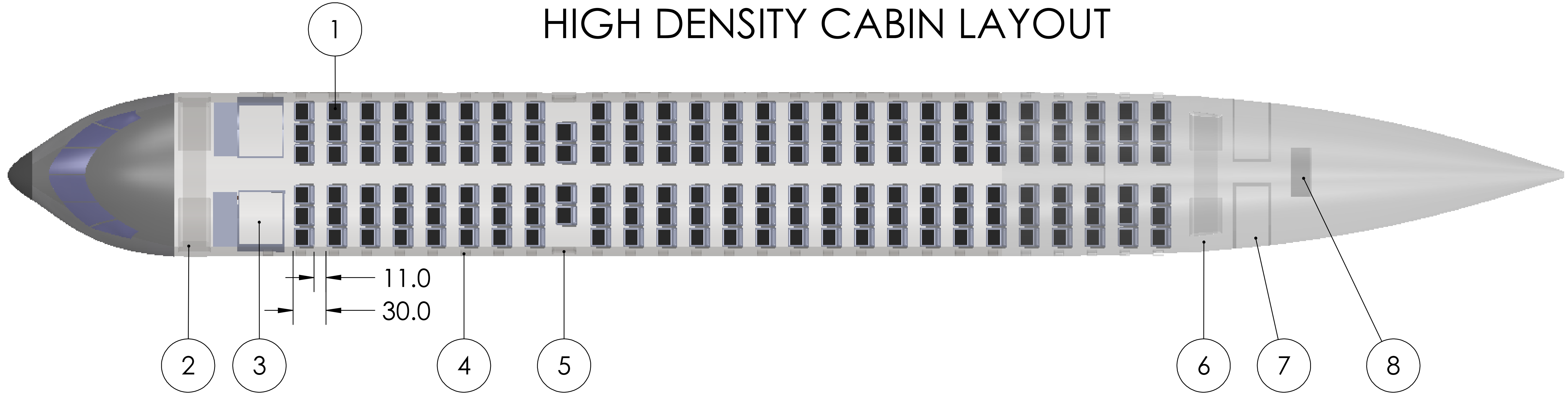
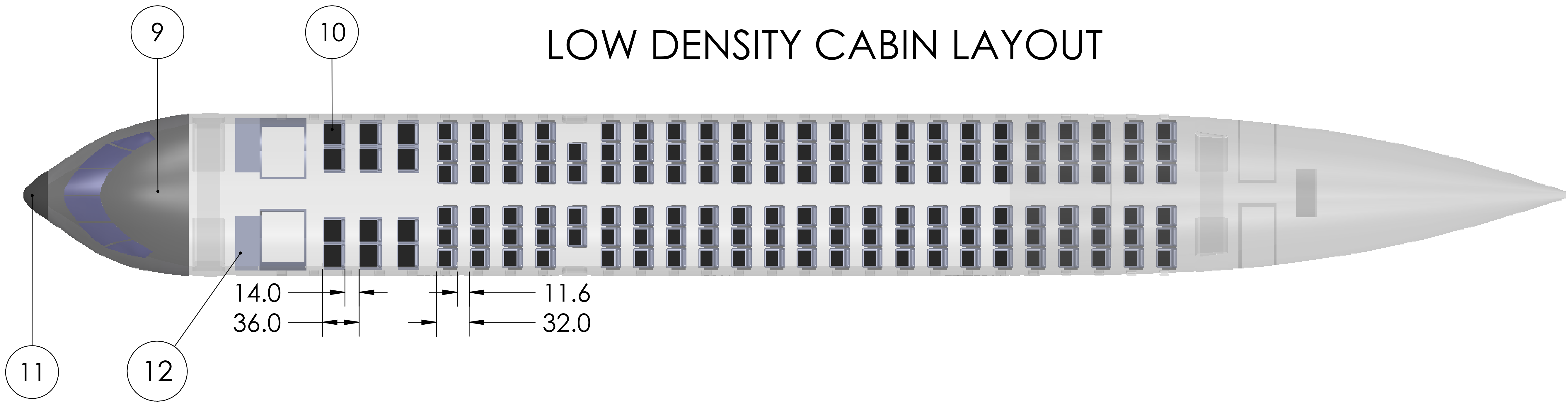


Figure 8: Inboard Profile

HIGH DENSITY CABIN LAYOUT



LOW DENSITY CABIN LAYOUT



1- COACH CLASS SEAT
2- FORWARD PASSENGER DOOR
3- FORWARD LAVATORY
4- WINDOW
5- EMERGENCY EXIT
6- AFT PASSENGER DOOR
7- AFT LAVATORY
8- AFT GALLEY
9- COCKPIT
10- FIRST CLASS SEAT
11- RADAR +DOME HOUSING
12- FWD GALLEY

	NAME	DATE
DRAWN	SWF	5/4/09
CHECKED	SCB	5/6/09
MGT APPR.	JRR	5/6/09

COMMENTS:

DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED.

GREENSPAN

TITLE: WB-1 Cabin Layout

SIZE	DWG. NO.	REV
B	FOLDOUT 2	3

SCALE: 1:110 WEIGHT: SHEET 1 OF 1

Airport Operations

During the evolution of the concept, Greenspan realized that the long wingspan of the WB-1 might cause operational problems at various airports. The wingspan of the WB-1 is 150 feet, whereas the aircraft it will replace have shorter spans. The Airbus A320-200 has a wingspan of about 112 feet and the Boeing 737-800 has a wingspan of about 113 feet.[10]

The FAA has specific Airplane Design Groups for aircraft based on size. Aircraft of the Group III size have wingspans of 79 to 117 feet and heights to 45 feet. Aircraft of Group III include the Airbus A320, Boeing 737, MD-80, and DC-9. Aircraft of the Group IV size have wingspans of 118 to 170 feet and heights less than 60 feet. Aircraft of Group IV include the Airbus A300, Boeing 757, Boeing 767, Boeing 787-300, DC-8, and DC-10.[10] The WB-1 fits within the Group IV size restrictions, but it would fit within the Group III size restrictions if its wingspan were 33 feet shorter.

The FAA also categorizes aircraft based on approach speed. The WB-1 has an approach speed of 135 knots. This places it in the Category C designation that includes aircraft with approach speeds of 121 to 140 knots such as the Airbus A320 and Boeing 737-800.[10] The Airport Type Code of the WB-1 is therefore C-IV.

The Group III and Group IV designations are important because of airport handling capability, including gate sizing. Airports have different types of gates to handle different sized aircraft. We are specifically interested in the Gate Types A and B. Gate Type A will handle Group III aircraft. Gate Type B will handle aircraft of the Group IV designation, but have a length less than 160 feet (such as with the Greenspan WB-1, with an overall length of 126 feet).[11] Therefore, the issue arises that the WB-1 will need to use Gate Type B, whereas the Group III aircraft it will replace use Gate Type A. Other parameters for Group IV aircraft require greater runway and taxiway dimensions than Group III aircraft.

To allow the WB-1 to serve those areas where only Type A gates are available, airlines will have the option of adding folding wings to the aircraft. With the option installed, the wingtips fold up 90° at a position 20 feet from the wingtips. The resulting wingspan, 110 feet, is within the Group III requirements. The additional height of the folded wingtip will remain under the 45-foot restriction. The folding wingtips require a hydraulic actuation system and a locking and latching mechanism. This option will not require control or fuel system alteration. The weight penalty for the system may be significant. If any operator would have selected it, a similar folding wingtip option would have added 3,000 pounds to the Boeing 777.[12]

Aerodynamics

Aerodynamic Concept

Engineers design a majority of modern aircraft's wings assuming turbulent flow. With low sweep and a low chord, it is probable that the WB-1 can have a considerable amount of laminar flow. The factors that contribute to laminar flow are low Reynolds numbers, low wing sweep, a favorable velocity distribution, and minimum surface roughness. The primary benefit of laminar flow is a reduction in skin friction.[13] Laminar flow is difficult to achieve for transonic transports because of the high Reynolds numbers resulting from the extensive wing sweep used to reduce transonic drag.

Greenspan decided to utilize laminar flow over the wing, based on the success that the HondaJet has with natural laminar flow. Wind tunnel testing showed that Honda's proprietary SHM-1 airfoil, used on the HondaJet, delays the transition point at least 45% of the chord. Honda was able to achieve a high max lift coefficient and a low profile drag coefficient.[14] Additional wind tunnel tests have shown that it is possible to achieve at least a 60% chord laminar flow in velocities up to Mach 0.8.[15]

High aspect ratio wings are important because they can reduce induced drag. This is evident from the definition of the induced drag coefficient, shown below.

$$C_{D,i} = \left(\frac{1}{\pi e AR}\right) C_L^2$$

In addition, the maximum lift-to-drag ratio increases with the square root of the aspect ratio. However, high aspect ratio wings tend to stall sooner than low aspect ratio wings.[16,17]

Planform Configuration

Greenspan found the wing area using the iterative sizing method previously discussed. Using the TOGW of 117,200 pounds for the aircraft and the wing loading of 108.2 pounds per square foot, the area of the wing becomes 1083.33 square feet. The wingspan was restricted to 150 feet, and when combined with the planform area the resulting aspect ratio was 20.8. The taper ratio of 0.4 was selected based on natural laminar flow research.[18] A high aspect ratio, strut-braced wing allowed the WB-1 to utilize a low thickness-to-chord ratio and a slightly swept wing. The WB-1 employs a leading edge sweep of 7.83 degrees. The low sweep generates a transition Reynolds number of approximately $2.0\text{x}10^6$, allowing the flow to remain laminar along the surface of the wing.[18] Figure 9 shows the wing planform, and Table 5 provides pertinent planform characteristics.

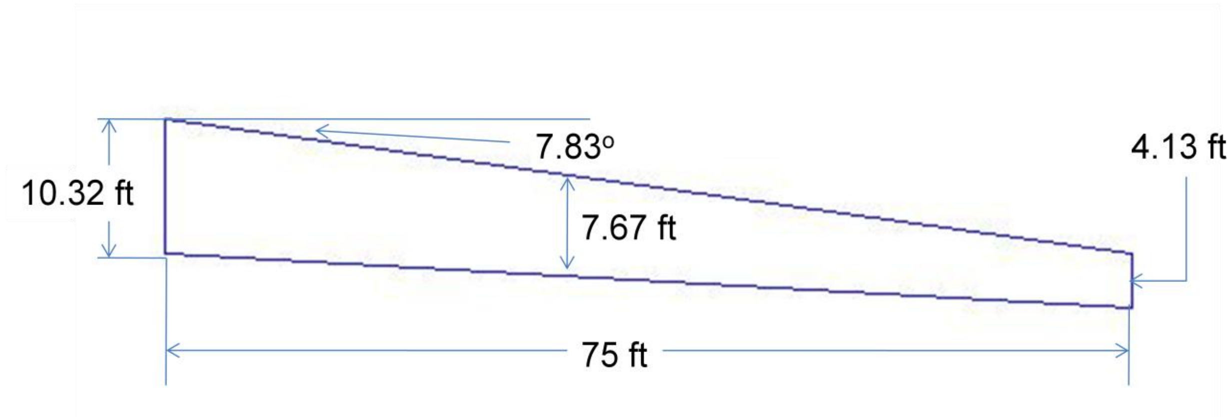


Figure 9: Wing Planform (Half-span)

Table 5: Wing Planform parameters

Root Chord (ft)	10.32
Tip Chord (ft)	4.13
Span (ft)	150
Area (ft^2)	1083.33
Leading Edge Sweep (deg)	7.83
Aspect Ratio	20.8
Mean Aerodynamic Chord (ft)	7.67
Average Chord (ft)	7.22
Taper Ratio	0.4
t/c	10%
Wing Loading (lbs/ft^2)	108.2
Span *e*	0.938

Airfoil Geometry

For the WB-1, Greenspan based airfoil selection upon the need for an efficient transonic airfoil that achieves natural laminar flow. The WB-1 will use a supercritical airfoil, in particular an airfoil from the NASA SC(2) series. This series has better performance in the subsonic region and improved wake drag compared to previous supercritical airfoils due to the elimination of drag creep.[19] The airfoils were designed for cruise lift coefficients of 0.4, 0.6, and 0.7, as well as thickness-to-chord ratios of 10%, 12%, and 14%. A design lift coefficient of 0.6 was chosen since the WB-1 requires a cruise lift coefficient of at least 0.47. The desired thickness-to-chord ratio was determined from the Korn Equation:

$$M_{DD} = \left(\frac{k_A}{cos(\Lambda)}\right) - \frac{t/c}{cos(\Lambda)^2} - \frac{C_L}{10\,cos(\Lambda)^3}$$

The Korn Equation is a function of the thickness-to-chord ratio, design lift coefficient, wing sweep and the airfoil technology factor, k_A. The technology factor was set at 0.95 because of the advanced supercritical airfoil. Greenspan desired a drag divergence Mach number of 0.8 for the WB-1. The wing sweep was already determined earlier to be 7.83°, leaving thickness-to-chord ratio to be the unknown. The maximum thickness-to-chord ratio for the sweep angle of 7.8° was found to be 10.9%. An airfoil that meets these parameters is the NASA SC(2)-0610, shown in Figure 10.

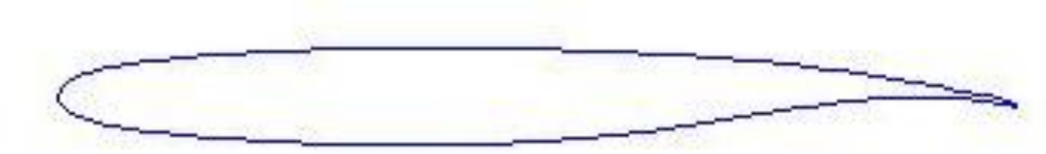


Figure 10: NASA SC(2)-0610 airfoil cross section, M_{DD} 0.8, Re 1.92×10^6

High-Lift Systems

Like most modern airliners, the use of a high lift system will assist the aircraft during takeoff and landing. Many different high lift systems were considered, but there were constraints on the decision. The RFP called for the aircraft to have a maximum balanced field length of 7,000 feet on a hot day (86°F). The WB-1 will not have leading edge devices in order to keep the leading edge as simple and as smooth as possible. The required C_{Lmax} for takeoff and landing are 1.5 and 2.0 respectfully

Table 6 presents the high lift system used for this aircraft. A single slotted flap was chosen as the high lift system due to its simple geometry and its ability to provide the amount of lift required during takeoff and landing. The WB-1 will have a flap length of 25% of the wing chord. The extending mechanism for the flaps will be contained inside the airfoil to reduce drag, eliminating the need for external mechanism fairings. Table 6 also shows the configuration shape and the C_{Lmax} for each of the configurations. Roskam's Part VI was used to calculate the lift coefficients of the flaps and the required deflections needed to produce them.[20]

Table 6: C_{Lmax} for different configurations

Configuration	Flap Deflection	C_L	C_{Lmax}
Cruise	0°	0.47	1.743
Takeoff	20°	1.50	1.998
Landing	52.5°	2.00	2.605

Drag Characteristics

The wing geometry is crucial in determining the drag due to lift, induced drag, since the span efficiency and the aspect ratio are drivers. For our design lift coefficient, the induced drag coefficient is 0.0181.

Table 7 shows the breakdown of the drag build up for the WB-1. The buildup includes the components that make up the aircraft and their respective wetted areas. These components are the main contributors to the drag since they are most affected by the flow. The wetted area, fineness ratio, and the reference lengths for each component were the defined inputs for the computer code FRICTION, which estimates skin friction and form drag.[21] The drag table was compiled for a flight condition of Mach 0.8 at an altitude of 35,000 feet. The drag buildup provided the total zero-lift drag coefficient of the aircraft. Table 8 and Table 9 present the drag buildup for the takeoff and landing conditions, respectively.

Table 7: Drag Buildup for Cruise, Mach 0.8 Re 1.92×10^6

Component	Wetted Area	Fineness Ratio	C_{Df}	ΔC_D	% Total Drag
Wings	2263.55	0.120	0.00111	0.00311	17%
Fuselage	4677.58	0.100	0.00133	0.00605	33%
Horizontal Tail	606.813	0.100	0.00177	0.00127	7%
Vertical Tail	670.868	0.100	0.00156	0.00124	7%
Strut	435.2	0.100	0.00201	0.00104	6%
Nacelles	522.998	0.058	0.00260	0.00128	7%
Wing/Body Fairing	305	0.370	0.00208	0.00099	5%
Landing Gear Fairing	305	0.370	0.00208	0.00099	5%
Pylon	41.28	0.048	0.00281	0.00012	1%
Antennae and Appendages				0.00097	5%
Steps and Gaps				0.0005	3%
Vents and Inlets				0.0003	2%
Miscellaneous				0.0002	1%
Total Zero Lift				0.01806	100%

Table 8 Drag Buildup for Takeoff, Mach 0.2 Re 1.42×10^6

Component	Wetted Area	Fineness Ratio	C_{Df}	ΔC_D	% of Total Drag
Wings	2263.55	0.120	0.00123	0.00345	14%
Fuselage	4677.58	0.100	0.00146	0.00663	27%
Horizontal Tail	606.813	0.100	0.00195	0.00139	6%
Vertical Tail	670.868	0.100	0.00172	0.00136	5%
Strut	435.2	0.100	0.00222	0.00114	5%
Nacelles	522.998	0.058	0.00285	0.00141	6%
Wing/Body Fairing	305	0.370	0.00228	0.00109	4%
Landing Gear Fairing	305	0.370	0.00228	0.00109	4%
Pylon	41.28	0.048	0.00308	0.00013	1%
Antennae and Appendages				0.00097	5%
Landing Gear				0.00276	11%
Flaps Deflected				0.00254	10%
Steps and Gaps				0.0005	2%
Vents and Inlets				0.0003	1%
Miscellaneous				0.0002	1%
Total Zero Lift				0.02496	100%

Table 9: Drag Buildup for Landing, Mach 0.234 Re 1.66×10^6

Component	Wetted Area	Fineness Ratio	C_{Df}	ΔC_D	% of Total Drag
Wings	2263.55	0.120	0.00118	0.00333	13%
Fuselage	4677.58	0.100	0.00142	0.00646	25%
Horizontal Tail	606.813	0.100	0.00189	0.00135	5%
Vertical Tail	670.868	0.100	0.00167	0.00132	5%
Strut	435.2	0.100	0.00215	0.00111	4%
Nacelles	522.998	0.058	0.00277	0.00137	5%
Wing/Body Fairing	305	0.370	0.00222	0.00106	4%
Landing Gear Fairing	305	0.370	0.00222	0.00106	4%
Pylon	41.28	0.048	0.00300	0.00013	1%
Antennae and Appendages				0.00097	5%
Landing Gear				0.00276	11%
Flaps Deflected				0.00380	15%
Steps and Gaps				0.0005	2%
Vents and Inlets				0.0003	1%
Miscellaneous				0.0002	1%
Total Zero Lift				0.02572	100%

The span Oswald Efficiency Factor, *e*, for this aircraft was calculated to be 0.938 using the computer code LIDRAG.[22] The code incorporates the spanwise lift distribution and plots it against the corresponding half span location. Figure 11 shows the plot of the output from a vortex lattice method code, VLMpc.[23]

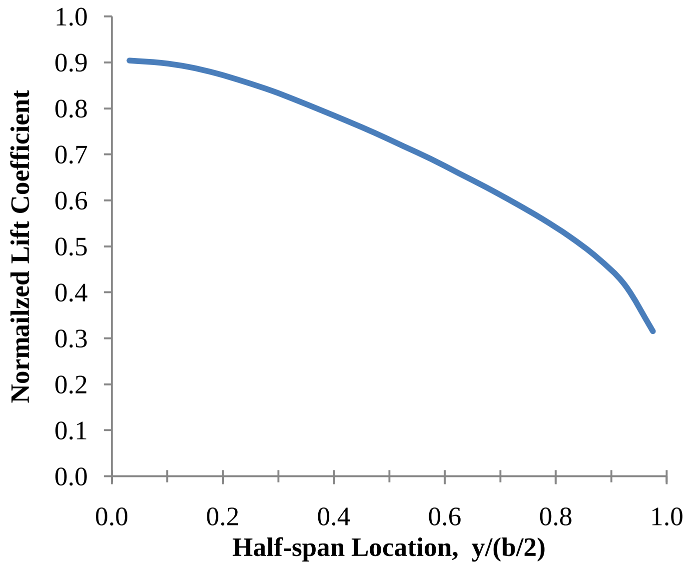


Figure 11: Spanwise lift distribution

Figure 12 shows the drag polar for the aircraft at cruise. The lift and drag coefficients were calculated for a range of angles of attack from -5° to 15° at a Mach of 0.8. The maximum lift-to-drag ratio is 29.1. Figure 13 and Figure 14 show the drag polar for the takeoff and landing configurations, respectively. The maximum lift-to-drag ratio for the takeoff configuration is 20.0 and 20.2 for the landing configuration.

