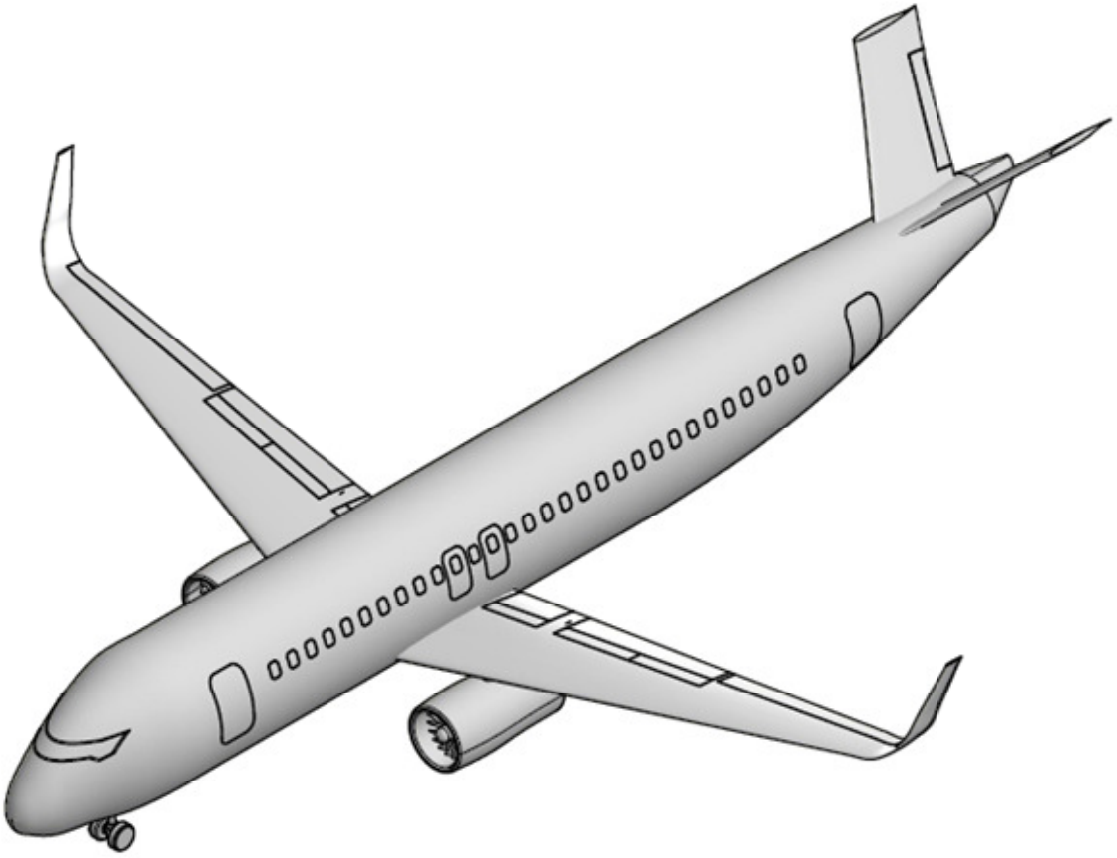
BioJet

BC-175



Response to 2009/2010 AIAA Foundation Undergraduate Team Aircraft Design Competition