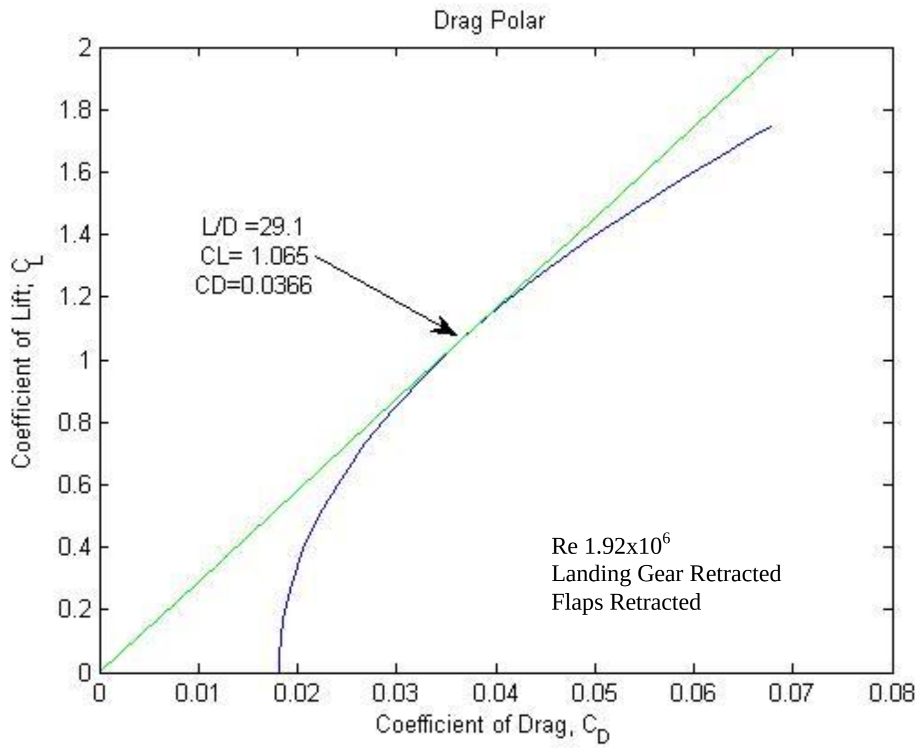


Figure 12: Drag Polar for Cruise, Mach 0.8

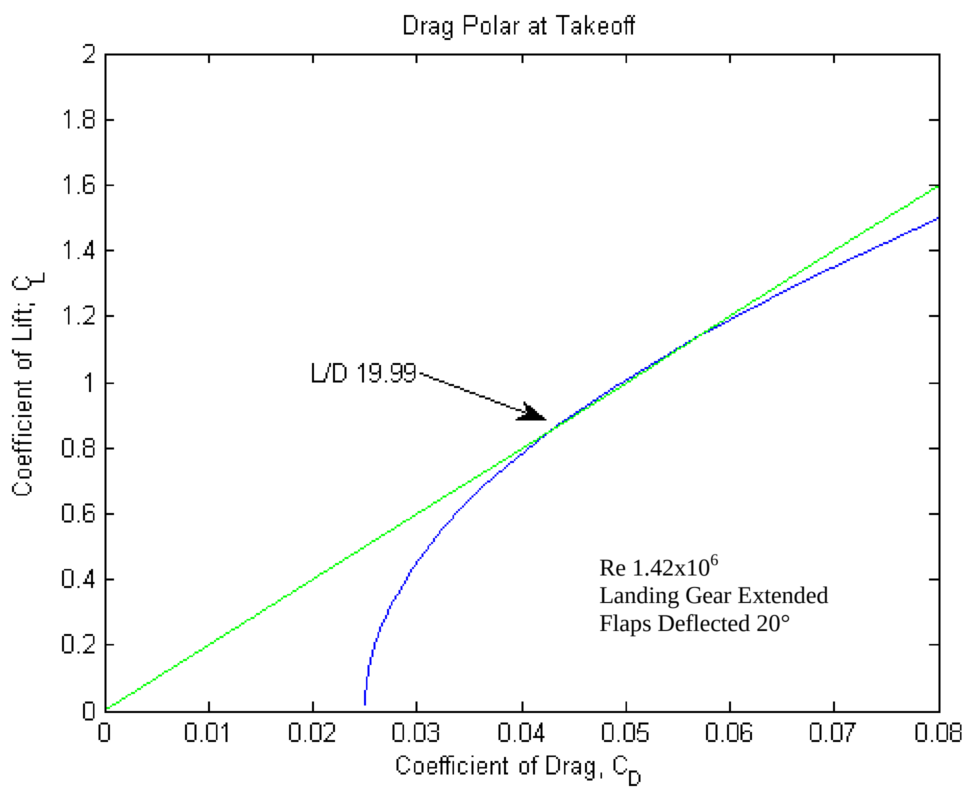


Figure 13 Drag Polar at Takeoff, Mach 0.20

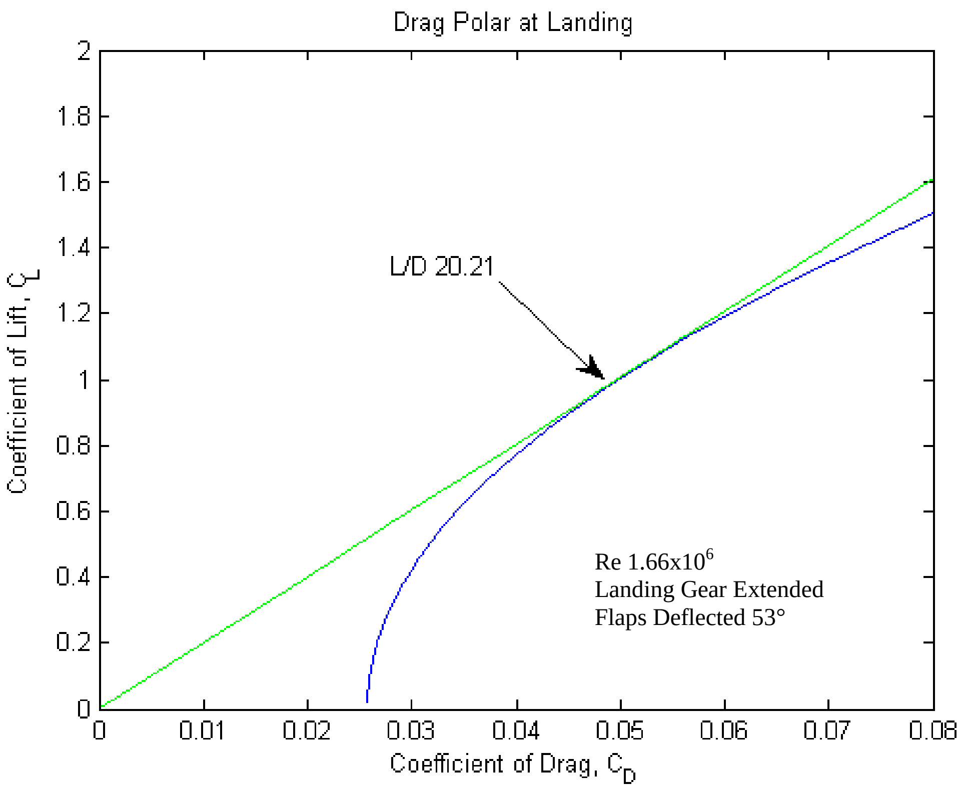


Figure 14 Drag Polar for Landing, Mach 0.234

Figure 15 illustrates the wave drag addition to $C_{D,0}$ and drag divergence Mach number for the WB-1. Drag divergence Mach number is defined by $dC_D/dM = 0.1$. Flying at Mach 0.80 results in a wave drag contribution of 20 drag counts to the total drag.

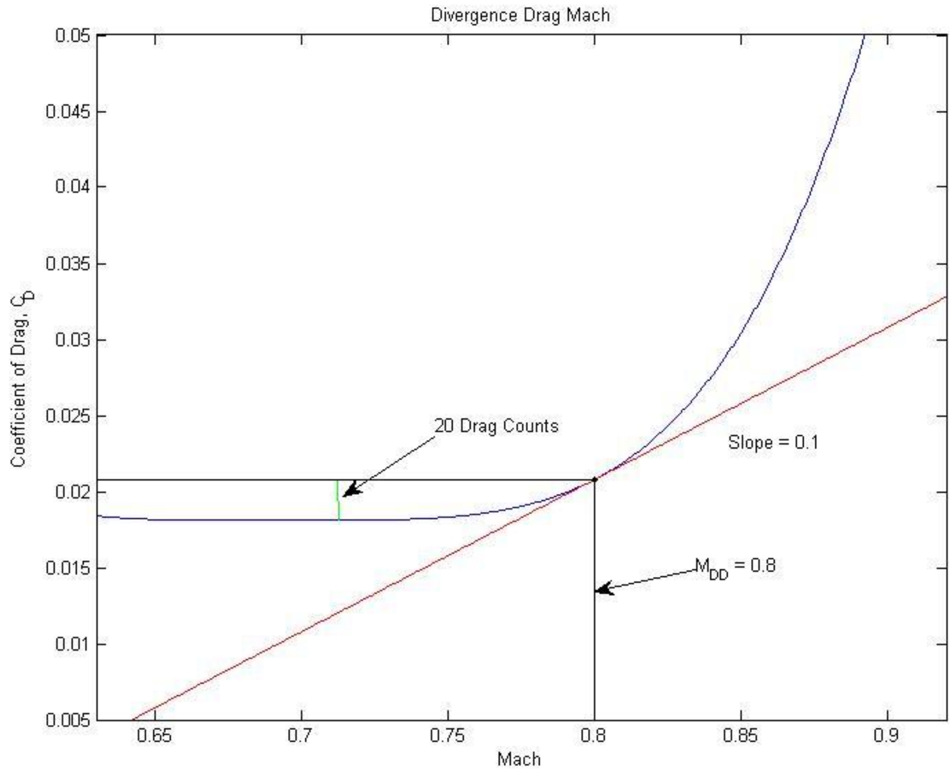


Figure 15: Drag divergence Mach number

Aerodynamic Drag

The lift-to-drag ratio is a measure of an aircraft's aerodynamic efficiency. Figure 16 shows the lift to drag ratios for various Mach numbers at 35,000 feet. The maximum cruise lift-to-drag ratio is 29.1 and occurs at Mach 0.5335. However, at our cruise speed of Mach 0.8 the lift-to-drag ratio is only 21.7.

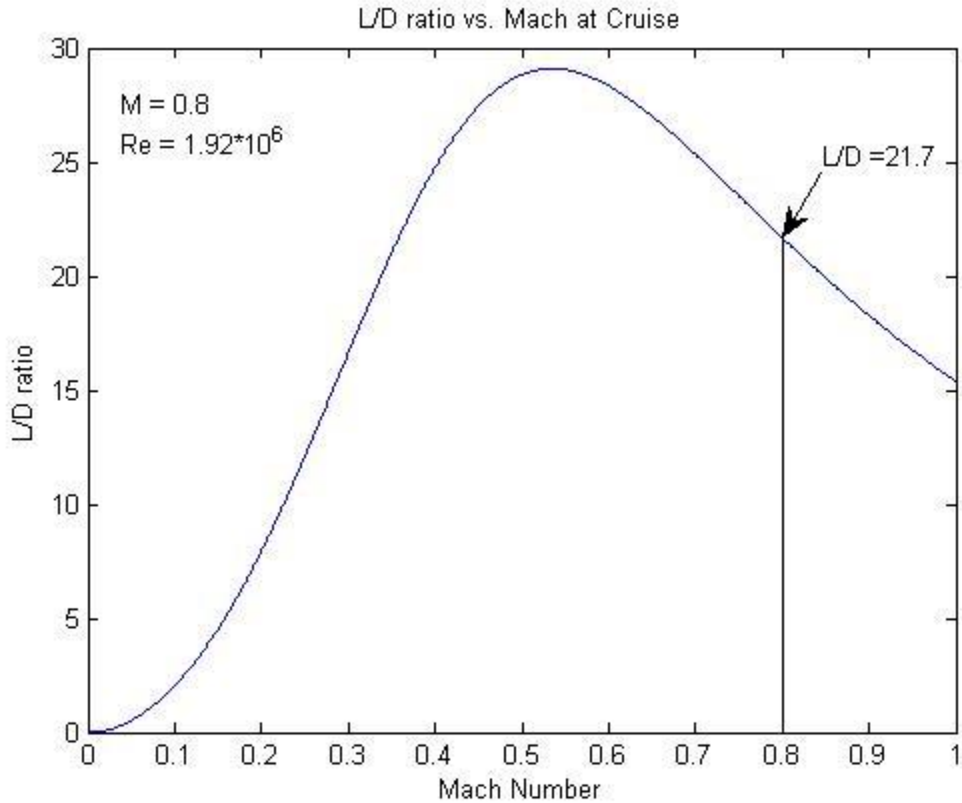


Figure 16: Lift-to-Drag Ratio over a range of Mach numbers

Figure 17 shows the lift-to-drag ratio versus angle of attack for the WB-1. The maximum lift-to-drag ratio of 29.1 occurs at an angle of attack of 6 degrees. Figure 18 shows the affect that Mach number has on the lift-to-drag ratio at different altitudes. Lower Mach numbers reach their maximum lift-to-drag ratios at lower altitudes, proving it is inefficient to fly that slowly at the cruising altitudes.

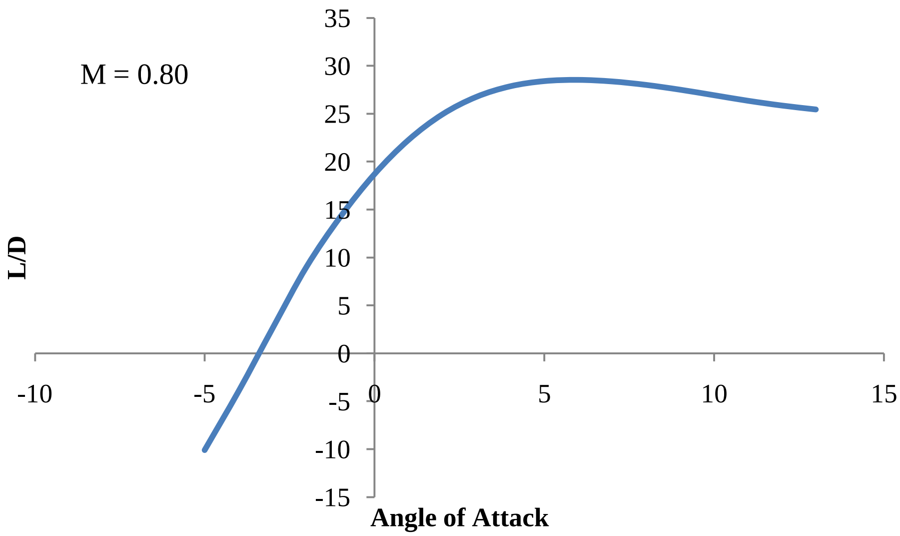


Figure 17: *L/D* versus Angle of Attack

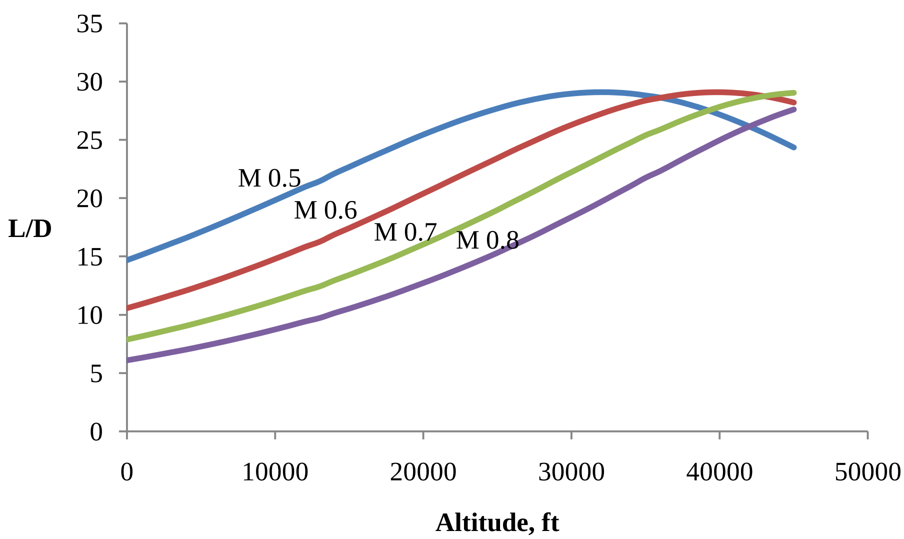


Figure 18: *L/D* versus Altitude

Noise Considerations

During all phases of flight, the engine is a major contributor toward the total noise generated by the aircraft. Airframe noise is much more prominent during approach than at other phases of flight, as the airplane is traveling slower than at takeoff and the engines are producing less thrust. In addition, extended landing gear and high-lift devices increase turbulent flow.[24] Therefore, Greenspan made efforts to reduce airframe noise, in addition to engine noise. Fairings around the exposed landing gear and tight gaps and seals reduce the generation of turbulence.

Turbulent flows contain eddies and currents with local velocities varying from the free-stream velocity. When eddies and currents mix with the free stream at the edges of the wake, pressure fluctuations are generated which cause noise.[24] In order to reduce noise, we must reduce the turbulence generated by the aircraft. The wake of an aircraft is largest in slow flight with high lift coefficients. Such conditions often involve the use of high lift devices, which generate additional wakes and vortices at their edges, creating more turbulence. Therefore, reducing the amount of high lift devices on the aircraft reduces the turbulence and noise. Greenspan has shunned the use of leading edge slats to avoid this problem.

In addition to high lift devices, turbulent flow over the aircraft's lifting surface will generate noise. With the use of the high aspect ratio of the strut-braced wing, Greenspan believes the selected airfoil will maintain laminar flow over a majority of the chord length. Not only should this reduce noise, it should also reduce drag and improve the overall efficiency of the aircraft.

Propulsion

Engine Selection

Since the WB-1 will be an improvement upon the Boeing 737-800 and Airbus A320-200, Greenspan examined the engines used by those aircraft as a starting point. These aircraft use high bypass ratio turbofans, which have been a standard for many years. Due to the RFP requirements, particular emphasis was placed on selecting an engine with a high fuel efficiency and low noise. The most obvious engine type that fulfills these criteria is the current generation of high bypass ratio turbofans. Greenspan considered turbojets and low bypass ratio turbofans for the WB-1, but quickly discarded these options due to their high noise and poor fuel efficiency. Turboprops were considered due to their high fuel efficiency, but also discarded due to their high noise and the public perception of propeller engines being old technology. However, Greenspan strongly considered a hybrid of the turbofan and turboprop, commonly referred to as the propfan. They provide incredible fuel economy and are able to operate at the transonic speeds of modern airliners due to the construction of the propeller blades.[25] Ultimately, Greenspan eliminated propfans because the excess noise offset any benefits gained by the increase in fuel economy. Therefore, Greenspan determined that a high bypass ratio turbofan would be the best choice in meeting the requirements of the RFP concerning improving fuel efficiency and passenger comfort.

The constraint diagram determined that the aircraft would be designed with a thrust to weight ratio of 0.273. Since the aircraft has a maximum TOGW of 117,200 pounds, that leaves the aircraft needing approximately 46,000 pounds of thrust. Greenspan considered two-, three-, and four-engine configurations for the WB-1, but ultimately decided that two engines was the most logical choice. The three-engine configuration was discarded due to the difficulty of implementing an engine into the tail structure. Similarly, the four-engine layout was eliminated because of cost and maintenance concerns. Greenspan's desire for a two engine aircraft means that each engine must be capable of producing approximately 23,000 pounds of thrust. This is comparable to the amount of thrust produced by the engines of the 737-800 and A320-200.[2] Therefore, Greenspan examined engines that lay in the 20,000 to 25,000 pound thrust class. Through several engines were studied, the most promising are listed in Table 10 with their pertinent statistics. The IAE offering was eliminated due to its lower bypass ratio and higher weight than the other selections. Greenspan also decided to discard the CFM56 because of its high SFC compared to the PurePower 1000G, as well as the idea that staying with the current generation of engines would not improve the fuel efficiency or noise characteristics of the aircraft. Therefore, Greenspan chose the Pratt and Whitney PurePower

1000G, shown in Figure 19, as the powerplant for the aircraft. Though not yet in production, its predicted delivery date of 2013 is well before the WB-1's expected entry into service.

Table 10: Turbofan Performance Characteristics[26]

Characteristic	CFM56 – 5A1	IAE V2522 A5	PurePower 1000G
Thrust (lb)	25,000	23,000	23,000
Weight (lb)	4,995	5,074	<5,000
Fan Diameter (in)	68.3	63.5	73
Bypass Ratio	6.0	5.4	6.9
Cruise SFC	0.596	0.575	0.554

Figure 19: Pratt and Whitney PurePower 1000G[3]

The PurePower 1000G is capable of producing 23,000 pounds of thrust. After weight reductions, the thrust-to-weight ratio increased to 0.392. Although higher than the original design point, Greenspan is comfortable with the current thrust loading because it will allow Greenspan to produce a larger, heavier, or long-range version of the WB-1 without requiring the extensive research required to integrate a different engine.

The PurePower 1000G has a high bypass ratio and a large fan for its thrust class. The higher bypass ratio allows for the reduction of fuel consumption since most modern turbofans produce the majority of their thrust through the fan. The PurePower 1000G is a geared turbofan, which enables the fan to spin at a slower rate than the turbine. This is instrumental in the reduction of the overall engine noise, as well as fuel efficiency since each component can operate at its optimum rate.[3] An added benefit of the slower fan is that it allows Greenspan to more effectively contain a rotor burst. All bursts will be contained in the nacelle, which will minimize damage to the rest of the aircraft in the event of an engine failure. Figure 20 and Figure 21 show the change in engine thrust and fuel consumption with velocity and altitude of the PurePower 1000G.

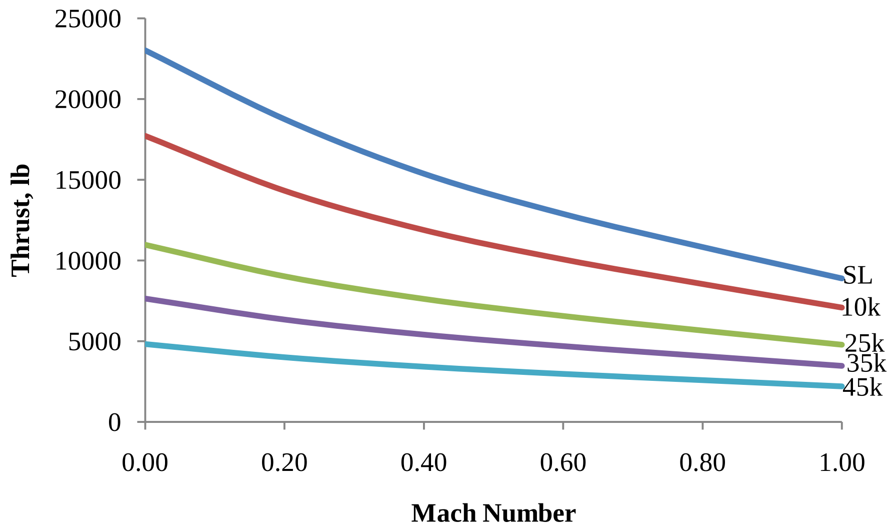


Figure 20: Thrust versus Altitude and Mach number

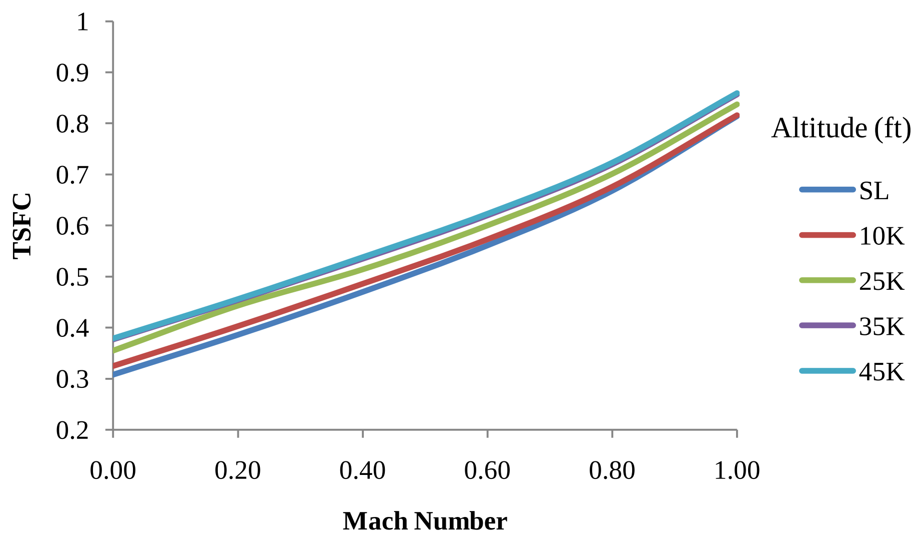


Figure 21: TSFC versus Altitude and Mach Number

Emissions Considerations

The PurePower 1000G contributes to the overall environmental friendliness of the WB-1 by reducing the emissions of the engine. Specifically, Pratt and Whitney highlights large decreases in carbon dioxide and nitrous gas emissions over current generation powerplants, with some instances seeing reductions of approximately 50%.[3] Taking all of these considerations into account, the PurePower 1000G will provide Greenspan with an effective and environmentally friendly solution to our power needs.

Noise Considerations

During all flight phases, the engines generate noise. Therefore, Greenspan made the greatest effort to reduce noise emitted by the engines. One way to achieve this feat is to reduce the jet exit velocity. The jet velocity contributes a great deal to the power of the noise emitted by the engine. Below 600 meters per second, the noise power is proportional as follows:

$$Power_{Noise} \propto \frac{\rho_{exhaust}\, V_{exhaust}^{8}\, D_{exhaust}^{2}}{a_0^2}$$

Above 600 meters per second, the noise power is proportional as follows:

$$Power_{Noise} \propto \rho_{exhaust}\, V_{exhaust}^{3}\, D_{exhaust}^{2}$$

These relationships show that it is beneficial to reduce the exhaust speed. One way to achieve lower exhaust velocity is mixing the jet exhaust with the bypass flow. This slows the speed of the exhaust, reducing the velocity gradient between the exhaust and the free-stream, thereby decreasing pressure fluctuations and noise. [27]

The Pratt and Whitney PurePower 1000G geared turbofan promises to outright meet the 20 dB noise reduction requirement of the RFP.[3] By reducing the fan speed to its most efficient operating rotation rate, the core operates at its most efficient rotation rate. The noise reduction claim is arbitrary because regulation requirements vary with aircraft TOGW. Pratt and Whitney do not give a TOGW for which they make their claim.

To reduce noise further, advanced acoustic dampening material lines the engine. Acoustic treatment is common to some engines, especially around the exhaust flow of either the jet or the bypass fan. This treatment absorbs some of the pressure fluctuations to reduce the noise transmitted to the receivers.[24]

Related Systems

The aircraft will require an Auxiliary Power Unit (APU) to start the engines. Greenspan has selected an APU manufactured by Hamilton Sundstrand that will produce approximately 1.45MW of energy.[28] This amount of energy is required because the aircraft uses reduced-bleed systems. In addition, it will be Extended-range Twin-engine Operational Performance Standards (ETOPS) certified in the case of an engine out situation. Honeywell will provide the mechanical and electrical engine controls. Finally, according to FAA regulations, the aircraft will be required to have an on-board inert gas generation system.[29] This system fills the fuel tanks with an inert gas in order to displace the oxygen and remove the possibility of a spark causing a fuel tank fire. Greenspan has chosen a system manufactured by Honeywell, which uses nitrogen as the inert gas.

Maintenance Access and Engine Removal

Since the strut connects to the engine nacelle, Greenspan made special considerations to ensure the ease of engine maintenance. Since Pratt and Whitney removes the vast majority of its engines by first sliding the engine forward, then dropping it out, Greenspan designed a simple hinge mechanism on the engine nacelle with this in mind. The lower half of the nacelle will hinge upward and latch onto the underside of the wing via simple hooks at the front and rear of the nacelle. This will allow the engine to drop straight down, as well as allow ample room for routine engine maintenance that may not necessarily require engine removal. Figure 22 details the mechanism. When the latches are not in use, they will be flush with the underside of the wing and nacelle. This will be their natural position, in order to ensure that they do not come down during flight and cause unnecessary drag.

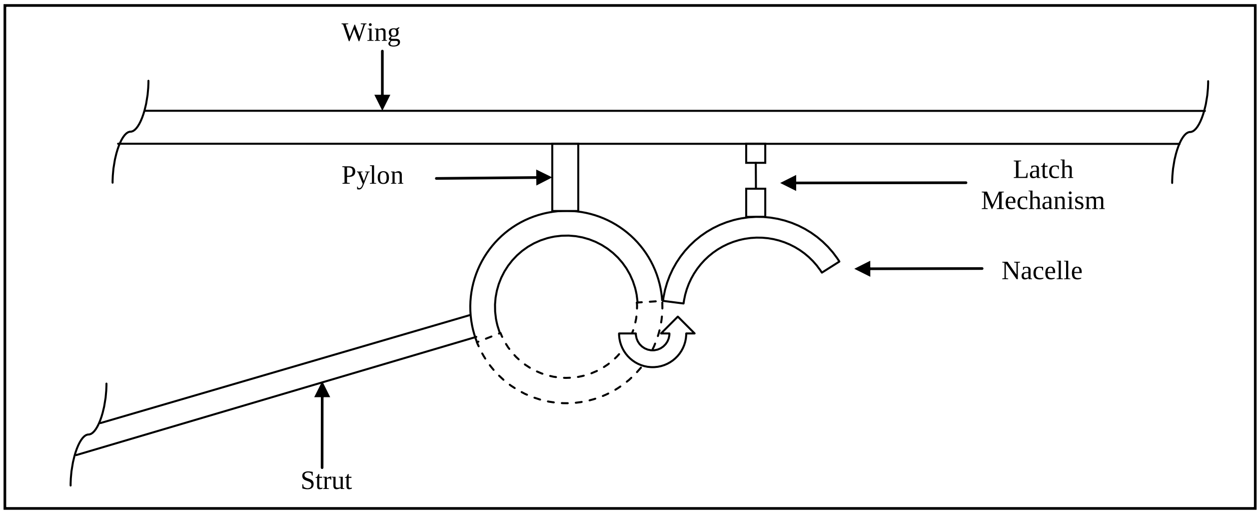


Figure 22: Nacelle Maintenance Mechanism

Performance

Methodology

The mission analysis conducted by Greenspan involved the collaboration of the aerodynamic, propulsion, and weight disciplines of aircraft design. Greenspan conducted the analysis via a MATLAB code designed to give preliminary estimates of range and fuel burn for concept aircraft. Mike Morrow originally wrote the program, with improvements made by Chris Cotting.[30] Greenspan made several changes to the code, including limiting the airspeed to subsonic and overall code efficiency boosts. The program uses inputs such as an engine deck, transonic drag buildup, configuration data, aerodynamic constants such as maximum lift coefficient and Oswald efficiency, and a mission profile. The program outputs mission time and fuel burn, along with other useful information such as rate of climb, true airspeed, and lift-to-drag ratio. The mission code was crucial to the design process as it allowed Greenspan to evaluate the effectiveness of configuration changes. Greenspan conducted the mission analysis after every significant design change in order to measure their impact on the WB-1's performance. The mission analysis was especially significant in confirming our decision to go with a composite airplane, as the code showed significant fuel reduction over a conventional aluminum aircraft. The output of the code also allowed Greenspan to calculate fuel burn and mission time, which were important factors in calculating the cost analysis of the aircraft.

Mission Performance

Greenspan utilized the mission analysis to find the most efficient combination of cruise altitude and Mach number given a set amount of fuel. The fixed fuel weight used in this analysis was 7,650 pounds, which is the amount of fuel needed to complete the 500 nautical mile mission. Greenspan investigated combinations with altitudes ranging from 30,000 feet to 43,000 feet and Mach numbers ranging from 0.6 to 0.85. This data shows that the WB-1 achieves its best cruise range at an altitude of 30,000 feet and a Mach number of 0.75. However, a speed increase to Mach 0.8 would not greatly penalize the aircraft in terms of fuel weight, and any small increases in weight could be offset by the increased speed at which the aircraft could carry its passengers to their destination. In addition, Greenspan determined that an altitude increase to 35,000 feet would have a similarly negligible effect on the aircraft weight. In terms of the 500 nautical mile mission, the change in altitude and speed would require the WB-1 to carry approximately 400 pounds of extra fuel, while removing approximately two minutes from the cruise time. Greenspan concluded that the increase in fuel, which is roughly equivalent to two extra passengers and their luggage, is acceptable given the decrease in the time it takes to complete the mission. Figure 23 shows the results of this analysis. The black vertical line represents the design speed of Mach 0.8.

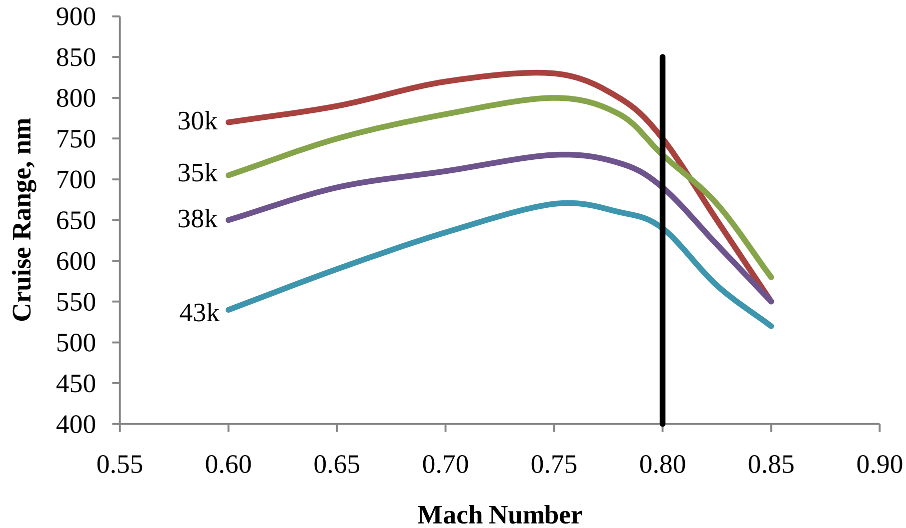


Figure 23: Cruise Range versus Mach number and Altitude Given for 500nm Fuel Load

With the altitude and Mach number fixed, the mission analysis was conducted for each cruise range outlined in the RFP. Figure 24 shows the mission designed by Greenspan, with Table 11 detailing each mission segment. Segments 1 through 5 constitute a normal mission for an airliner. Segments 6 through 10 were included to simulate a diversion to another airport. This was necessary in order to demonstrate that Greenspan had accounted for FAA mandated reserves in its mission calculations.

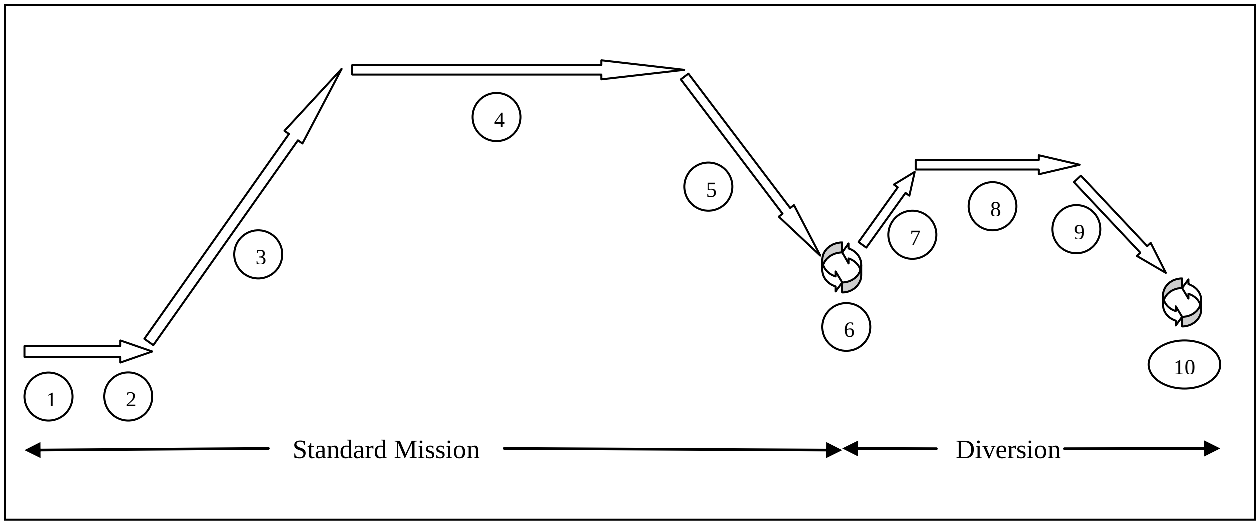


Figure 24: Mission Summary

Table 11: Mission Segments

Mission Segment
1. Idle Thrust
2. Full Thrust, Takeoff
3. Climb
4. Cruise
5. Descend
6. Loiter
7. Climb for Diversion
8. Cruise
9. Descend
10. Loiter for Approach

Table 12 presents the data generated by the mission analysis using the mission summary in Figure 24. Greenspan numbered each mission according to its frequency of utilization as stated in the RFP. Therefore, the 500 nautical mile mission was labeled Mission 1 since it will be performed on 50% of all flights. Similarly, the 1,000 nautical mile mission and the 2,000 nautical mile mission will be performed on 40% and 10% of flights, respectively, and were therefore labeled as Mission 2 and Mission 3. A 2,800 nautical mile mission was included as a maximum range mission to show that the aircraft is capable of such a mission while still maintaining a lower fuel usage then the current generation of aircraft. In addition, this was the maximum range stated by the RFP and was therefore used to size the aircraft since this iteration would have the highest TOGW. Table 12 represents this exercise as Mission 4. The WB-1 greatly outperforms the current generation of narrow-body airliners in all mission scenarios.