Presented by Virginia Polytechnic Institute and State University

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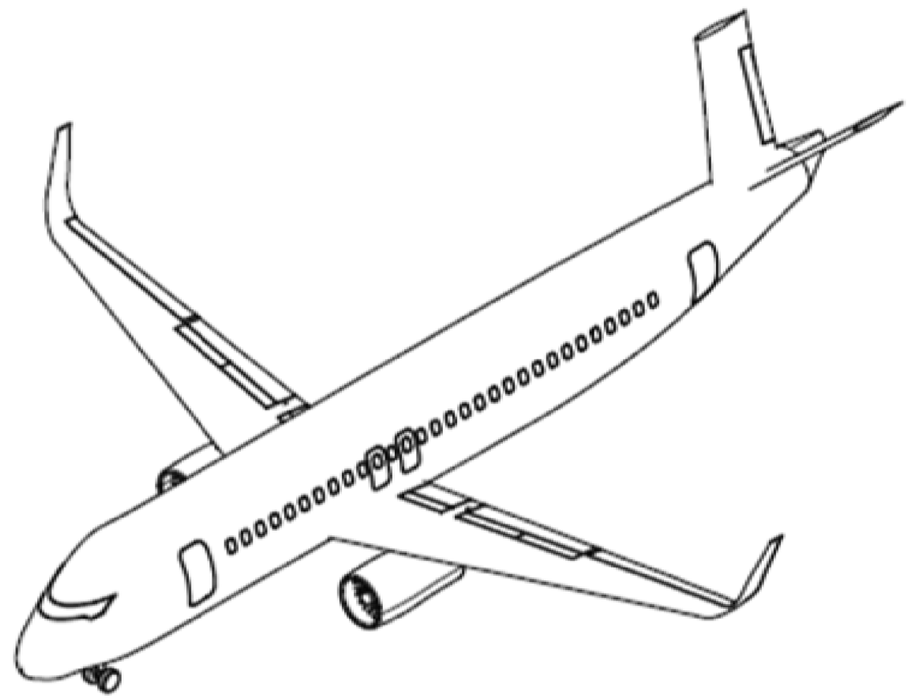
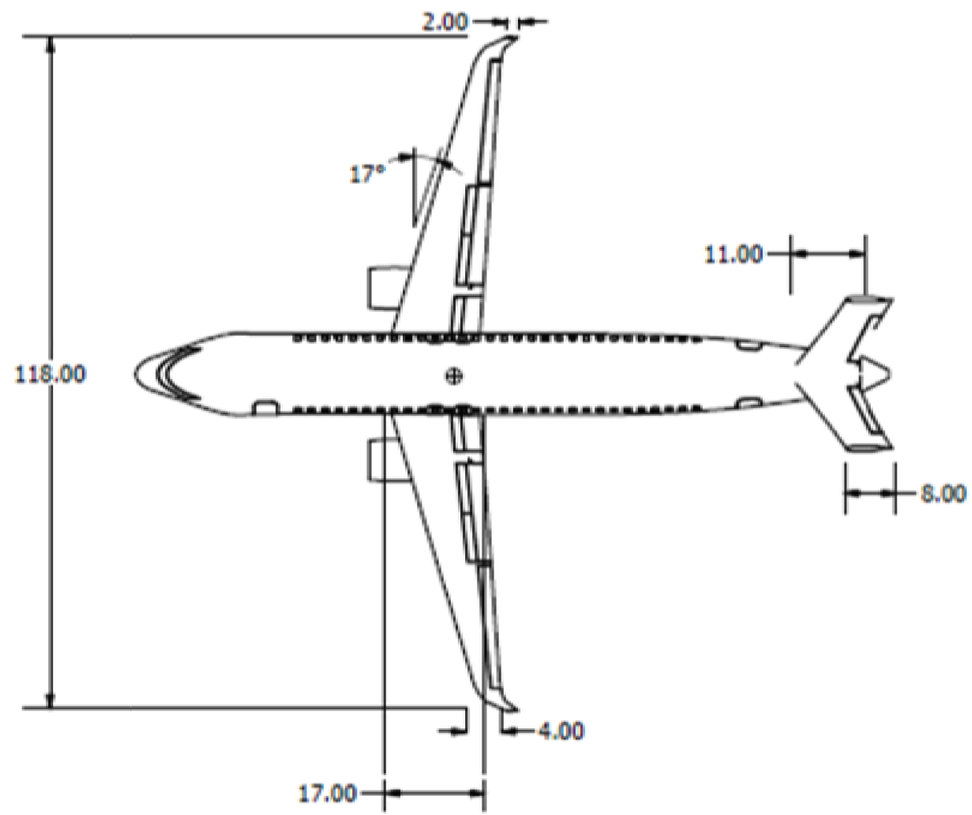
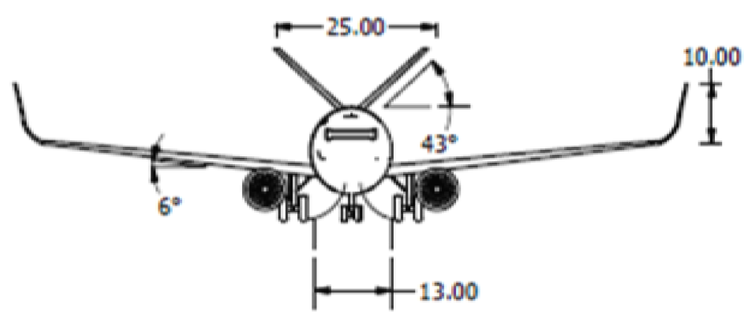
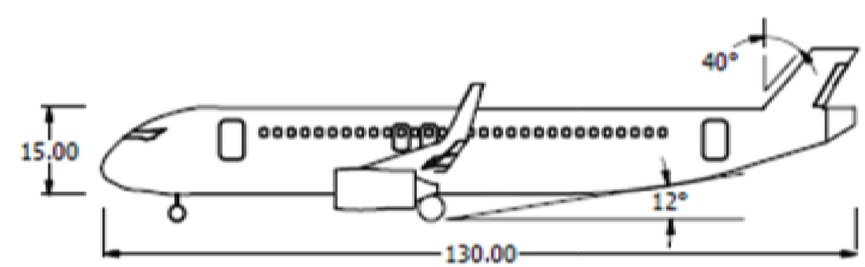
Executive Summary

Biojet is pleased to present its response to the request for proposal from the American Institute of Aerodynamics and Astronautics received on October 1, 2009. It calls for the development of a commercial airliner with a capacity of 175 passengers, entering service in 2020, primarily as a replacement for the Boeing 737/Airbus A320. This vehicle is in high demand as existing aircraft in this category were not designed from the ground up to utilize alternate fuels. The RFP requires a reduction in emissions and improved cost effectiveness for the operator, and Biojet provides those solutions. This aircraft will have a range of 3,500 nm with lower fuel consumption than current aircraft. Our aircraft exceeds the design requirements by increasing L/D_{max} by 27% as compared to current aircraft in its class. The aircraft's cruising speed is Mach 0.8 specified in the RFP. The aircraft has a balanced field length of 5930 ft and a landing speed of 124 knots. Additionally, the aircraft has an initial cruise altitude of 35,000 feet and a maximum cruising altitude of 41,000 feet. As an additional requirement, Biojet designed the aircraft to fit the class III gates that accommodate both the Boeing 737 and A320. The Biojet concept is a tube and wing design with a V-tail, which has been used in some aircraft but has not been used commercially. The concept is compared to the existing aircraft throughout the design and shows benefits in many areas. Biojet utilizes advanced technologies in the design ensuring that it fulfills the requirements of the RFP. These include the use of composite materials, advanced airfoil design, and advanced engine technologies. Biojet is proud to present the BC-175 as the next generation commercial airliner.









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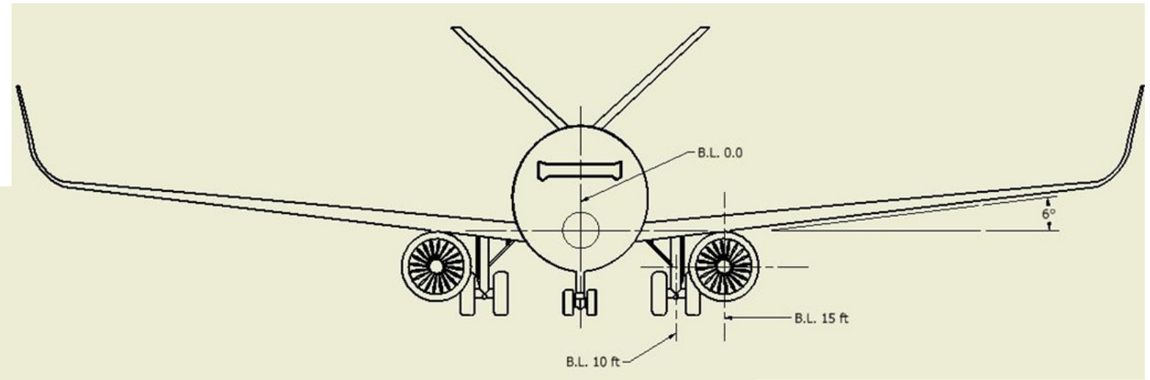
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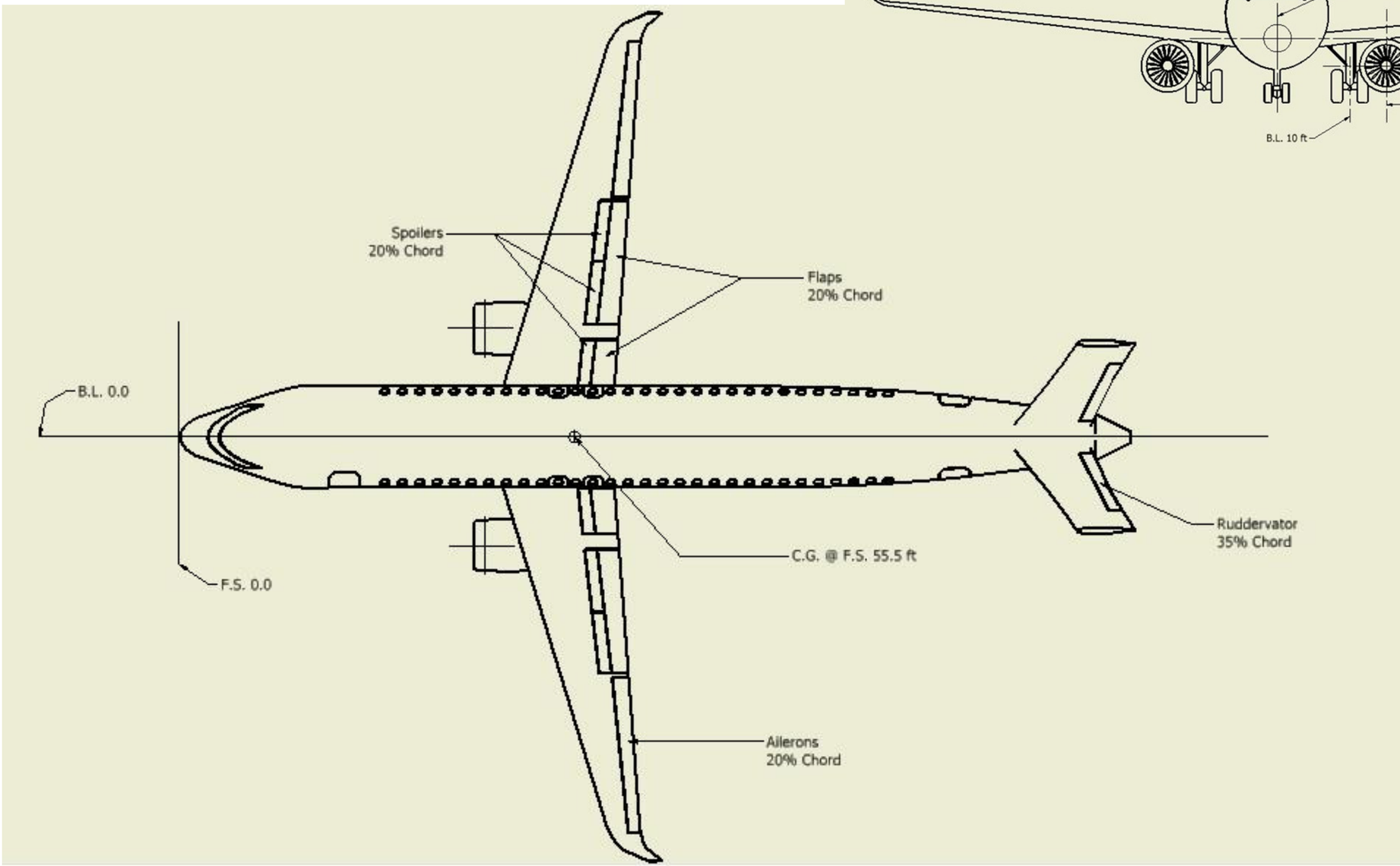
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Flaps
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B.L. 0.0
Ruddervator
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C.G. @ F.S. 55.5 ft
F.S. 0.0
Ailerons
20% Chord