Table 12: Mission Data

	Mission 1	Mission 2	Mission 3	Mission 4
Cruise Range (nm)	500	1000	2000	2800
Mission Utilization	50%	40%	10%	Max Range
Empty Weight (lb)	90,000	90,000	90,000	90,000
Initial Fuel Weight (lb)	7,650	11,800	20,300	27,250
Cruise Speed (Mach)	0.8	0.8	0.8	0.8
Time After Cruise (min)	86	151	281	386
Fuel After Cruise (lb)	1832	1806	1818	1834
Total Range (nm)	653	1155	2157	2960
Final Fuel Weight (lb)	61	36	48	64
Total Time (min)	124	189	319	424
Fuel Burn (lbs/seat)	38.79	70.97	123.20	169.44

Table 13 compares the mission performance for the maximum range operation with the Boeing 737-800. Although the total range of the aircraft are similar, the fuel burn over the same range is substantially lower for the Greenspan concept. This is a result of its low weight, combined with the increased efficiency of a strut-based airframe. The fuel burn presented is that of the 2,800 nautical mile mission to demonstrate that the WB-1, in its heaviest configuration, outperforms the Boeing 737-800.

Table 13: Mission Comparison with Boeing 737-800

	Greenspan	Boeing 737-800[2]
L/D	22.8	15
Range (nm)	2960	2945
Fuel Burn (lb/hr)	4235	5300

Field Performance

The RFP requires that the concept have a balanced field length of less than 7,000 feet. Greenspan conducted a rigorous analysis of field performance through the methods outlined in Raymer.[14] Table 14 summarizes the takeoff and landing distances. Greenspan performed calculations for both a standard day (59°F) and a hot day (86°F), but since the hot day distances are greater, only they were included in Table 14. As per FAA requirements, Greenspan computed landing distances without the benefit of thrust reversal. Furthermore, the landing distance presented was calculated to simulate an emergency. The calculations utilized a landing weight of 100,300 pounds, or approximately 85% of the maximum TOGW of 117,200 pounds to show the landing distance required should there be an emergency return to the airport.

Table 14: Summary of Takeoff and Landing Distances for Hot Day Standard

Takeoff		Landing	
Ground Roll (ft)	1992 ft	**Approach (ft)**	1000 ft
Obstacle Clearance (ft)	1745 ft	**Ground Roll/ Braking (ft)**	4581 ft
Total Distance (ft)	4316 ft	**Total Distance (ft)**	6567 ft

While the data presented in Table 14 is below that of current competing aircraft, the most important measure of an aircraft's field performance is the balanced field length. As mentioned above, the RFP states that the balanced field length must be below 7,000 feet on a hot day (86°F) at sea level. Greenspan not only met this criterion, but also improved upon it with the added incentive that the balanced field length is also below 7,000 feet on a hot day (86°F) at an altitude of 5,000 feet in order to simulate a flight out of Denver. Table 15 summarizes the results of these calculations.

Table 15: Balanced Field Length

Balanced Field Length	
Standard Day (59°F) (ft)	5620
Hot Day (86°F) (ft)	5889
Hot Day (86°F), Denver (ft)	6772

All of the distances calculated were below that of current generation airliners. In some cases, the WB-1 demonstrated a large improvement over current aircraft, which will enable Greenspan to fly out of airports that are currently too small for a Boeing 737-800. This will allow new markets to open that were previously unserviceable due to the field length requirements of the current fleet of short haul airliners. Table 16 compares the field performance characteristics of the WB-1 with current generation aircraft in below.

Table 16: Field Performance Comparison[2]

	Greenspan WB-1	Boeing 737-800	Airbus A320
Landing Distance (ft)	6,567	5,400	4,890
Balanced Field Length (ft)	5,620	6,890	6,400

Noise Abatement

Greenspan considered various methods for reducing the noise signature of the WB-1. One method considered was to modify the flight path of the plane during approach or departure. For example, steepening the approach path to 5° from 3° reduces the area affected by the aircraft noise.[31] While Greenspan recognized the perspective benefit of operational modification, the WB-1 takes no credit for these operation advances. However, the aircraft is capable of performing low-noise approaches and departures.

Systems

The RFP requires that the proposed design operate more efficiently than aircraft currently in service. Therefore, it is reasonable to assume that the aircraft systems play a role in the overall efficiency of the aircraft operation. Furthermore, the RFP states that the design must be certifiable by 2018, and meet all FAA requirements. Many FAA requirements are extremely specific, and many of them refer directly to aircraft operation and/or the aircraft systems. As a result, Greenspan identified the major aircraft systems as being essential to a successful and efficient design.

Reduced-Bleed Concept

Many of the aircraft systems, in the past, have depended heavily on hydraulics, pneumatics, heat, and air. Historically, the major source of heat and air has been air siphoned off the engine at various stages of the compressor. Bleed air is commonly used for powering certain pneumatics and heat dependent systems, such as wing anti-icing. However, there is a current shift away from this technology to something believed to be more efficient. The shift consists of using as little bleed air as possible, and instead using electrical means to power the aircraft systems. Reducing bleed air allows the engine to operate more efficiently. Furthermore, electric power generation is much lighter than the heavy, metal ducting required for channeling bleed air.[5]

Due to these benefits, Greenspan made it a goal to incorporate this type of concept into the aircraft design. Scrutinizing the reduced-bleed, electric systems on the Boeing 787 and the Airbus 380 helped Greenspan develop and integrate a reduced-bleed system for the WB-1. The Boeing 787 is nearly an all-electric system, only using bleed air for engine nacelle de-icing.[32] The Airbus A380 is not an all-electric system, but does make use of some advanced technologies in the fields of electric actuation. [33]

A large power supply is required to power the aircraft systems. Batteries alone do not provide sufficient power for the aircraft systems and must be supplemented. Generators power the Boeing 787 all-electric system. The APU starts the generators, which are geared to the engines for engine start-up. Once the engines are running and self-sustaining, the APU is shutdown. However, the engines keep the generators running, which then provide power to the aircraft systems. Figure 25 is a basic diagram of the WB-1 electrical system, strongly based on the Boeing 787 model.[26]

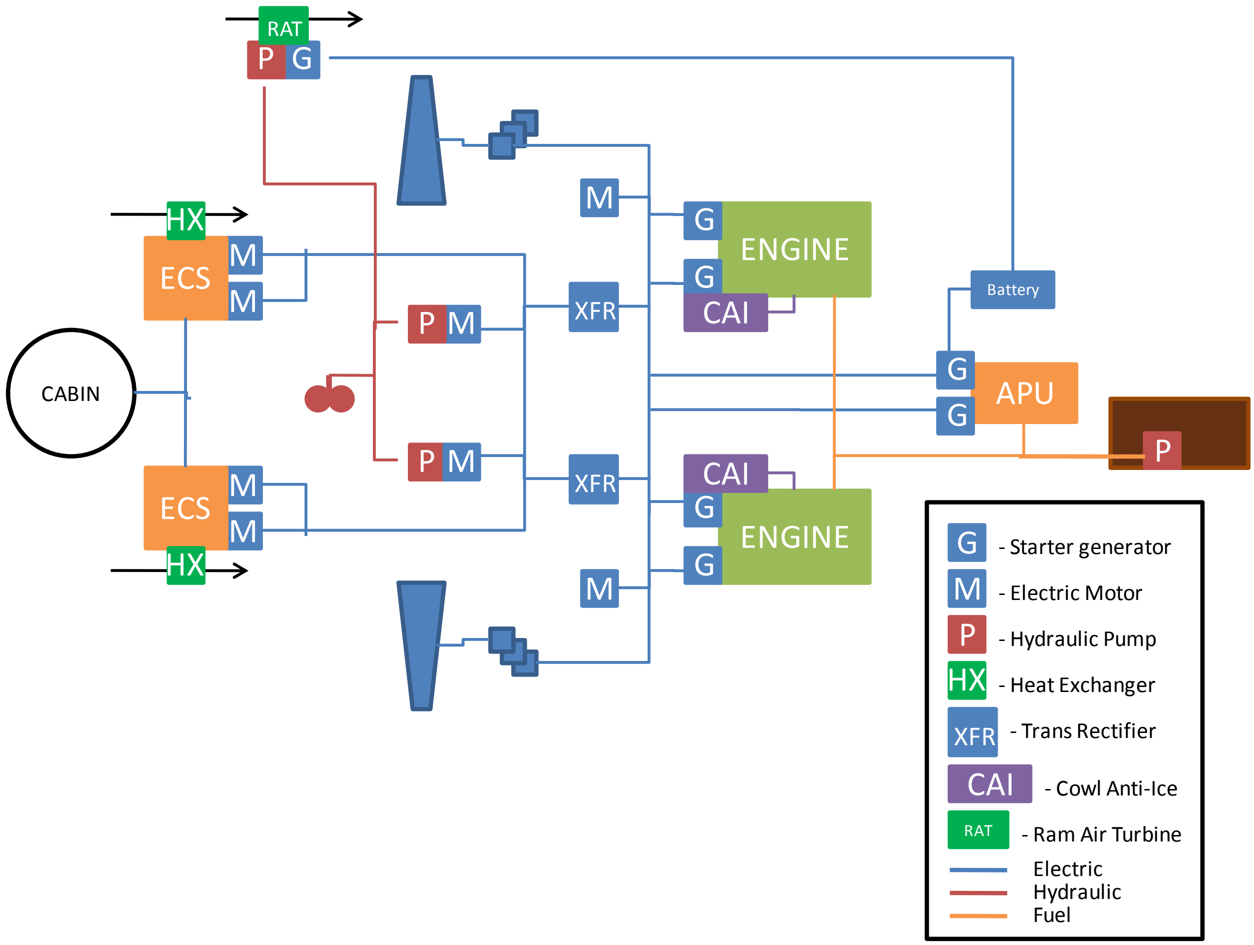


Figure 25: Reduced-bleed System Concept

Incorporating reduced-bleed systems greatly affects the other aircraft systems. The pros and cons of these affects will be discussed in the subsequent sections concerning the overall electric, environmental control, hydraulic, pneumatic, anti-ice, and de-ice systems.

Landing Gear System

Landing gear integration is an important part of the design process because it involves the aircraft balance during taxiing, takeoff, and landing. Landing gear sizing involves many variables, and therefore is very sensitive to geometric changes and weight changes. This results in an iterative sizing process outlined in Figure 26.

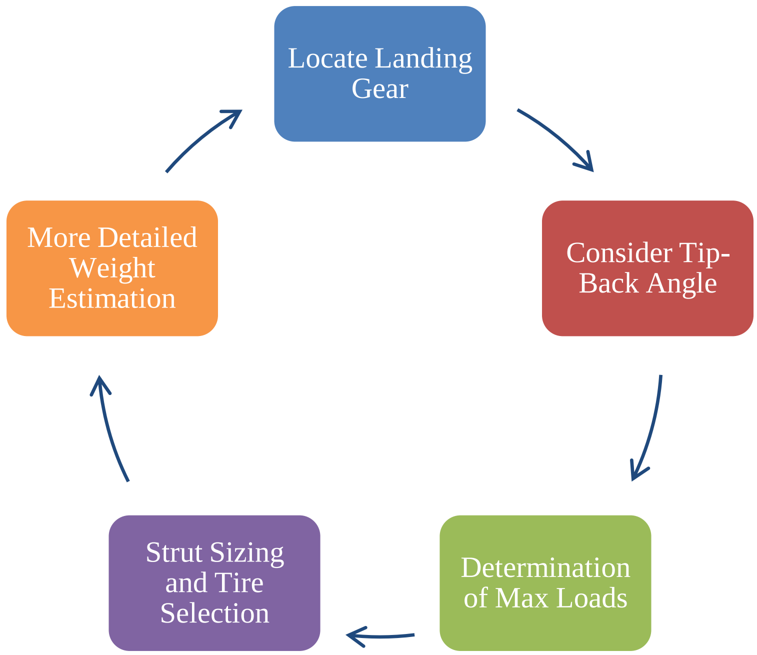


Figure 26: Landing Gear Iterative Sizing Method

The first iteration consists of estimating the weight, locating the main gear just behind the CG, and locating the nose gear several feet behind the nose. The required 10° to 15° tip-back angle determines a forward limit on the main gear location. This drove the main gear, wing, and the center of gravity aft on the WB-1. The loads on the landing gear depend on the geometry depicted in Figure 27 and the equations that follow. Strut sizing and tire selection result from the required loads, which in turn yields a more accurate weight estimation of the landing gear. Repeating the process several times accurately sizes and locates the landing gear of the aircraft.

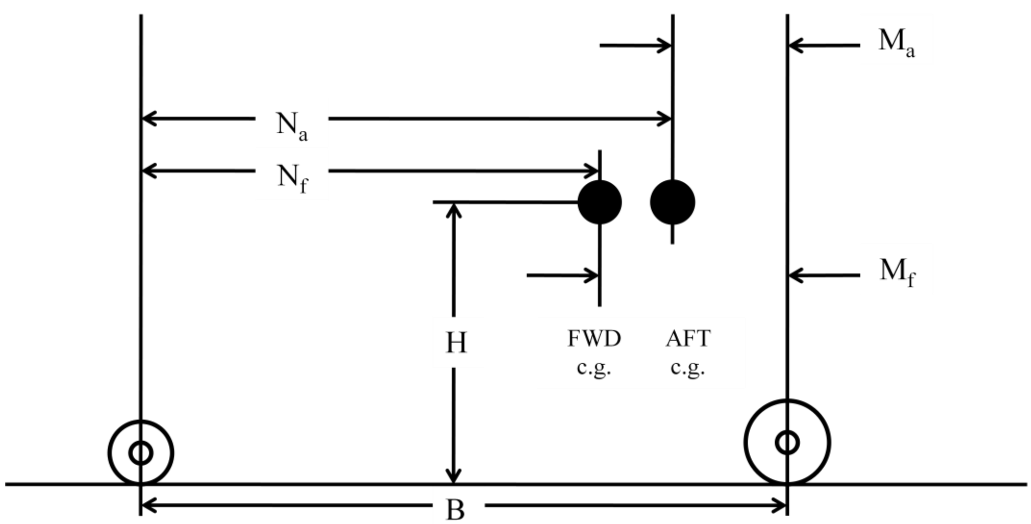


Figure 27: Landing Gear Geometry Diagram [14]

The required loads are governed by the following equations:

$$Max\ Static\ Load = \frac{WN_a}{B}$$

$$Max\ Static\ Load\ Nose = \frac{WM_f}{B}$$

$$Min\ Static\ Load\ Nose = \frac{WM_a}{B}$$

$$Dynamic\ Braking\ Load\ Nose = \frac{10HW}{gB}$$

Table 17 contains the landing gear loads, while Table 18 contains the final sizing of the WB-1 landing gear. Due to the light weight of the aircraft, the loads on the gear are relatively small compared to other transport aircraft carrying 150 or so passengers. This results in a lighter landing gear, which slightly reduces both drag and noise at takeoff and landing.

Table 17: Landing Gear Loads

	Loads (lbs)
L_{max}	30,085
L_{max} nose	6,913
L_{min} nose	2,490
L_{brake} nose	4,608

Table 18: Landing Gear Sizing

	Main Gear	Nose Gear
Diameter (in)	39.8	29.0
Width (in)	14.0	11.0
Rolling r (in)	16.50	13.0
Stroke (in)	11.68	11.68
L_{oleo} (lbs)	15,043	11,521
D_{oleo} (in)	4.24	3.71
Strut Length (in)	29.20	29.20
Weight (lbs)	2,713	272

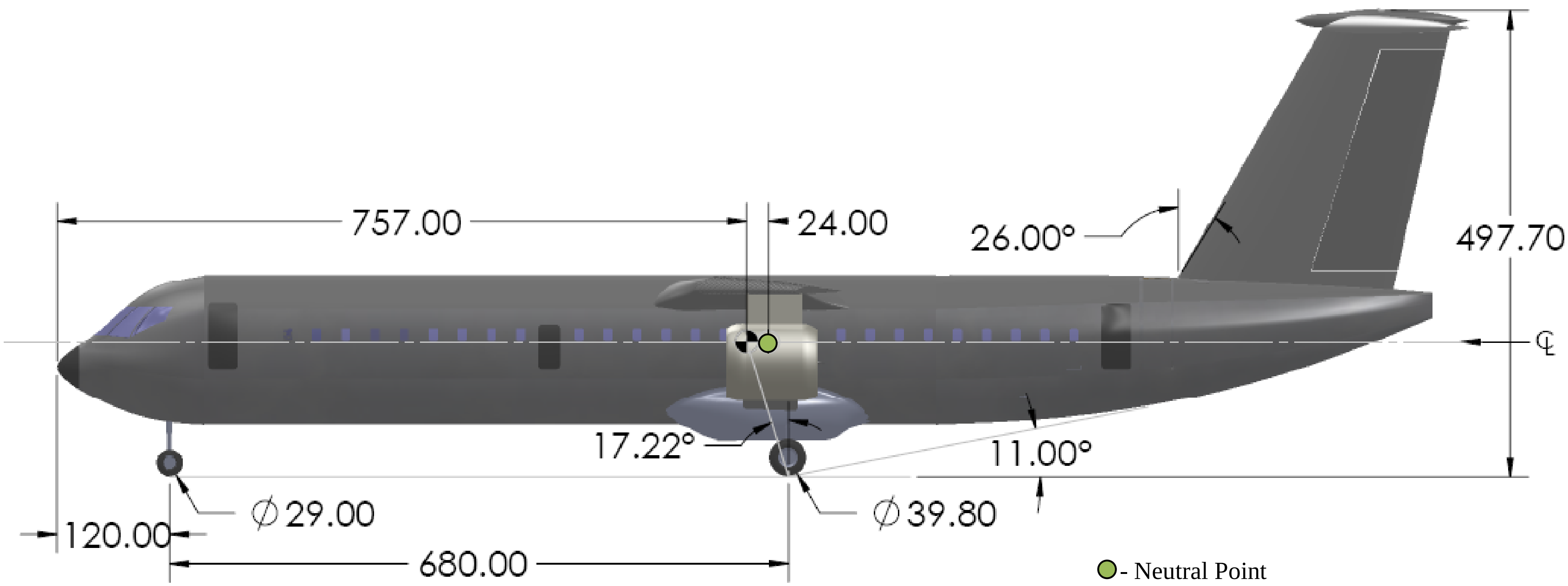


Figure 28: Landing Gear Placement Diagram

Flight Deck Furnishings

Modern aircraft, like the WB-1, are highly integrated and automated. Above all, safety is the number one concern in aviation. On the flight deck, as with every other aspect of the design, redundancy and reliability is stressed. The WB-1 will possess advanced flight control systems, fully integrated avionics, extensive automatic flight capability, a comprehensive suite of situational awareness tools, and more than capable communication and navigational systems.

Despite the abundant automation capability, it is possible that pilots will hand-fly the aircraft during the frequent short flights. The WB-1 has been designed with the pilot in mind; therefore, rather than joystick controls, a traditional yoke and rudder will be available for primary flight control. Where a joystick seemingly implies that the aircraft is in control, the yoke should instill a sense of authority for the pilots.

A single vendor will supply many of the systems in order to ease integration. For example, Rockwell Collins and Honeywell both offer comprehensive suites for the cockpit. At this time, a specific vendor has not been selected. Advances in technology are expected between the time this proposal is prepared and when the aircraft will be delivered. The cost of the flight deck systems will be substantial. Therefore, it is important that an active bidding process be carried out among different vendors.

By picking the avionics when the aircraft is first conceived, the systems may be out-of-date when delivered. Recent advances that have required retrofits include the Wide Area Augmentation System (WAAS), FAA's Next-Generation Air Transportation, and cessation of satellite monitoring of the 121.5 emergency frequency. WAAS is an improvement to the GPS system to allow for precision instrument approaches. The FAA is designing the Next-Generation Air Transportation System to be more efficient and safe. The improvements will require transponder equipment to include Automatic Digital Surveillance-Broadcast (ADS-B) capability. The switch from satellite monitoring from 121.5 to the 406 MHz frequency requires an updated to Emergency Locator Transmitter (ELT). To prevent innovation from negatively impacting our design, our cockpit will be highly flexible. Figure 29 shows a basic concept for our flight deck.