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Abbreviations

AIAA	– American Institute of Aeronautics and Astronautics
ANOPP	– Aircraft Noise Prediction Program
APS	– Air Purification System
APU	– Auxiliary Power Unit
BFL	– Balanced Field Length
BWB	– Blended Wing Body
CFRP	– Carbon Fiber Reinforced Plastic
CFRP	– Carbon Reinforced Plastic
CG	– Center of Gravity
EBHA	– Electro-backup-hydrostatic Actuator
EHA	– Electro-hydrostatic Actuator
FAA	– Federal Aviation Administration
FAR	– Federal Aviation Regulations
FML	–Fiber Metal Laminate
GFP	– Graphical Flight Planning
GLARE	– Glass Reinforced Fiber Metal Laminate
ICAO	– International Civil Aviation Organization
INAV	– Integrated Navigation
LCD	– Liquid Crystal Display
LED	– Light-emitting Diode
LRC	– Long Range Cruise
MAC	– Mean Aerodynamic Chord
MFRD	– Multifunction Radar Display
MTOW	– Maximum Take-off Weight (lbs)
N.P.	– Neutral Point
NASA	– National Aeronautics and Space Administration
PCU	– Power Control Unit
RFP	– Request For Proposal
S.M.	– Static Margin
THSA	– Trimmable Horizontal Stabilizer Actuator
TOGW	– Take Off Gross Weight
TRA	– Terrain Radio Altitude
VIA	– Versatile Integrated Avionics
LCC	– Life Cycle Cost
RDTE	– Research Development Testing Evaluation
ASM	– Available Seat Mile
DOC	– Direct Operating Cost
IOC	– Indirect Operating Cost
AEP	– Aircraft Estimated Price

Nomenclature

AR – Aspect Ratio
b – Wing Span
c – Chord (ft)
C_{acq} – Acquisition Cost
C_{D0} – Coefficient of Profile Drag
C_{Di} – Coefficient of Induced Drag
C_D – Coefficient of Drag
C_{Dtrim} – Coefficient of Trim Drag
C_{Dw} – Coefficient of Wave Drag
C_{Lmax} – Maximum Coefficient of Lift
C_{Lp} – Lift Coefficient due to Pitch
C_{Lr} – Lift Coefficient due to Rudder
$C_{L\alpha}$ – Lift Coefficient due to Angle of Attack
$C_{L\beta}$ – Lift Coefficient due to Sideslip
$C_{L\delta r}$ – Lift Coefficient with Rudder Deflection
C_{Mq} – Moment Coefficient due to Pitch
$C_{M\alpha}$ – Moment Coefficient due to Angle of Attack
C_{Navail} – Yawing Moment Available
C_{Np} – Yawing Coefficient due to Pitch
C_{Nr} – Yawing Coefficient due to rudder
C_{Nreq} – Yawing Moment Required
$C_{N\beta}$ – Yawing Coefficient due to Sideslip
$C_{N\delta r}$ – Yawing Coefficient due to Rudder Deflection
C_{opsdir} – Indirect Operating Costs
e – Oswald's efficiency factor
g – Gravity (ft/s2)
k_A – Airfoil Technology Factor
L/D – Lift to Drag Ratio
l_{to} – Take-off Field Length (ft)
M – Mach Number
M_{crit} – Critical Mach Number
M_{DD} – Drag Divergence Mach Number
N_{yr} – Number of Years Aircraft is Operated
R_{bl} – Total Annual Block Miles Flown (nm)
S – Wing Area (in2)
t/c – Thickness to Chord Ratio
T/W – Thrust to Weight
T_c – Thrust at Cruise (lbs)
T_o – Thrust at Take-off (lbs)
V_A – Approach Velocity (knots)
W – Weight (lbs)
W/S – Wing Loading
W_{empty} – Empty Weight of Aircraft (lbs)
W_{fixed} – Fixed Weight (lbs)
W_{fuel} – Weight of Fuel (lbs)
β – Sideslip angle
δa – Aileron Deflection
δr – Rudder Deflection
Λ – Wing Sweep
ρ_{sl} – Density at Sea Level (slug/ft^3)
σ – Density Ratio
φ – Flight path angle

1. Introduction

Biojet's proposal for the BC-175 provides a solution to the AIAA RFP. As the demand for renewable fuels increases, the integration of biofuels into aircraft is necessary. Providing a replacement for the commercial aircraft class of the Boeing 737 and Airbus A320 results in the greatest overall impact. The BC-175 is designed from the ground up to achieve this goal. The BC-175 will shape the future of the airline industry for years to come.