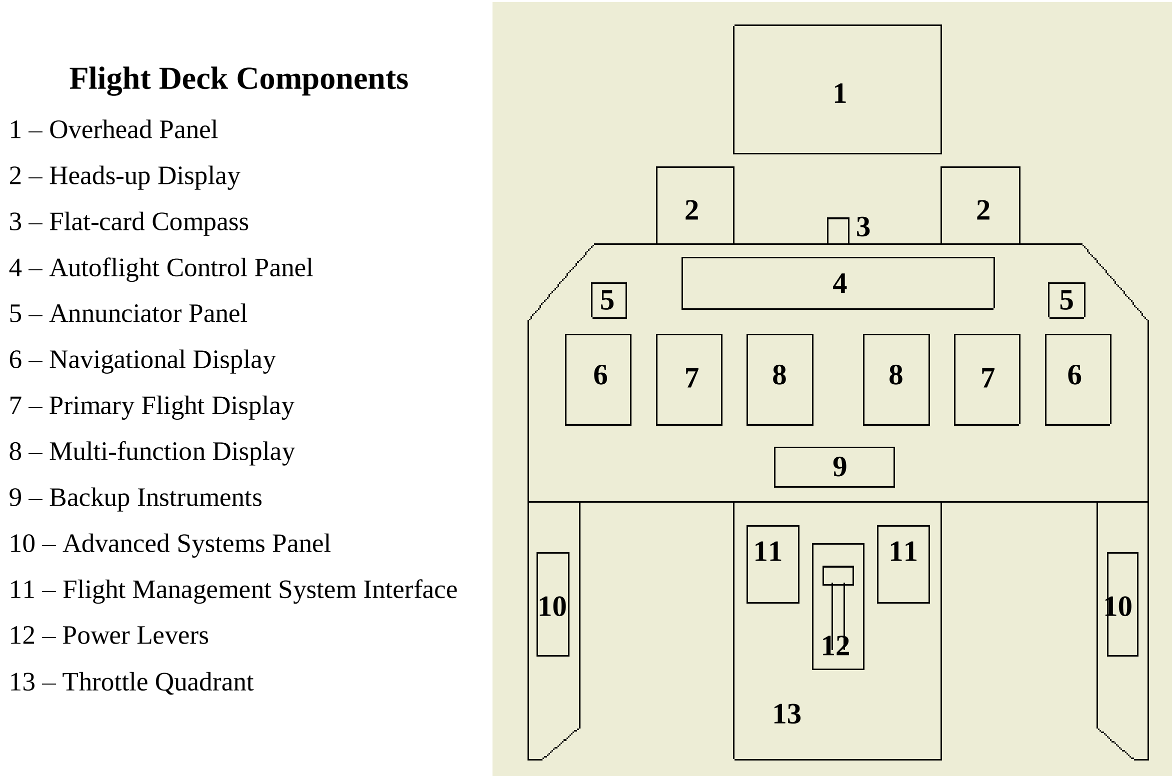


Figure 29: Flight Deck Diagram

Table 19 is a brief listing of some components and capabilities Greenspan will request that the vendors provide for the WB-1. Some capabilities are not currently in service, such as a touch-screen interface, however it is possible that they will be available at the time of certification.

Table 19: Listing of Flight Deck Systems and Capabilities

3-D Weather Radar	Electronic Flight Bag
Dual Mode-S Transponders (ADS-B Capable)	Reduced Vertical Separation Capability
Dual Heads-Up Displays	Low Visibility Approach Capability
Enhanced Vision Systems	Aircraft Security (Cameras, etc)
Integrated Situational Awareness (Weather, Traffic, Terrain, and Navigation)	Various VHF and UHF Navigational and Communication Radios
Redundant Flight Management Systems	Position and Anti-collision Lighting
Enhanced Pilot Interface	Cabin Entertainment and Communication Systems
Touch-Screen Displays	Runway and Taxiway Incursion Prevention
Inertial Referencing Systems	Engine Monitoring and Controls
Radar Altimeter	Systems and Airframe Health Monitoring
Cockpit Voice and Flight Data Recorders	Satellite Communications
Data Transmission Services	Capability of Flight Data Uplink to Operator

Electrical Powering of Other Aircraft Systems

Reduced-bleed systems eliminate and simplify the pneumatics and hydraulics, but complicate the electrical system. Keeping hot air inside the engine allows the engine to operate more efficiently.[26] Furthermore, routing electrical wiring is less invasive then a bleed air ducting, freeing up space in the cabin. This also relieves strain on the aircraft cooling system, because the ducting typically requires cooling.

Four starter-generators geared to the engines provide power for the aircraft systems. The generator and accompanying systems distribute power throughout the aircraft, power avionics, control surface actuation, environmental control system, wing anti-icing system, and other systems.

Hydro-mechanical and Electro-static Actuation

Using electro-static actuators reduce the hydraulic system size, and its accompanying weight. The starter generators power small electric motors that generate the actuation of the control surfaces. Multiple electro-servo motors throughout the aircraft provide redundancy for control surface actuation. By using this for all control surfaces, hydraulics are limited to the landing gear. There will be at least four independent systems for flight controls, offering ample redundancy.[5]

Hydraulic System, Pneumatic System, and Ram Air Turbine (RAT)

Electric motors directly power two hydraulic pumps, which serve the sole purpose of deploying and retracting the landing gear. No pneumatics are used in the aircraft for actuation. As with the Boeing 787, the only bleed air that the WB-1 utilizes is for engine nacelle de-icing. Due to the proximity of the nacelle to the bleed air port, no bleed air is routed through the aircraft.

A ram air turbine (RAT) can be mechanically deployed in the event of power loss. The RAT will provide enough power generation to feed a battery that would power as many as two starter generators. This provides enough emergency power to serve the critical aircraft systems until landing. Furthermore, the RAT will power a hydraulic pump connected to the hydraulic system used for extending the landing gear.[26]

Anti-icing and De-icing System

The de- and anti-icing system is very simple compared to conventional aircraft and a significant weight saver. The system consists of electric blankets along the leading edge of the wings and the horizontal and vertical tail. It is a rather self-explanatory idea, but the electric blankets would provide enough heat to the leading edge to prevent and remove any ice that may have accumulated.

Environmental Control System and Systems Cooling

The environmental control system implemented in this design is quite different from most aircraft, and is even different from the Boeing 787. The WB-1 will be equipped with an all fresh-air system, consisting of ram air being compressed to the atmospheric pressure at 6,000 feet, feed the compressed air to the front of the fuselage cabin, and allowing it to flow and collect at the back of the aircraft for dumping. The air is never re-circulated, which improves passenger comfort by removing stale air from the system. Greenspan felt this was a worthy cause, since the RFP outlines ergonomics as an important consideration. In addition, such a system provides many other benefits in relation to the aircraft cooling system.

When bleed air, ram air, and re-circulated air are all used for ECS and aircraft cooling, there is a mix of hot and cool air. This is a highly inefficient method because the air gains excess energy in the engine's gas generator compressor, which must be removed from the bleed-air before it can be used. By just using ram air, the cooling packs do not need to be as large. Furthermore, the systems that need to be cooled are not hot bleed air pneumatics, but rather more electronics. Although electronics need significant cooling, it has been found that the all electric system will require less cooling, thus leading to smaller cooling packs.

Cabin Entertainment Furnishings

The cabin furnishings are adjustable to the airline needs and the WB-1 is compatible with the state of the art furnishings. The weight breakdown considered furnishings that included not only the seats, overhead stowage, lavatories, and galleys, but also personal entertainment systems for each seat, and an additional electronics bay to serve as a base for onboard entertainment.

Emergency Equipment

Although designs continue to improve, sometimes aviation accidents occur. Greenspan will integrate every discernable lesson learned from the incidents of the past in all aspects of design. Further, the aircraft will be designed such that the pilots have the utmost ability to handle the situation. The WB-1 will integrate technologies to ease pilot workload so that they can focus on flying the aircraft.

In terms of passenger safety, the WB-1 includes provisions for evacuation of passengers from six separate doors along the fuselage, shown in Figure 30. Two doors in the front of the cabin and two in the rear are Type A doors which include an inflatable slide capable of handling two people abreast. Two doors near the midsection of the fuselage in front of the wing are Type I and contain inflatable slides capable of handling one person abreast. In the case of a water landing, all slides double as temporary emergency life rafts. Life vests are located under the seats and all seat cushions are designed for use as floatation devices.

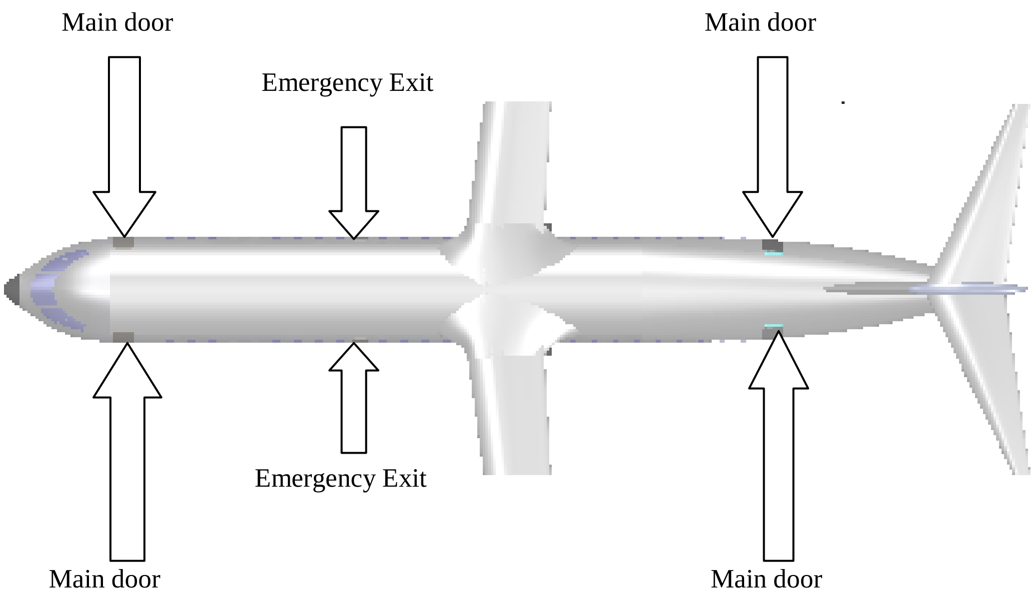


Figure 30: Emergency Exits

In the event of depressurization, emergency oxygen will be supplied to masks located above the seats for each passenger. Oxygen canisters will provide sufficient oxygen for each passenger grouping during an emergency decent. Emergency oxygen for the flight crew is provided in portable bottles to allow them to continue to assist passengers during an emergency. Auxiliary oxygen is also available at all times on the flight deck.

Fire suppression is accomplished through automated Halon deployment systems distributed throughout the cargo bay, avionics bays, galleys, and engines. Fire extinguishers are positioned throughout the cabin and cockpit for use by the cabin crew.

Weight and Balance

The aircraft weight has an extremely *heavy* influence on every aspect of the aircraft design process. Therefore, Greenspan identified having a detailed and accurate weight breakdown as one of their main priorities. The following subsections will detail how the weight was broken down, how the various weights were estimated, and how they relate to the design requirements outlined in the RFP.

Weight Breakdown

The weight was broken down into the following major categories: total component weight, maximum payload weight, and maximum fuel capacity. Figure 31 details the entire weight breakdown of the WB-1 and the individual centers of gravity.

Total Component Weight

The structural weight consists of the main fuselage, nose, wings, empennage, strut, bulkheads, and frames. Greenspan chose to integrate as much composite material as possible to help reduce the weight of the aircraft. Reducing the weight of the aircraft would help to reduce fuel, which would in turn help Greenspan to meet the operating cost and fuel burn requirements. The powerplant weight is simply the weight of the engines and the propulsion system. The fixed equipment weight consists of all of the aircraft systems, such as the electrical system, landing gear, and the environmental control system. Systems sizing considered the aircraft functionality needs, the passenger ergonomic needs, and FAA requirements.

Payload Weight and Payload Requirements

The RFP outlines two payload requirements shown in Table 20:

Table 20: Payload Requirements

Payload	Conditions	Weight
Long-Range Payload	150 passengers 225 lbs/passenger	33,750 pounds
Maximum Payload	Full High-Density @ 185 lbs/passenger Full Cargo Hold @ 8 lbs/ft^3	40,986 pounds

	COMPONENT	WEIGHT (lb)	X_{cg}	Y_{cg}	Z_{cg}	W_i*X_i	W_i*Y_i	W_i*Z_i
Structure	Left Wing	909	869	0	240	790,316	0	218,252
	Right Wing	909	869	0	240	790,316	0	218,252
	Horizontal Tail	800	1,650	0	540	1,319,840	0	432,000
	Vertical Tail	734	1,542	0	372	1,131,988	0	273,051
	Fuselage	4,358	800	0	157	3,486,414	0	684,209
	Strut/Nacelles	405	869	0	157	352,380	0	63,659
	Nose Gear	265	220	0	60	58,300	0	15,900
	Bulkheads/structure	2,500	849	0	157	2,122,500	0	392,500
	Structure Total	**10,881**						
Powerplant	Engines	9,988	869	0	157	8,680,269	0	1,568,116
	Exhaust and Thrust Reverser	1,540	989	0	157	1,523,167	0	241,780
	Air Induction Systems	200	959	0	157	191,814	0	31,400
	Fuel System	640	919	0	157	588,205	0	100,480
	Powerplant Total	**12,368**						
Fixed Equipment	Flight Control System	1200	770	0	150	924000	0	180000
	Landing Gear	2700	900	0	80	2430000	0	216000
	Avionics and Instrumentation	2,130	120	0	100	255600	0	213000
	Surface Controls	2,540	770	0	190	1955800	0	482600
	Hydraulic System	200	770	0	128	154000	0	25600
	Electrical System	4,000	770	0	100	3080000	0	400000
	APU	840	1575	0	180	1323000	0	151200
	Oxygen System	1,580	770	0	128	1216600	0	202240
	Air Conditioning System	1,580	770	0	128	1216600	0	202240
	Anti-icing system	200	730	0	200	146000	0	40000
	Furnishings	5,130	870	0	128	4463100	0	656640
	Operating Items	3,128	870	0	128	2721360	0	400384
	Weight of trapped fuel and oil	55	830	0	128	45650	0	7040
	Fixed Equipment Total	**25,283**						
Payload	Total Component Weight	48,532	846	0	145	41,058,290	0	7,024,042
	Max Fuel Capacity	27,250	955	0	240	26,023,750	0	6,540,000
	Payload	41,400	860	0	128	35,604,000	0	5,299,200
	Takeoff Weight	**117,182**						

X_{cg}	876
Z_{cg}	161

	W_i*X_i	W_i*Y_i	W_i*Z_i
SUMS	102686040.2	0	18863241.71
CGs	876.2934084	0	160.97353

Figure 31: Complete Weight Breakdown (All CG locations in inches)

Fuel Weight and Fuel Storage

Throughout the design process, Greenspan wanted to make the most of the strut-braced concept. The high aspect ratio wing, small planform, high amounts of laminar flow, and significant structural weight reduction all resulted in a low drag buildup. This resulted in significant fuel weight reduction from the fuel weight required by comparator aircraft. The maximum mission of 2,800 nautical miles only requires 27,250 pounds of fuel. The 500 nautical mile mission uses a very small amount of fuel, which largely improves fuel burn.

Since the wing of the WB-1 is so small and thin, only a limited amount of fuel could fit in the wings. Therefore, the remaining fuel must be stored in the landing gear faring and the wing-body faring. Storing the fuel in the faring occupied a small amount of the cargo space.

Weight Comparison

Figure 32 and Figure 33 show very simple weight breakdowns of the Boeing 737-800, the Airbus A320, and the Greenspan WB-1. Figure 32 shows the empty, payload, and fuel weight as a percentage of the respective takeoff weight. Figure 33 shows the same weights, but in pounds rather than a percentage. After reviewing the two figures, it is easy to see the reduction that Greenspan achieved in both the empty and fuel weight. While being nearly 55,000 pounds lighter, Greenspan's design can carry roughly the same payload as the 737-800 and A320-200, with a maximum range of 2,800 nautical miles. Greenspan's TOGW is 117,200 pounds, while the 737-800 is 174,200 pounds and the A320-200 is 162,040 pounds.[2]

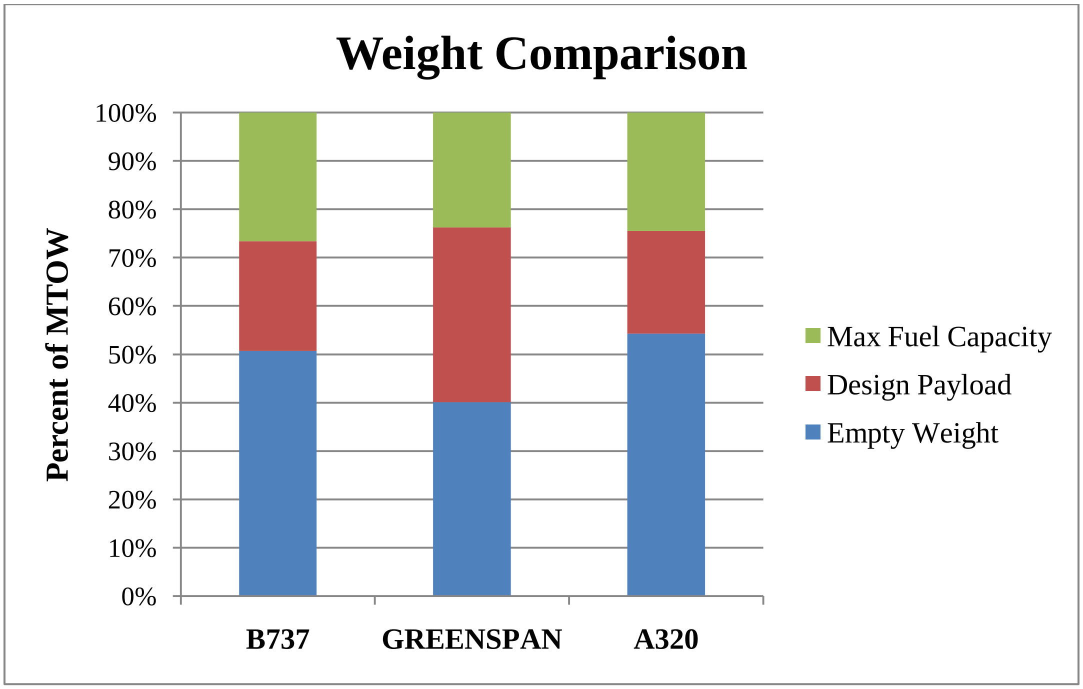


Figure 32: Weight Comparison as Percentage of MTOW[2]

Figure 33: Weight Comparison in Pounds[2]

Weight Balance

Balancing the aircraft became an important issue for landing gear integration and stability and control. The weight breakdown chart, Figure 31, calculates the individual centers of gravity as well as the overall center of gravity. Placing the wing box, the landing gear faring, as well as the aircraft systems, was an integral part of ensuring that the center of gravity of the aircraft was in an appropriate location relative to the landing gear and the neutral point. Further details of this are in the Stability and Control and the Systems sections of this report.

Figure 34 shows the CG travel as the aircraft is both loaded and unloaded. The neutral point defines the aft limit, while the forward limit is defined as the CG location corresponding to 30% static margin. Starting with an empty aircraft a partial payload could result in a CG that is too far forward. Therefore, it is important to consider that a partial payload should be loaded further aft. The figure also shows the effects of loading the rear and forward cargo holds. The fuel stored in the inner wing box is burned last, to maintain as much structural relief as possible. The fuselage tank contains the majority of the fuel and therefore results in the most CG travel.