1.1 RFP and Problem Analysis

The 2009-2010 AIAA Foundation Undergraduate Team Aircraft Competition Request for Proposal states that a suitable replacement aircraft design must include the following basic attributes. The aircraft is to carry 175 single class passengers, two flight crew members and cargo which requires a minimum 1,240 cubic feet. The cabin must be a minimum of 12.5 feet in width and 7.25 feet in height. The seats must be at least 17.2 inches wide, and 32 inches in pitch, with a seating configuration to allow for ample comfort. The aircraft will be able carry a payload of 37,000 pounds. It must not exceed a takeoff distance of 8,200 feet under normal operation. After climbing to an initial cruise altitude of 35,000 feet, the aircraft may continue to climb to a maximum cruise altitude of 41,000 feet at which it must sustain cruise at Mach 0.8. A 25% increase in L/D_{max} over similar aircraft is required and the use of laminar flow technologies is suggested. A nominal range for the aircraft is 1,200 nautical miles, while its maximum range extends to 3,500 nautical miles. To meet these goals the integration of advanced materials is used to reduce the weight. The vehicle must also satisfy the Federal Aviation Regulations for

commercial aircraft of its type, defined by the Federal Aviation Administration. Table 1.1 below contains the stated general requirements.

In addition to these requirements, as this aircraft is a replacement for the Boeing 737 and Airbus A320 it must be able to use the Class III gate which limits wingspan to under 118 feet [1]. This requires either a limit on the aircraft span, or a method of reducing the span when the aircraft is not in flight.

Table 1.1: RFP Requirements

Safety and Airworthiness Regulations	2 Member Flight Crew
175 Passengers (1 Class)	32” Pitch, 17.2” Width, Seating
Minimum 12.5’ high, 7.25’ wide Cabin	1240 ft^3 Cargo Volume
37,000 lb Payload Capacity	8200’ Takeoff Distance
140 KCAS, Max Landing Speed	Mach 0.8, Cruise Speed
Mach 0.83/ 340 KCAS, Max Op. Speed	35,000’ Initial Cruise Alt.
41,000’ Max Cruise Alt.	1200 nm, Nominal Range
3500 nm, Max Range	Operation on Biofuel

In addition, the request for proposal outlines the design-to-be with challenging improvements, over current aircraft of this nature. A craft that is both environmentally friendly and that offers accelerated fuel efficiency stands to be the primary objective of the design. To achieve this, the currently used fuel, Jet-A will be replaced through an adaptation to biofuels. On the following page, Figure 1.1 shows a comparison web of current aircraft designs, their capabilities, and environmental impacts with varying engine configurations.