The MAC is only 7.67 feet and the total CG travel is only 26 inches. The WB-1 will be making 50% of its flights at the design point highlighted in red on the figure. The CG travel during these flights is in close proximity to the quarter-chord, and the aircraft is least stable when fully loaded.

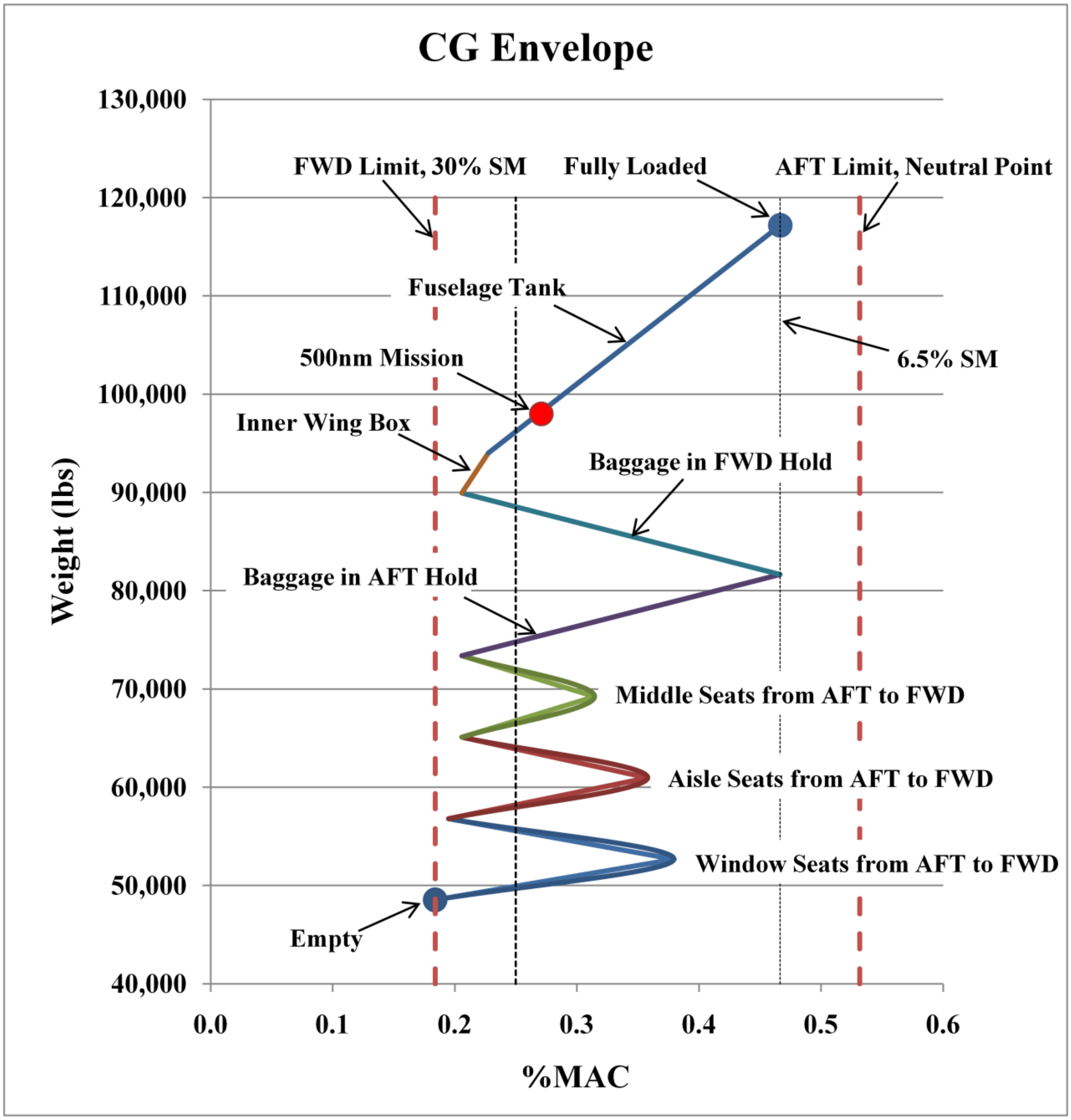


Figure 34: CG Envelope

Structures and Materials

Material Selection and Distribution

Composite materials have numerous advantages over conventional metals, such as aluminum. Currently, it is possible to realize up to 30% in weight savings due to advanced composites.[34] The material properties of composites contribute to simpler structures, reducing part counts, and therefore weight. In addition to lighter weight and reduced part counts, advantages of composites include: resistance to corrosion and fatigue, increased strength due to fiber orientation, and reduced machining requirements. Thus, advanced composites contribute to a reduction in maintenance and cost, an RFP requirement.

Specifically, the Greenspan conceptual design chose Carbon Fiber Reinforced Plastic (CFRP) in an epoxy matrix as the material to cover the majority of the fuselage, wings, and empennage. The thermosetting epoxy matrix lends itself to easier manufacturing and lower cost. Although the WB-1 is using mostly composite materials for major portions of external structures, aluminum will still be used on the leading edges of the wings and tail, following the lead of the Boeing 787.[5] Titanium will be used for the landing gear, where high stresses and loads occur.

In order to achieve high quality and structural integrity of composite products, the most up-to-date composite manufacturing techniques must be utilized. These include autoclave curing and automated tape layup, which allow larger sections of the fuselage to be constructed individually, before being combined to efficiently produce the fuselage.

Figure 35 shows the density to ultimate tensile strength ratio for materials considered for use on the WB-1. As one can see, carbon fiber is strong for its low density. Aluminum exhibits a superior density to tensile strength ratio compared to boron. As a result, boron epoxy was not chosen as a primary material. Titanium was also compared to show how high the ratio is to carbon fiber. Therefore, it was in the best interest of material selection to minimize the use of titanium.

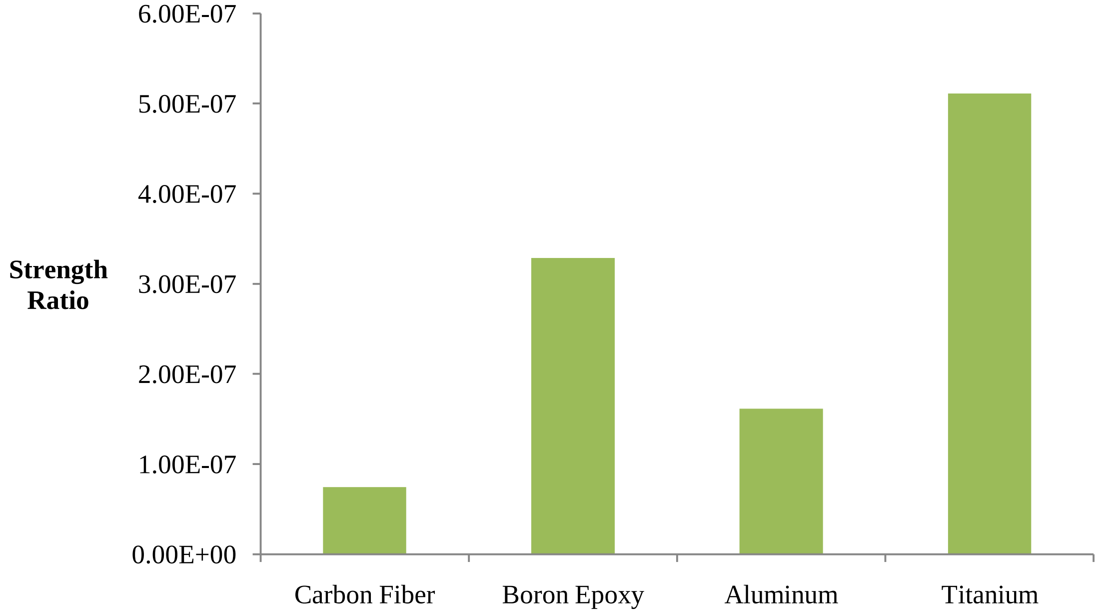


Figure 35: Density/Tensile Strength Ratio[35]

Overall Loads

The V-n diagram shown in Figure 36 illustrates the flight envelope the aircraft can safely maneuver. The structural load factors are taken as +2.5 and -1, by convention. However, when accounting for various gust velocities, the structural load factor must be increased at the cruise velocity. As a result, the top line of the V-n diagram has a sharp peak. This peak mandates a higher structural load at cruise to allow for a 50 mile per hour gust. The other gust velocities are within the existing flight envelope.

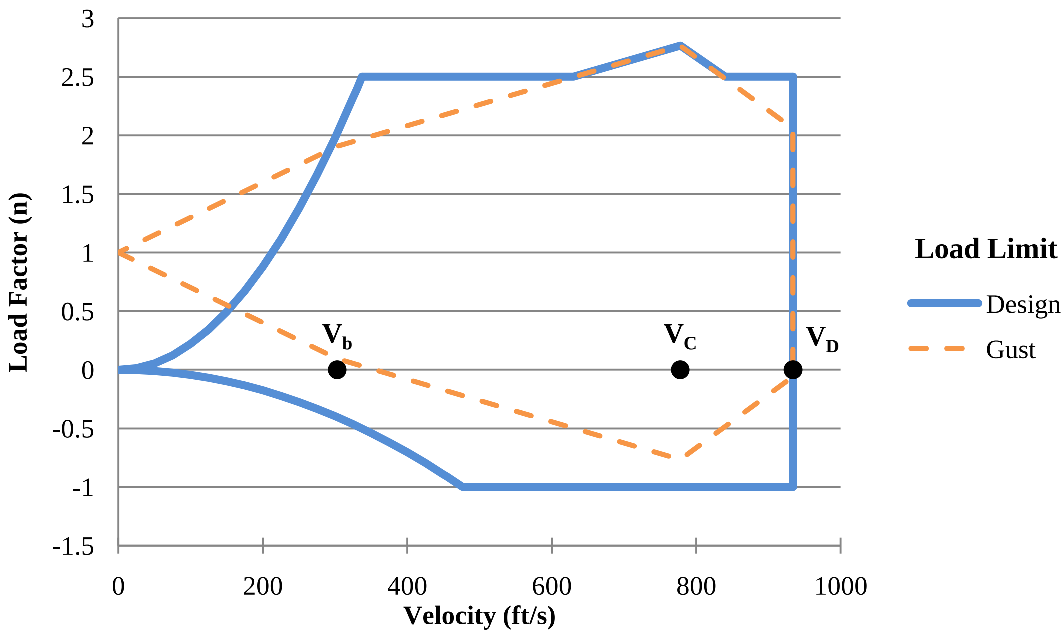


Figure 36: V-n Diagram

Specific Loading

Material selection and structural placement were intertwined throughout the design process. Since carbon fiber epoxy was selected as the primary material for the fuselage and wing skin, less internal structural material was required to attain structural stability.

The wing box is composed of a two-spar I-beam structure that takes advantage of the stressed composite skin. As a result, no stringers are necessary, as the carbon fiber skin can carry the loads and bending moments encountered during flight. The ribs are spaced at 22-inch intervals.[36] This follows from convention of aluminum skin stringer and rib configurations. By using a composite skin and the same rib spacing as current transport aircraft, stringers are not needed to prevent the buckling of panels. The forward spar is located 15% of the local chord, while the rear spar is 65% of the local chord. The fuselage has 12 bulkheads along the length of the fuselage tube to withstand external pressure loads, pressurization of the cabin, axial loads, and bending moments. Table 21 shows the function and position of the bulkheads. Analysis of frame spacing using honeycomb sandwich carbon fiber fuselage panels shows that using advanced material placements, such as three-dimensional braiding for frames, results in a cost and weight reduction of up to 25%, when compared to conventional skin-stringer configurations.[37] In addition to the initial weight savings, a lesser number of frames can be used in conjunction with the stronger skin to prevent buckling of the fuselage. The conventional frame spacing of 20 inches in current skin-stringer configurations can be doubled to 40 inches to further reduce weight. Although current research on frame spacing combined with composite skin seems new, more research and testing by the RFP date of 2018 should provide sufficient, validated proof of structurally sound, larger frame spacing. In addition, the fuselage will have a keel running the length of the tube that can support loads from the main landing gear, as well as the strut connection. There will also be four longerons running the length of the fuselage. Two longerons will be located at the passenger deck floor level, one on each side of the fuselage. These longerons will carry the axial loads from passengers and cargo below the passenger deck. Two other longerons will be located near the top of the passenger cabin on both sides of the fuselage. These longerons can carry loads from the top-mounted wing. It is also important to note the use of bonded doublers to support the structure around window cutouts. A two-pane doubler alleviates much of the shear and vertical fuselage bending, as well as pressure loads, that the aircraft is expected to encounter during flight.

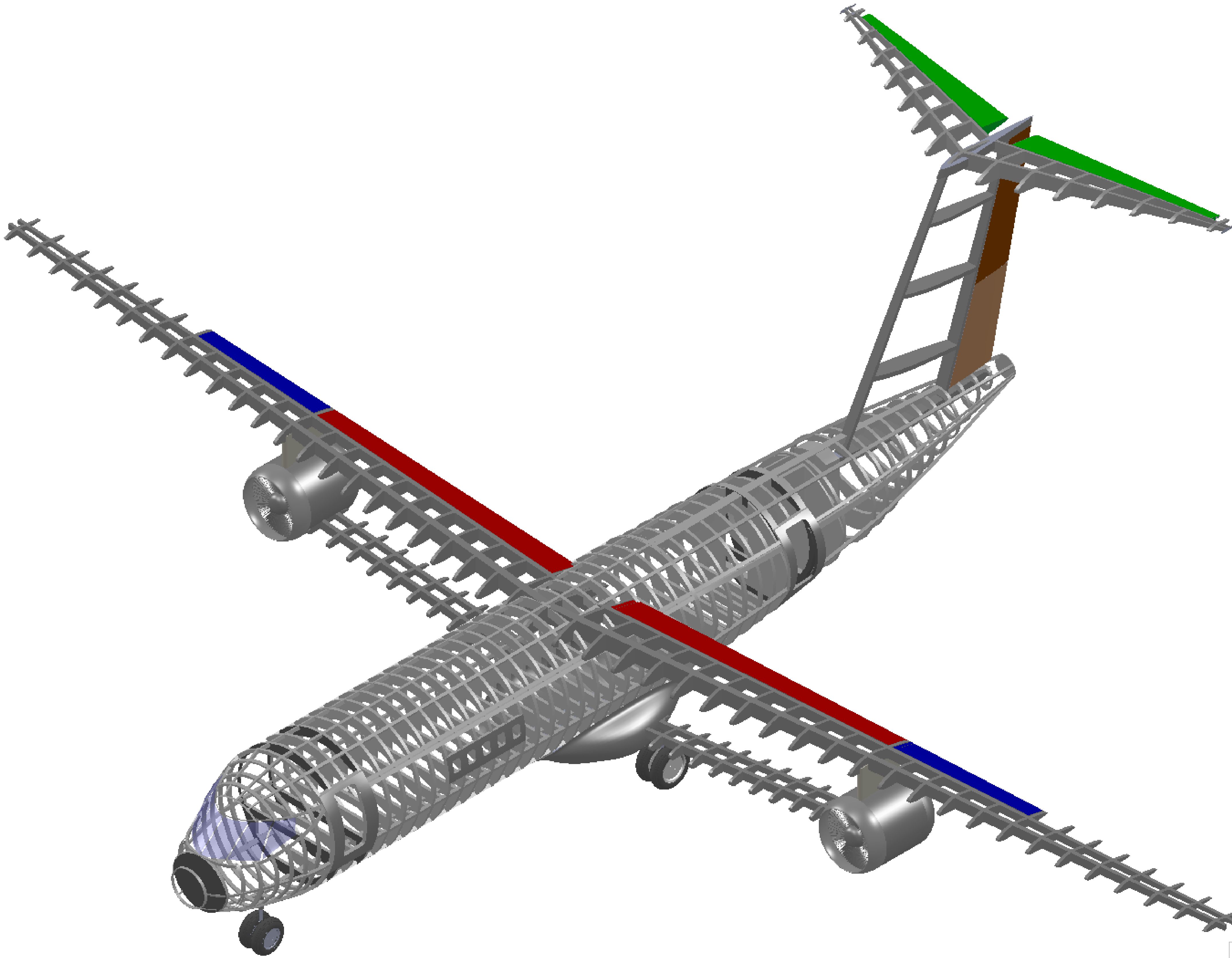
Table 21: Bulkhead Position and Location

Bulkhead	Description	Fuselage Station (in)
1	Forward Pressure Bulkhead	30
2	Nose Gear Attachment/Fuselage Bulkhead	120
3	Forward Cargo Door Support Bulkhead	148
4	Forward Cargo Door Support Bulkhead	240
5	Forward wing spar attachment/fuselage pressure bulkhead	625
6	Aft wing spar/fuselage bulkhead	698
7	Main gear mounting attachment/fuselage pressure bulkhead	840
8	Aft cargo door support bulkhead	1114
9	Aft cargo door support bulkhead	1206
10	Forward vertical tail spar attachment/Aft Pressure Bulkhead	1376
11	Aft vertical tail spar/fuselage bulkhead	1496
12	Fuselage bulkhead/APU Firewall	1500

The struts that support the wing are designed in a similar manner as the wing box. Although smaller, the strut spars will be located at 15% and 65% of the strut chord and have ribs spaced at 22-inch intervals. The bending moment can be handled by the skin, spars, and ribs, and therefore will not need extra stringers. The empennage will also follow the configuration of the wings and struts. There will be a two spar I-beam configuration that, together with the ribs and stressed composite skin, can carry the moments associated with roll, pitch, and yaw. The T-tail empennage utilized takes full advantage of the strength from carbon fiber epoxy skin to withstand these moments.

8 7 6 5 4 3 2 1

GREEN	ELEVATOR
BROWN	RUDDER
BLUE	AILERON
RED	FLAPS
BLACK	BULKHEAD



	NAME	DATE
DRAWN	SWF	5/6/09
CHECKED	SCB	5/6/09
MGT APPR.	JRR	5/6/09

COMMENTS:

DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED.

GREENSPAN

TITLE:

WB-1 STRUCTURE VIEW

SIZE	DWG. NO.	REV
B	FOLDOUT 3	2

SCALE: 1:115 WEIGHT: SHEET 1 OF 1

Strut Loading and Optimization

Greenspan's design of the WB-1 centers on the structural concept of the strut. The idea is that the strut will provide enough relief to allow for a very high aspect ratio wing. In turn, this allows for low sweep and a thin wing, which enhances laminar flow. Therefore, validating the structural feasibility of such a design is crucial. The free body diagram in Figure 37 serves as the foundation of the structural analysis. Optimally, the force through the strut will act through the center of gravity of the engine. The load will be carried in structural members encircling the engine within the nacelle.