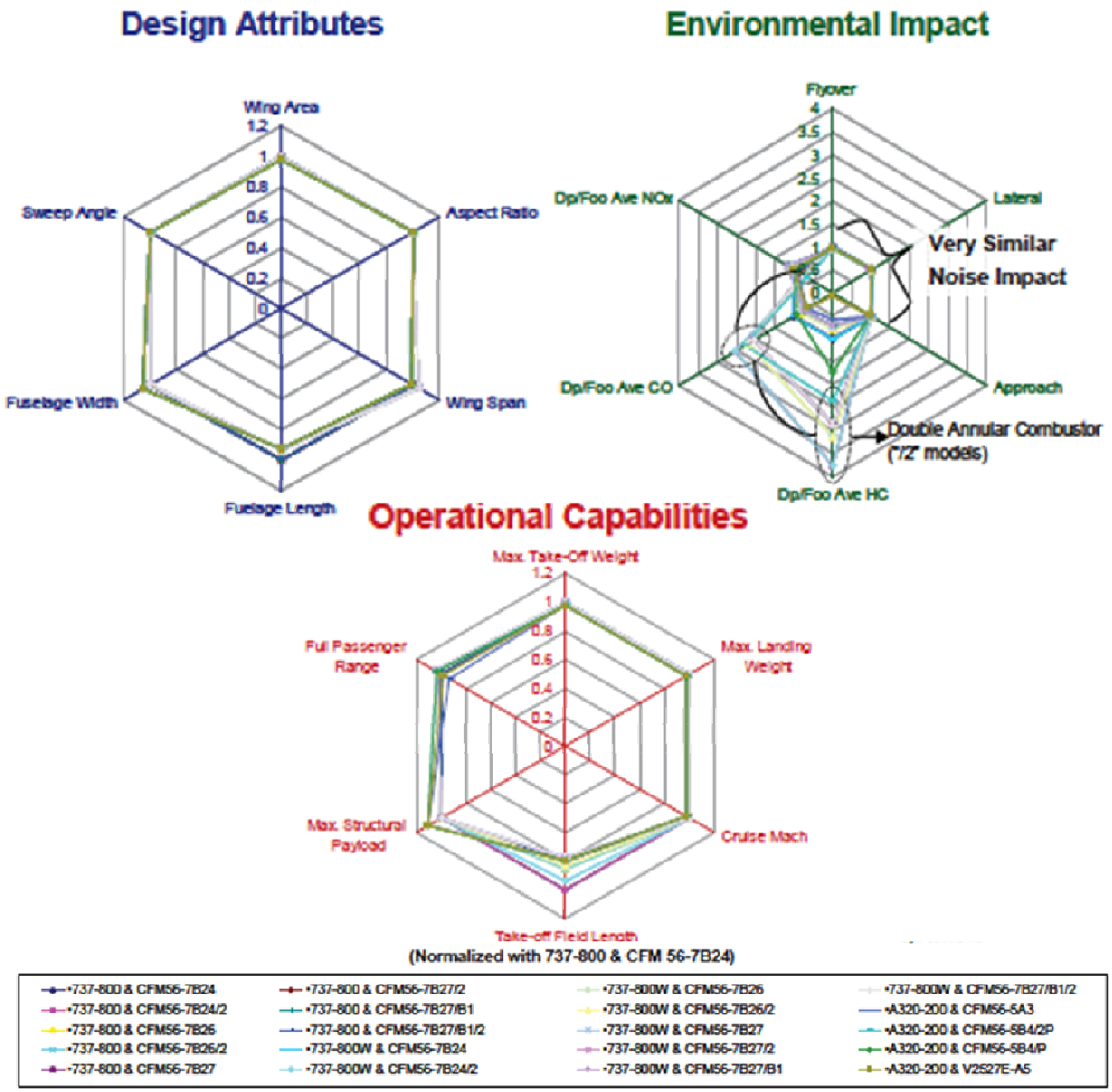


Figure 1.1: Current Aircraft Comparison[2]

The mission profile for the concepts is the same as that of the aircraft class that is to be replaced. This includes takeoff, climbs, cruise, descent and landing. Takeoff is occasionally grouped with the taxi out to the runway and ends once the aircraft clears 35 feet. The Climb segment can have many parts and ends when cruise altitude is reached. Then, the decent occurs until landing when including the approach stage. An additional reserve profile of about 200 nautical miles is also considered in case of a missed approach or detour. This calls for approximately 5% additional fuel. A general mission and reserve profile for a Boeing 737 is shown below.

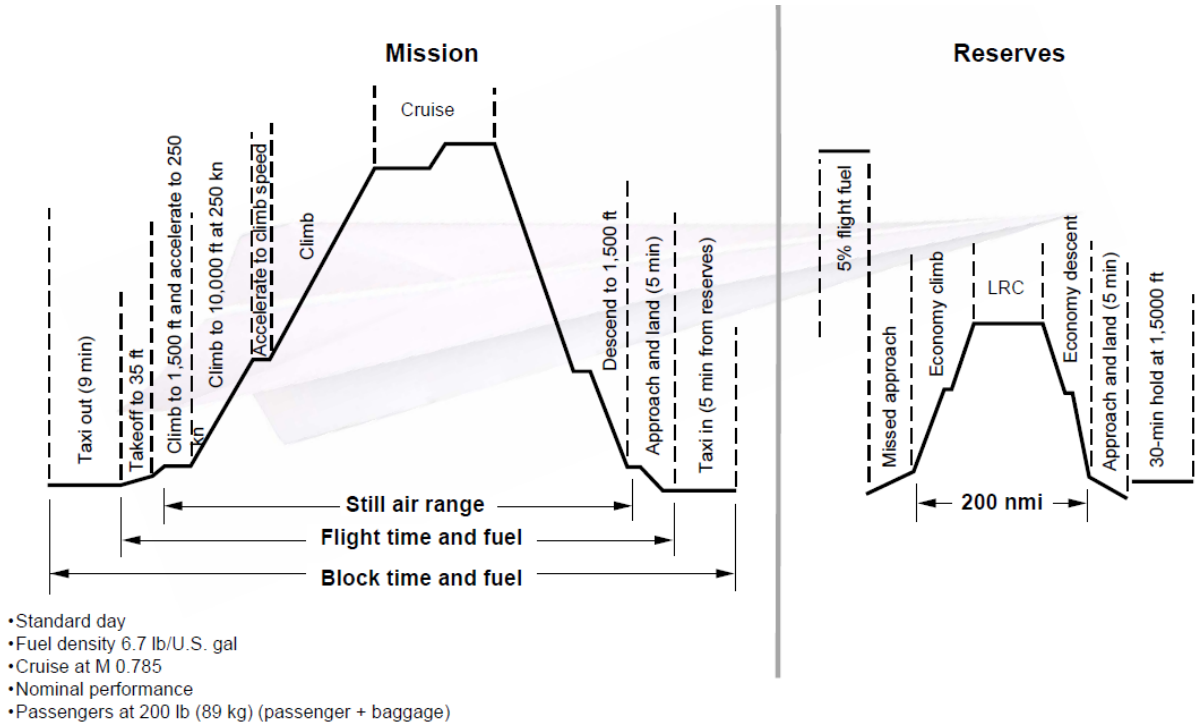


Figure 1.2: Boeing 737 Mission Profile

2. Configuration Concepts

The primary objective of the design is to satisfy the 2010 AIAA RFP. As mentioned above, the RFP discusses the need for more environmentally friendly commercial transports. The objective is to design a replacement aircraft, implemented by 2020, that utilizes advanced technologies, alternative fuels, and new operational procedures in an effort to reduce environmental impacts and dependence on foreign crude. This includes reducing noise, emissions, and the carbon footprint in addition to improving aerodynamic and mechanical efficiency. Many of these requirements can be achieved through applying advanced technologies. Based on these preliminary criteria, eight concepts were developed and compared. The final design concepts fell into two categories: Tube and Wing, and Hybrid Wing Body.

2.1 Current Aircraft

The RFP calls for an environmentally friendly, alternative fuel-based aircraft. The Boeing 737-800 and the Airbus A320-200 operate with similar mission profiles as mentioned in Section 1. Each carry around 175 passengers and have a range near 3,500 nm. These aircraft are considered conventional due to their common tube and wing configuration with vertical and horizontal stabilizers. Table 2.1 is a comparison of common specifications.

Table 2.1: Replacement Aircraft Comparison[3] [4]

		
Specifications	**Airbus A320-200**	**Boeing 737-800**
Crew:	2	2
Seating Capacity:	180 (dense)	162-189(dense)
Length:	123 ft 3 in	129 ft 6 in
Wingspan:	111 ft 11 in	117 ft 5 in
Wing Area:	1320 ft^2	1345 ft^2
Wing Sweep:	25.00 degrees	25.02 degrees
Height:	38 ft 7 in	41 ft 3 in
Cabin Width:	12 ft 2 in	11 ft 7 in
Fuselage Width:	13 ft	12 ft 4 in
Typical Empty Weight:	93,000 lb	91,108 lb
Maximum Takeoff	170,000 lb	174,200 lb
Cruise Speed:	Mach 0.78	Mach 0.78
Maximum Speed:	Mach 0.82	Mach 0.82
Takeoff distance:	6,900 ft	8,000 ft
Max. Loaded Range:	3,200 nm	3,060 nm
Max. Fuel Capacity:	7840 US Gal	6875 US Gal
Service Ceiling:	39,000 ft	41,000 ft
Aspect Ratio:	9.5	10.4
Cost:	$73.2-80.6 million	$72.5-81.0 million

Both aircraft are very similar in many major characteristics such as MTOW, seating capacity, and aspect ratio. It is evident that many new design techniques and technologies must be used to substantially improve current aircraft performance to RFP standards. The following sections discuss the designs that were considered in determining our final aircraft design.

2.2 Hybrid Wing Body Design

The Hybrid Wing design concept was introduced by Robert Liebeck in 1988[5]. It is a radical concept that has the capability to achieve high aerodynamic efficiency with other benefits such as decreased fuel consumption and noise reduction. The hybrid wing body, shown in Figure 2.1, can achieve improved efficiency due to reduced wetted area and therefore less skin friction drag. According to Liebeck up to 33% reduction in surface area is tangible[5]. To further achieve fuel efficiency, the "D-shaped" engine ducts are partially buried in the surface of the aircraft to ingest some boundary layer air[6]. This promotes laminar flow over the aircraft by inducting boundary layer air ahead of the engine.

The concept is an aircraft with integrated wings, fuselage and engines with no leading edge lifting devices. It has the potential to be the next generation commercial aircraft to dominate the skies.

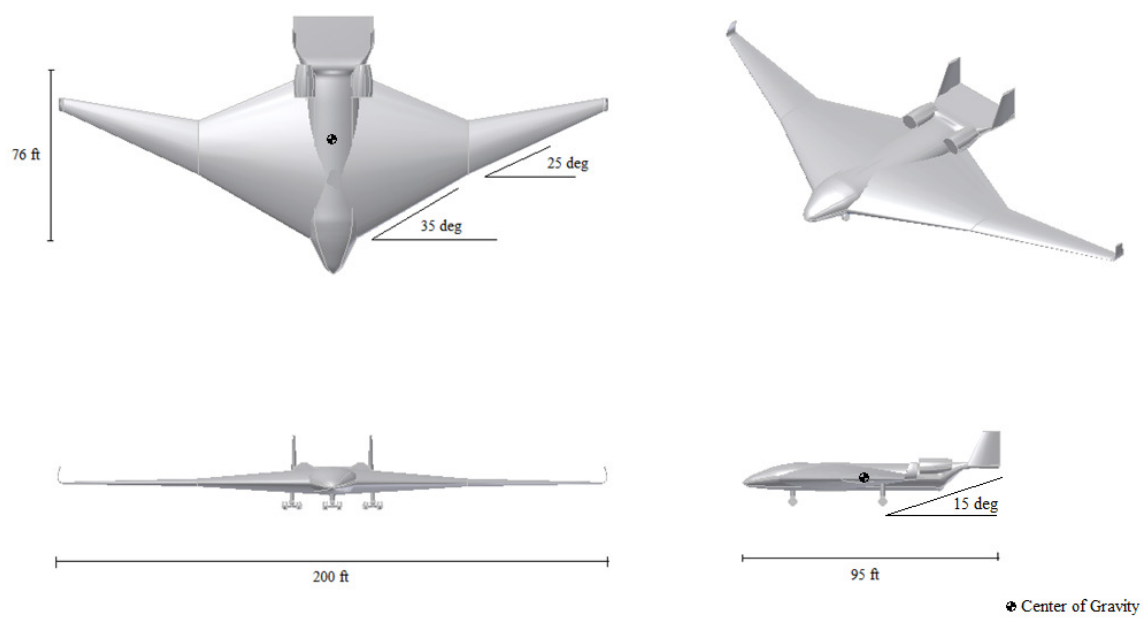


Figure 2.1: Three view and a 3-D drawing of the hybrid wing body concept

In addition to being very efficient, the hybrid wing body is also capable of noise reduction. The engines are placed on the upper surface of the aircraft where the forward engine noise is shielded and the rear engine noise can be neglected because it is not reflected from the lower surface of the wing. Also, the airframe noise is reduced due to the fact that there are no slotted trailing edge flaps [7].