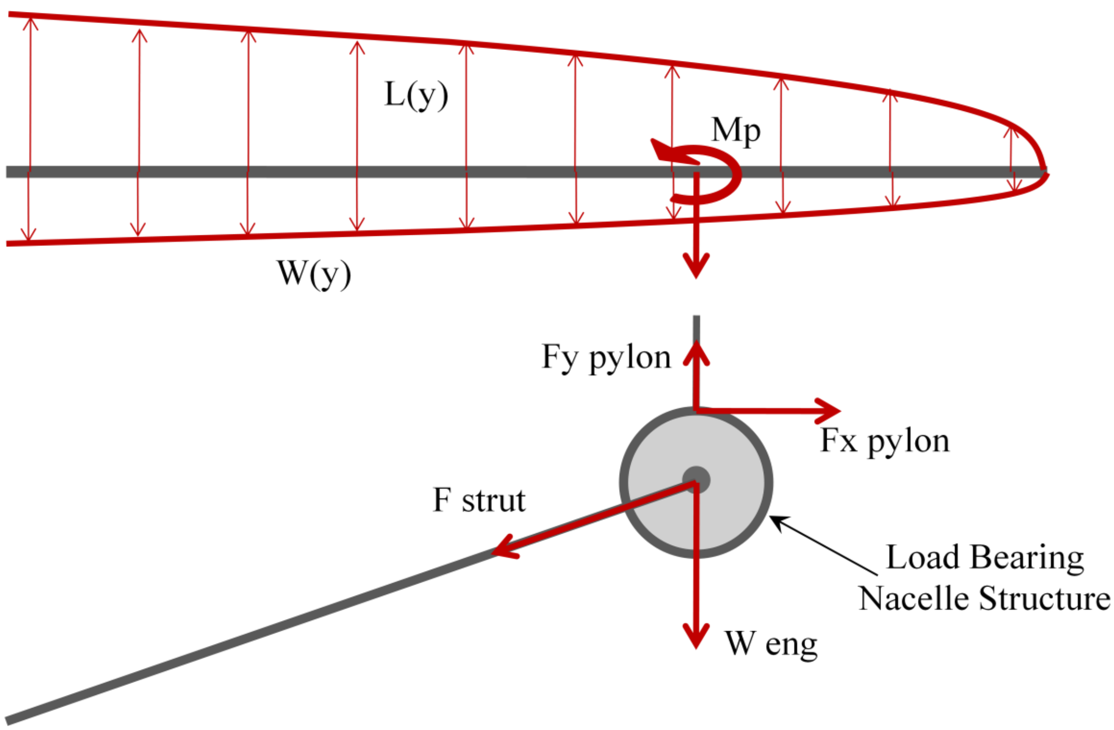


Figure 37: Free Body Diagram

The indeterminate system requires an iterative calculation. The process begins by estimating the wing weight and the force in the strut. Then, calculations lead to the lift and weight distributions on the wing. The next step of the process is calculating the shear force and bending moment distributions. The required thickness along the span is determined based on the shear force, bending moment, and material properties of the composite. This information allows the displacement at the strut connection to be calculated. This displacement allows a more accurate strut force to be determined. The wing weight and strut force are updated based on the new thickness distribution and the nodal displacement at the strut connection. The calculations are repeated until both the wing weight and strut force converge to a user defined tolerance.

Figure 38 illustrates the shear force, bending moment, and thickness distribution diagrams, which resulted from the iterative calculation. A load of +2.5g sizes the wing and strut, and the values are checked against the -1g case. The red line indicates the distributions that occur for a complete cantilever wing, while the blue line illustrates the ideal distributions of the strut wing. When running the calculation, the user defines certain geometric properties, such as the location of the strut/pylon connection, and so forth. When viewing the diagrams, think in terms of loading the wing up from the tip moving inboard to the root. The shear force builds up moving inboard, but the downward force in the strut creates a significant drop, relieving the inboard wing of large shear forces. The downward force in the strut creates a counter-acting moment, providing bending relief. This relief drastically reduces the required skin thickness.

In theory, moving the strut connection as far outboard as possible maximizes the relief. However, due to the way the engine is integrated, it slightly changes the optimized location of the strut connection. The reason being is that the pylon creates a moment that hinders the structural relief. The further out the strut connection, the shallower the strut angle. This increases the x-component in the strut, which increases the moment. Therefore, the optimized location for the WB-1 is about 55 feet from the fuselage centerline. However, the WB-1 due to engine out limitations has the strut connection at 35.5 feet from the fuselage centerline.

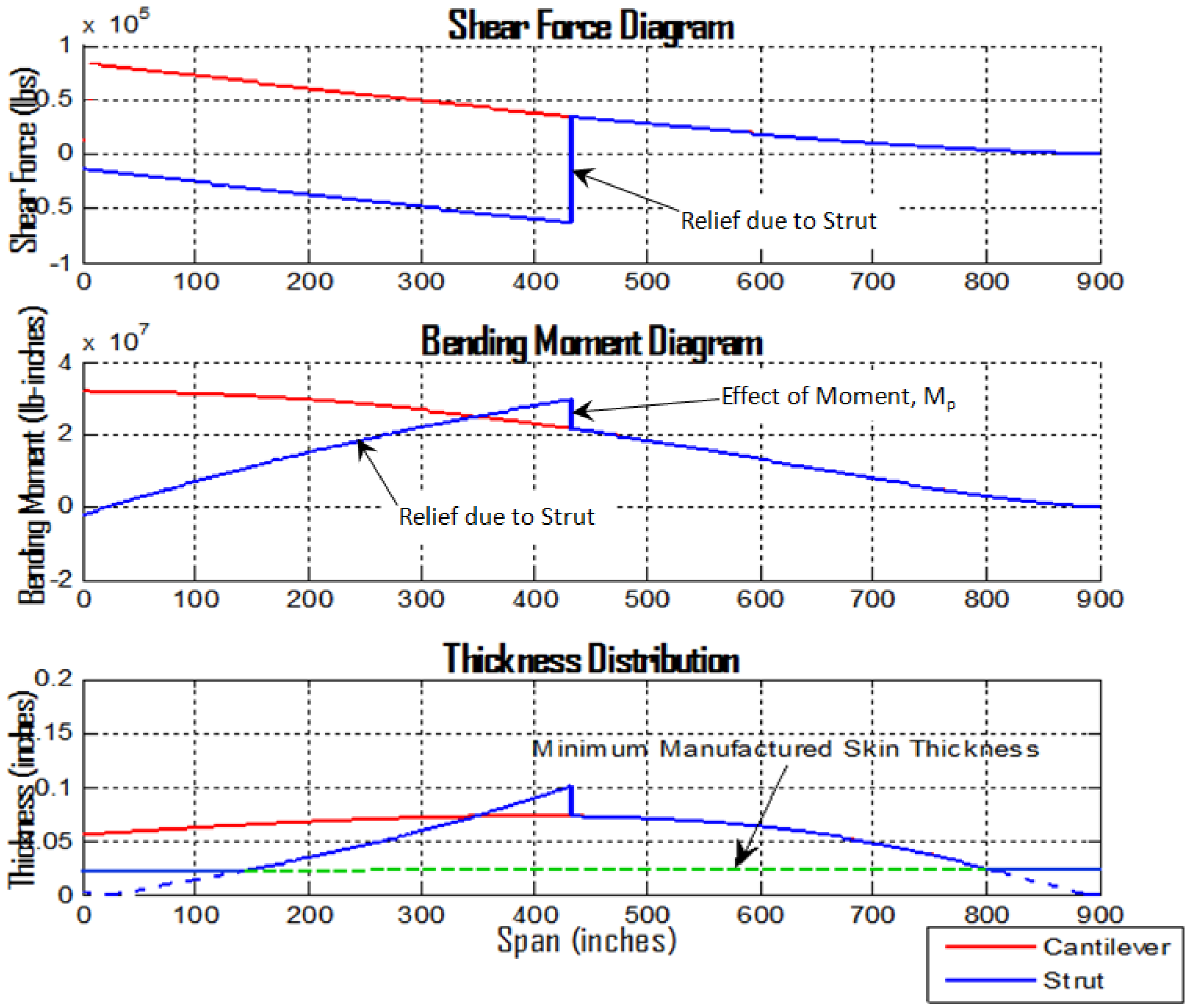


Figure 38: Strut Effect Diagrams

Stability and Control
Stabilizer Configuration

Greenspan investigated four options for empennage arrangement: a conventional layout, T-tail, cruciform, and V-tail. The wake of the wing and strut would subject the horizontal stabilizer to disturbed flow, possibly adversely affecting the flow over the control surfaces and creating more noise. The T-tail would place the horizontal stabilizer far out into the free stream with the added benefit of endplate effect on the vertical stabilizer and a longer moment arm for the horizontal surface. These benefits come at the price of weight. The vertical stabilizer would be heavier than that of the conventional tail due to additional structure to support the horizontal stabilizer. The cruciform arrangement would provide a compromise between the additional weight of the T-tail, while still keeping the horizontal stabilizer out of the wake of the wing. Unfortunately, it lost the benefit of endplate effect and introduced extra complexity into the interaction of the elevator and rudder. The V-tail presented an interesting solution, however such an arrangement would not yield enough benefit to warrant the extra complexity, especially considering the difference in magnitude between the requirements for longitudinal and lateral/directional sizing. Due to the wide placement of the engines and the one engine inoperative (OEI) case, the greatest size burden fell on the vertical stabilizer. Only seeking to satisfy this requirement resulted in a vertical stabilizer 40 feet tall with a surface area of 800 square feet. Hence, maximizing the efficiency of the vertical stabilizer was of utmost concern. As a result, Greenspan chose the T-tail arrangement in order to control OEI while maintaining a reasonable size for the vertical stabilizer.

All analysis for estimation of coefficients was conducted by a committee of three methods: a vortex lattice method (VLM) for initial design, a VLM for intermediary design, and the methods described by Roskam.[38,39,40,41] A matrix of weights applying to each method determined the final value, depending on reported reliability and confidence of results.

Horizontal Stabilizer Sizing

The longitudinal stability of the aircraft and the control power required for rotating the nose at takeoff sized the horizontal stabilizer. The objective was to make a stable aircraft under all conditions with a low nominal static margin (about 10-15%). The T-tail configuration added 12 feet to the moment arm of the horizontal stabilizer, allowing for a surface area of only 110 square feet. Placing the surface in the free stream away from flow influenced by the wing, fuselage, and engines also increased the effectiveness of the horizontal stabilizer. Such a small tail, however, could not adequately control the aircraft. Thus, available control power at takeoff drove the size of the horizontal stabilizer. The goal was to be able to reach a takeoff attitude of 8.7° angle of attack at 260 feet per second under normal conditions within 1.5 seconds. Accomplishing this required that the planform area be increased to 165 square feet. Figure 39 illustrates the horizontal stabilizer planform.

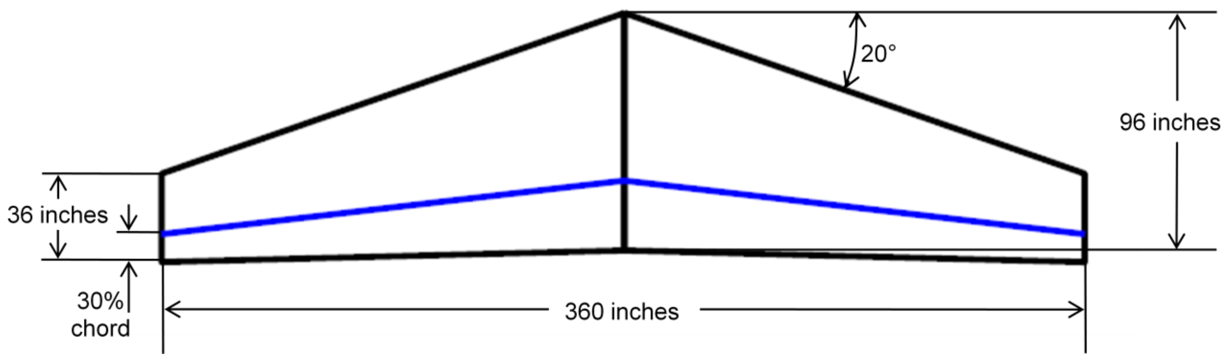


Figure 39: Horizontal Tail Planform

The WB-1 employs a variable incidence horizontal stabilizer for trim during all phases of flight. Due to structural limitations, the full range of motion for the stabilizer was limited to ±5 degrees. The airfoil chosen for the horizontal stabilizer was the NASA SC(2)-0010 supercritical airfoil, from the same series as the wing. Figure 40 shows a cross-section of the SC(2)-0010 airfoil used for the empennage. The primary feature of the airfoil was the fact that the stabilizer would exhibit similar properties to the wing. Finally, a leading edge sweep angle of 20 degrees allows the horizontal stabilizer to stall after the wing and to complement the overall shape of the planform.

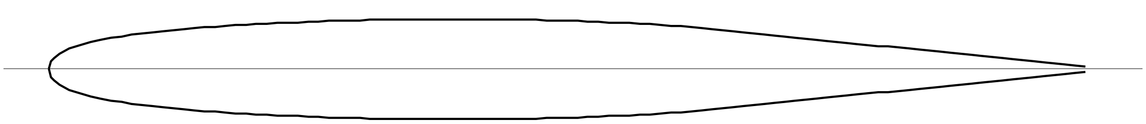


Figure 40: NASA SC(2)-0010 Airfoil

Vertical Stabilizer Sizing

As mentioned earlier, the optimum distance between the engines and the centerline of the fuselage was about 55 feet. In order to get the engines as far out as possible, the vertical stabilizer had to be as large as possible, without violating constraints on drag and structural integrity. It was decided that, for the purposes of drag and structural integrity, the vertical stabilizer be no taller than 25 feet. In order for the horizontal stabilizer to act as an endplate on the vertical stabilizer, the tip chord of the vertical stabilizer was set to match the 8-foot root chord of the horizontal stabilizer. The root chord was set to 20 feet to add more surface area. The vertical stabilizer features a leading edge sweep of 26° for both drag performance and to complement the planform as shown in Figure 41. As with the horizontal stabilizer, the airfoil chosen for the vertical stabilizer was the NASA SC(2)-0010.

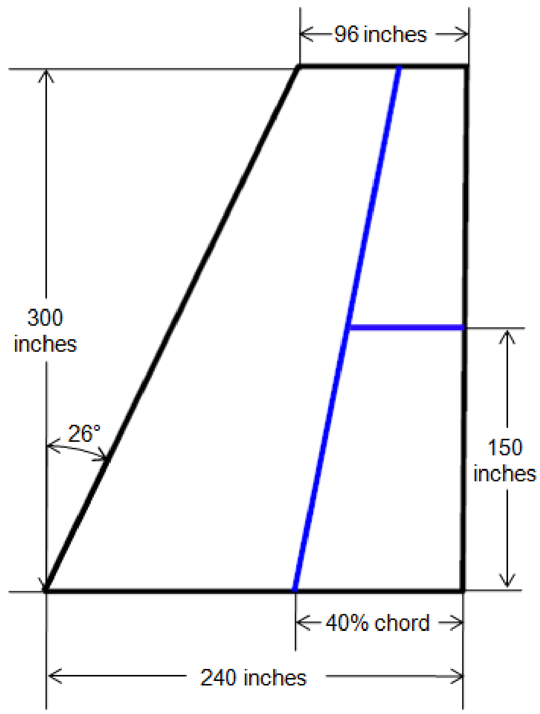


Figure 41: Vertical Tail Planform

Control Surfaces

The WB-1 features four primary control surfaces: elevators, ailerons, rudders, and spoilers. Table 22 includes a full list of control surfaces and their important attributes. The elevator occupies the rear 30% of the horizontal stabilizer and does not include a trim tab due to the variable incidence mechanism. The rudder chord is 40% of the vertical stabilizer chord and the surface is split into two sections, as seen in Figure 41. The lower section has the capability to operate independently of the upper section during high-speed flight while both sections work in unison during low-speed flight. The rudder also features a trim tab located on the trailing edge of the high-speed section with an overall chord ratio of 5%. As mentioned earlier, the vertical surface sports a duality of purpose. Not only must it be able to counteract the unbalanced yaw created by the OEI case, but its capability also dictates the usefulness of the strut. The engines needed to be 55 feet from the centerline in order to optimize the effectiveness of the strut. With this in mind, the analysis of the OEI condition was given extra consideration during the design process.

In the event that one engine becomes inoperative, the rudder counteracts the yawing moment created by the combination of asymmetric thrust of the operating engine and the windmilling drag of the inoperative engine. The rudder deflection produces an unbalanced side force, which can be countered by rolling the aircraft away from the inoperative engine no more than 5 degrees.[42] If rolling the wings is insufficient, sideslip away from the inoperative engine can counteract the remaining unbalanced side force. Achieving this extra sideslip requires further deflection of the rudder; however, it is preferable to the untrimmed alternative. The takeoff case was defined at sea level conditions, just out of ground effect, and at a forward velocity of 1.13 times the stall speed to conform to FAA regulations on minimum control speed.[43] Using maximum rudder deflection could have allowed the engine moment arm to be 48 feet. However, a rudder deflection of ±17 degrees maximum for trim ensured there remained sufficient control power to maneuver and land the aircraft. Aileron deflection and sideslip angle were similarly limited to ±10 and ±5 degrees, respectively. Figure 42 shows these restrictions and the effect of engine location on required control power. The maximum allowable engine moment arm dictated by the OEI takeoff case was 35.5 feet, 19.5 feet short of the goal. In comparison, the engines on a Boeing 737-800 are 15.8 feet from the centerline, less than half the distance achieved by Greenspan with the WB-1.[9]

Table 22: Control Surface Properties

	Surface Area (square feet)	**Deflection Range** (degrees)	**Percent Chord**	**Percent Half Span**
Elevator	49.5	±25	30	95
Variable Incidence Stabilizer	165	±5	100	100
Rudder	140	±25	40	90
Aileron	47	±30	20	24
Spoiler	103.6	0, +60	20	40.5

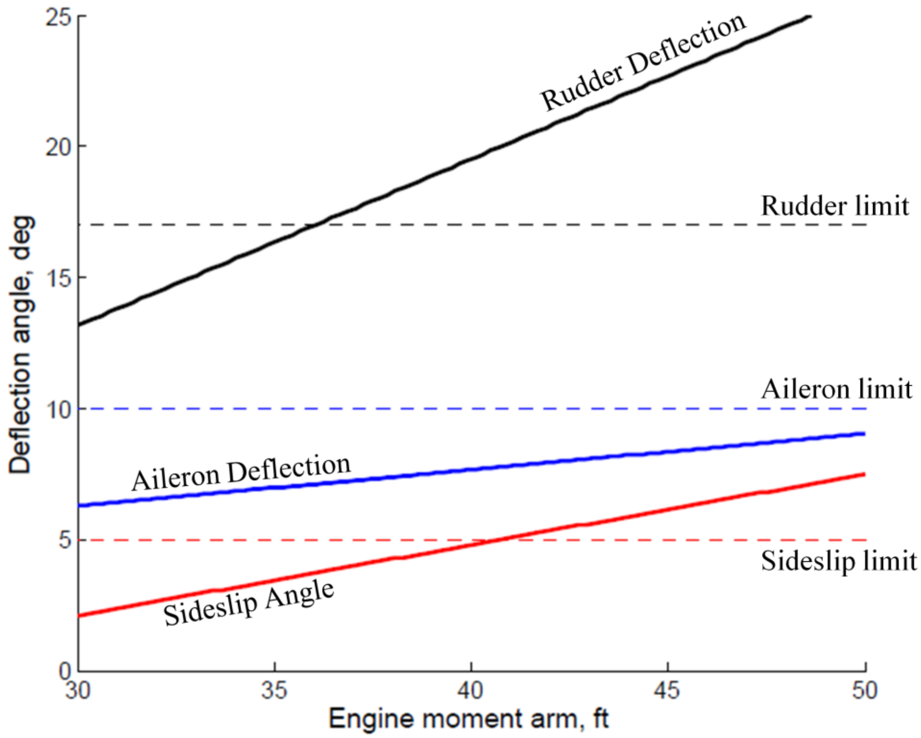


Figure 42: OEI Takeoff and engine placement, right engine inoperative

A combination of ailerons and spoilers controlled roll in the WB-1. Given the extreme length of the wings, ailerons could not be placed near the wingtips due to possibility of excess twist if used. To compromise, the ailerons are located further inboard on the wing, just outside the flaps. The ailerons have a chord ratio of 20% and extend from 37 feet to 55 feet semispan. There is also a trim tab on the right-hand aileron encompassing the inner 50% span of the aileron with an overall chord ratio of 5%. Spoilers were added just forward of the flaps to augment the control power of the ailerons. These also proved beneficial during the OEI case as they provided favorable yaw that reduced the deflection required by the rudder. The combined surfaces are capable of rolling the aircraft to a 30-degree bank angle in 2.2 seconds at 155 knots. This meets the military requirement of 30-degree bank angle with full surface deflection in 2.5 seconds.[42]

Pitch-up

Whenever considering a T-tail arrangement, it is wise to consider the high angle of attack characteristics. Unfortunately, the true characteristics can only be found using comprehensive CFD or a wind tunnel. Greenspan conducted a preliminary investigation into the possibility of pitch-up issues in deep stall based on the data collected on the DC-9.[44] With a distance of 59.5 feet behind and a height of 25 feet above the apex of the wing, the wash from the wing would blanket the horizontal stabilizer at an angle of attack of 22.8 degrees. Since the wing has a very high aspect ratio, it will quickly reach its maximum lift coefficient at around 13 degrees angle of attack. This means that stall should occur about 10 degrees before the horizontal stabilizer loses effectiveness. Since it is entirely possible for full deflection of the elevator to bring the aircraft into a dangerous angle of attack, the inclusion of limitations in the control system such as pilot feedback (stick-shakers) and automatic angle of attack limitation would be prudent in order to prevent excursions into deep-stall.

Dynamic Analysis

Given stability derivative estimates collected by the three methods mentioned earlier, the dynamic modes of the WB-1 were investigated using approximate methods of estimation as suggested by Roskam.[42] Greenspan investigated these modes for the cruise case and compared them to military airworthiness regulations presented by Roskam.[42] The cruise took place at an altitude of 35,000 feet on a standard day, a Mach number of 0.8, and a lift coefficient of 0.47. Table 23 compares the results of analysis with the requirements outlined in MIL-F-8785C.

This preliminary analysis reveals that the phugoid mode is stable, the short period is not quite acceptable, and the lateral-directional modes are entirely satisfactory. To bring the short period up to a level 1 condition, Greenspan calculated a feedback gain for the pitch rate based on suggestions from Roskam.[42] Figure 43 overlays the closed-loop response using the rate gain on top of the open-loop response to demonstrate its effectiveness. The short period now only takes a single cycle to damp out versus the two and a half cycles open-loop. Though the lateral/directional modes are acceptable by military standards, the Dutch roll can cause discomfort to passengers, so it is beneficial to minimize its effect as much as possible.[45] As a result, a yaw damper is included in the flight control system to increase the Dutch roll damping without adversely affecting the spiral mode. This damper reduces the oscillations to about half those required to damp the open-loop response, as shown in Figure 44.

Table 23: Dynamic Modes and Requirements

Short Period Frequency (1/s)	1.93	Level 1
Short Period Damping Ratio	0.27	Level 2
Phugoid Damping Ratio	0.085	Level 1
Spiral Condition	0.014	Level 1
Dutch Roll Frequency (1/s)	2.57	Level 1
Dutch Roll Damping Ratio	0.14	Level 1
Roll Time Constant (s)	0.308	Level 1

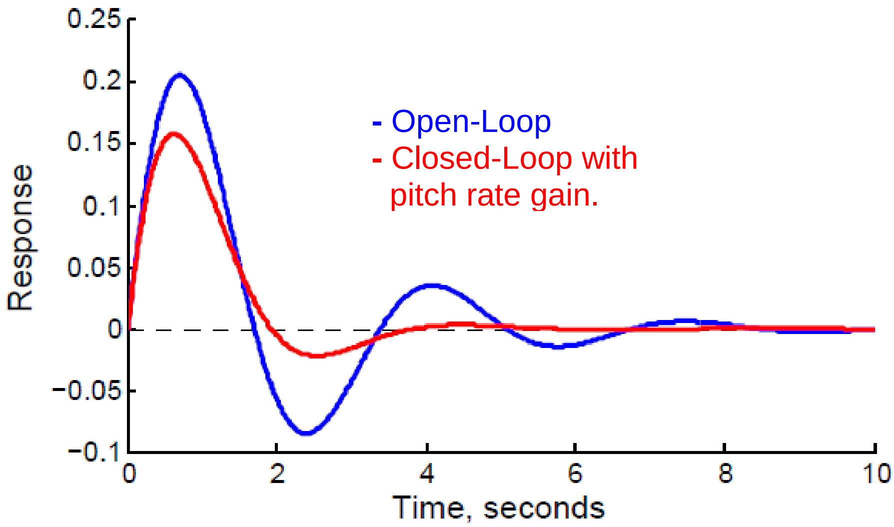


Figure 43: Short Period response, with and without controller.

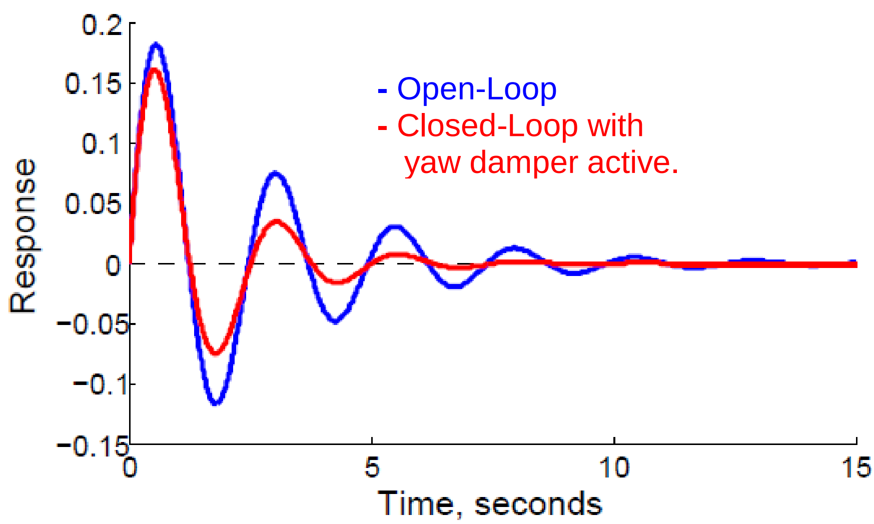


Figure 44: Dutch roll response, with and without yaw damper.

Noise

The RFP specifically states that the design is to address the growing concern regarding the environmental impact of aircraft, including the noise generated by commercial aircraft. Therefore, the RFP requires the aircraft to produce noise levels at least twenty decibels, cumulative, below the current regulation requirement. Our engine selection has already promised to meet this requirement, however, Greenspan feels as though we must do more. Therefore, we will integrate low noise design features wherever possible.

Pressure fluctuations in the atmosphere generate noise. Often, not all noise generated is in the range where it directly affects humans. Therefore, a number of adjustments and scales exist to examine exactly how much the noise generated will affect people. Subjective effects, including tone duration, are accounted for in the measurements obtained to meet the requirements of the current international and federal regulations and the RFP. Specifically, the Effective Perceived Noise Level (in EPNdB) will be necessary to measure the noise levels that are transmitted to the subject at the measurement point.[24]

Regulations and Requirements

Currently, Subpart B of Part 36 of Chapter 14 of the Code of Federal Regulations in the United States defines the noise requirements for aircraft to earn FAA certification. These requirements closely mirror those of the International Civil Aviation Organization (ICAO) in Annex 16, Volume I, Appendix 2, Amendment 7 - specifically, Chapter 4. This requirement is actually 10 cumulative decibels lower than the superseded Chapter 3 requirements.[46]

The noise level is measured at three distinct points of an aircraft's flight. The first (sideline noise) being at a point 450 meters to the side of centerline of the runway, at whichever distance the highest noise level is measured during takeoff and climb-out. The second (flyover noise) measurement occurs 6,500 meters from the start of the takeoff roll, in-line with the runway centerline. The third measurement (approach noise) is obtained during approach at a distance of 2,300 meters from touchdown while the aircraft is on a 3˚ glide-path.[47] Figure 45 is a graphic representation of these measurement points.

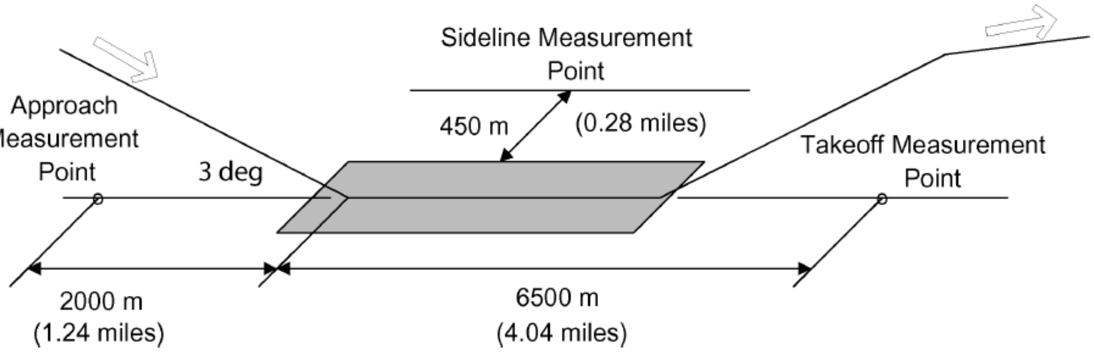


Figure 45: Noise Measurement Positions[48]

Each of the three measurements has a different maximum requirement. To meet Chapter 4 requirements, sum of the noise levels at each measurement point must be 10 decibels below the total sum of the maximum allowed levels of the Chapter 3 requirement. However, no one measurement may exceed the maximum allowed value by Chapter 3, nor may any one measured value contribute less than a 1 decibel margin to cumulative reduced value.[24] By adding in the requirements of the RFP, the total noise level must be 30 decibels below the total sum of the maximum levels for each measurement of the Chapter 3 requirement.

Using the maximum takeoff gross weight of 117,200 pounds, Greenspan established the noise limitations for the WB-1. Table 24 displays resulting Chapter 3 requirements, calculated using the formulas specified in the regulations. To meet the requirements of our design problem, the sum of these noise levels calculated at each measurement point must be 30 dB less than the Chapter 3 sum, or less than 254.5 dB.

Table 24: Noise Requirements for Greenspan Aircraft Concept

Noise Measurement Point	Chapter 3 Maximum Noise Level (EPNdB)	Noise Requirement (EPNdB) (Assuming Each Point Has Equal Contribution)
Approach	99.4	89.4
Fly-over	89.6	79.6
Sideline	95.5	85.5
Sum of All Points	284.5	254.5

Comparison

Figure 46 displays the approach noise levels of current aircraft and the current regulations. For simplicity's sake, we will assume that there is an equal reduction of 10 decibels at each measurement point from the ICAO Chapter 3 requirement. Therefore, the Greenspan WB-1 would lie along the "Stage 3 -10dB" line in Figure 46.

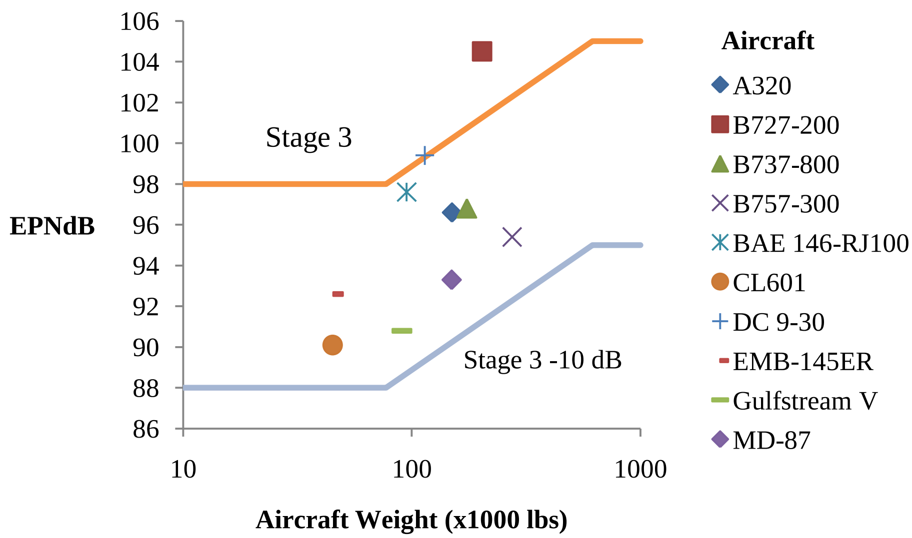


Figure 46: Various Noise Levels of 2-Engine Aircraft[49]

Cost

When trying to sell an aircraft line to an airline, two costs are going to be of particular interest to the airline. The first is the aircraft price. The aircraft price is a good indicator of the acquisition cost, the cost of the aircraft program. The second cost is the operating cost. This tells the airline specifically how much it is going to cost them to fly the aircraft from point A to point B. The operating cost is so important that a difference in fractions of a penny will be enough for the airline to choose the competitor. The RFP outlines the operating cost as a very important design objective, and therefore, Greenspan identified it as a huge priority throughout the design process.

Methodology and Concept

Greenspan first identified the requirements in the RFP to be maintaining an acquisition cost commiserate with current, in-service aircraft and an operating cost reduction of 8% from current, in-service aircraft. An additional design objective to reduce the operating cost 10% was also posed.

From here, Greenspan wanted to specify these requirements in dollar amounts. From a variety of sources it was found that comparator aircraft, the Boeing 737-800 and Airbus A320-200, cost anywhere between $70 - $75 million dollars.[50] Southwest Airlines is the cheapest operating airline, with an operating cost of 8.78 cents per nautical seat-mile.[8] Greenspan's cost requirements are listed in Table 25.

Table 25: Greenspan's Design Requirements

Design Requirements	
Aircraft Price	$70 - $75 M
Operating Cost	8.08 ¢/nsm

Greenspan developed an algorithm that would evaluate the acquisition cost, the aircraft price, and the operating cost based on very specific aircraft characteristics and operating conditions. The algorithm was modeled after many of Roskam's methods as outlined in his volume on Cost. The cost results and Manufacturing sections of this report discusses in more detail the algorithm and its inputs. It was important to validate the algorithm before its results could be accepted. The validation resulted by testing a 737-800 and seeing how the results compare to what Greenspan identified as the current aircraft price of a Southwest Airlines 737-800 and the current operating cost of a Southwest Airlines 737-800. The test results are in Table 26.

Table 26: Cost Algorithm 737-800 Data Match

Algorithm Match	
Aircraft Price	$70.8 M
Operating Cost	8.69 ¢/nsm

These results validate the algorithm. The aircraft price of $70.8 million falls in the $70 - $75 million range, and the operating cost is only off 0.09 cents per nautical seat mile. Therefore, Greenspan was confident in using the algorithm to evaluate the cost of their strut-braced design.

Results of Cost Analysis

The acquisition cost is comprised of research, development, and test evaluation costs, manufacturing costs, technology factors, and the total number of airplanes in the aircraft program, among other things as well. A certain fixed cost, which is usually very large, is associated with any aircraft program. Therefore, the aircraft price multiplied by the number of aircraft planned for the program needs to be enough to cover this fixed cost. This is the best description of how aircraft price relates to acquisition cost. The acquisition cost turns out to be such a large number, it is paid over a long period, and therefore Greenspan chose to evaluate its competitiveness based on the aircraft price.

Greenspan's strut-braced design has an estimated aircraft price for a 500 aircraft program of **$65.7 million** per aircraft and for a 1,500 aircraft program of **$55.7 million** per aircraft. This is a competitive price and is actually a slight reduction from the $70 - $75 million range required.

The operating cost takes into consideration maintenance and crew costs, as well as a fuel cost of $2.50 per gallon at 6.7 pounds per gallon. Table 27 shows the results of the cost analysis. The first portion of the table shows the operating cost for the entire mission, including loiter and reserves. The second portion of the table shows the operating cost for the fuel burn from the tarmac to the end of the first approach. The highlighted values identify the compliant operating costs achieving the 8% reduction. Furthermore, the fuel burn requirement of 41 pounds per seat for the 500 nautical mile mission is met with a fuel burn of 38.79 pounds per seat.

Table 27: Operating Cost Results

Range (nm)	653	1,155	2,157	2,960
Fuel Weight (lb)	7,650	11,800	20,300	27,250
500 AC Program Operating Cost ($/nsm)	0.0802	0.0788	0.0766	0.0737
1500 AC Program Cost ($/nsm)	0.0784	0.0772	0.0751	0.0722

Range (nm)	500	1,000	2,000	2,800
Fuel Weight (lb)	5,818	10,645	18,482	25,416
500 AC Program Operating Cost ($/nsm)	0.0804	0.0791	0.0769	0.0737
1500 AC Program Operating Cost ($/nsm)	0.0792	0.0779	0.0755	0.0722
Fuel Burn (lbs/seat)	38.79	70.97	123.2	169.44

Manufacturing

This design makes heavy use of composites, with an all-composite fuselage and all-composite wings. Therefore, certain manufacturing challenges need to be considered. Composite fuselages have been successfully manufactured on a smaller scale, and Boeing has demonstrated the feasibility of large-scale composite manufacturing. Do note that a technology factor was included in the cost analysis, raising the overall manufacturing cost. However, due to the small size of the wings, and the reduced aircraft weight, the manufacturing cost dropped back down, and resulted in a cheaper airplane.

Family Concept

For the future family concept, Greenspan hopes to incorporate several designs that cater towards different airline needs. For instance, Greenspan feels that the strut-braced configuration has immense potential to produce a very successful business jet, which would accommodate approximately 30 to 40 passengers. Furthermore, Greenspan hopes to design an extended range configuration as well as a freighter configuration. These two aircraft would provide efficient means of offering passengers low cost, long distance flights, and the cargo carrier would offer low cost transport of freight. These two markets are saturated with business, but have room for challenging competition. Greenspan's family concept addresses many of the needs and desires of the airline market. Fortunately, our engine and wing planform are sized to allow for easy development costs of these additional models.

Concluding Remarks

There are three primary requirements that drove the concept selection, as well as the design process: noise abatement, fuel burn, and operating cost. Greenspan immediately identified that the use of an unconventional configuration along with the utilization of advanced technologies would be integral to the success of the design. Through research and analysis, Greenspan chose to design a strut-braced aircraft. This configuration allows for such a dramatic increase in wingspan and aspect ratio that it made the design requirements feasible. The use of composite materials for nearly all aircraft components further aided in weight reduction. Overall, the strut and the composites, coupled with the choice of the PurePower 1000G turbofan, significantly reduced the fuel required to fly the maximum range mission. This allowed the next design iteration to have an even lower weight, which would further reduce the fuel required. Using this design process, the WB-1 achieves the most challenging design requirements laid out by the RFP. Table 28 is a summary of the major requirements in the RFP, whether or not Greenspan's WB-1 achieves the requirement, and a page number of where further details can be found.

In conclusion, the strut-braced configuration with composite materials provided the weight reduction, aerodynamic benefits, and fuel reduction necessary to meet the high priority requirements in the RFP. Many of these requirements are unattainable with the current generation of transcontinental airliners, therefore a new approach to civil transport was needed. By utilizing the advantages of a strut-braced configuration, the WB-1 operates at the conditions demanded by the RFP with a significant improvement in fuel burn and noise over current generation transport aircraft.

Table 28: Request for Proposals Summary

Parameter	Requirement	Met?	Supporting Information
Passenger Capacity	150 Passengers (2 Classes)	Yes	Page 27: Interior Layout
Cargo Capacity	7.5 ft^3/passenger	Yes	Page 27: Cargo Configuration
Maximum Range	2800 nm	Yes	Page 49: Mission Performance
Cruise Speed	.78 Mach	Yes	Page 49: Mission Performance
Initial Cruise Altitude	> 35,000 ft	Yes	Page 49: Mission Performance
Maximum Operating Altitude	43,000 ft	Yes	Page 49: Mission Performance
Maximum Landing Speed	135 kts	Yes	Page 52: Field Performance
Takeoff Field Length	7,000 ft	Yes	Page 52: Field Performance
Community Noise Level	ICAO Ch. 4 -20 db	Yes	Page 86: Noise Comparison
Fuel Burn	≤41 lb/seat	Yes	Page 89: Results of Cost Analysis
Operating Cost	8% Reduction	Yes	Page 89: Results of Cost Analysis

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