The main concerns for a hybrid wing body are stability and control, and structures. Due to lack of horizontal tails and aft CG position the aircraft is longitudinally unstable. An advanced digital flight control technology may solve this problem. Another challenge comes from structures, where the hybrid wing body requires a unique approach to the pressurization of the aircraft. Due to unconventional shape of the fuselage, a cylindrical approach is futile.

By comparing the advantages and disadvantages of the hybrid wing body to other designs (Table 2.2), it was proposed to go onto the final selection. HWB design is able to easily achieve the 25% increase *L/D* ratio along with a significant reduction in noise. The large increase in *L/D* is possible due to a single large lifting surface.

Table 2.2: Pro-Con Chart for HWB

Pro	Con
• Can achieve max efficiency due to reduction of surface area • Reduction in fuel consumption and emissions • Less noise • More room for fuel and luggage • Comfortable space for passengers	• Non-conventional fuselage shape • Structure complexity • Difficulty manufacturing • Increase in cost due to large span • Stability and control complexity

Using Raymer[8] we estimated initial aerodynamic characteristics of the design. These estimations were used to calculate the final T/W vs. W/S graph, presented in Figure 2.2. The area bounded by the constraint curves is feasible and the design point is indicated by the star.

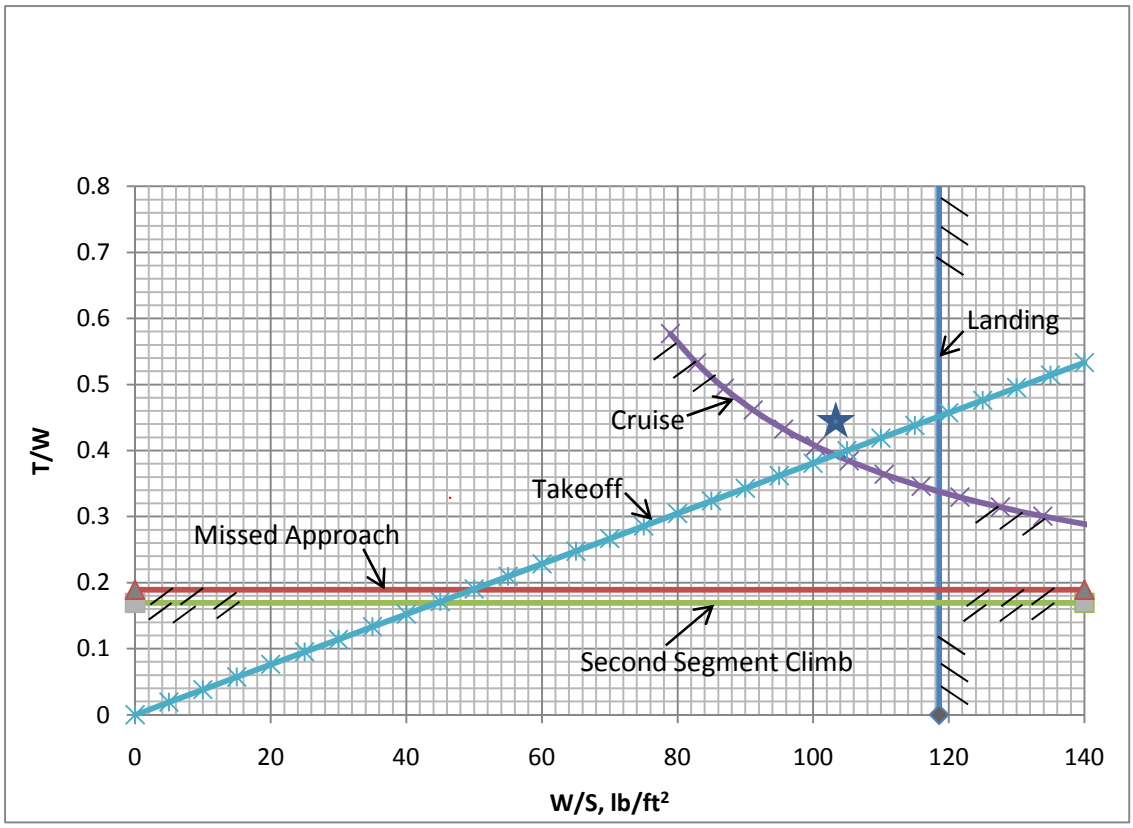


Figure 2.2: BWB Sizing optimization.

From this chart a design point was chosen where the wing loading was set at 72 lb/ft^2 and the thrust to weight was at .285.

The final sizing for the HWB design is based on the output from Nicolai's program[9]. The inputs used for the sizing program came from several different sources. The weight constants used were from the general transport values given in the read me file provided with Nicolai. The values of cruise Mach number, fixed weight, and the mission radius came from the RFP. The aspect ratio was taken from the other sizing data. The specific fuel consumption comes from the engine data for the current engines being used. Once all the data was entered, the program was run. The program gave a maximum takeoff weight of 138,000 lbs and a fuel weight of 34,000 lbs.

2.3 Tube and Wing Concept

The Tube and Wing is similar to the design that is used in current aircraft. This concept is based on the same wing-fuselage configuration as the conventional aircraft. However, it employs the use of a V-tail and a C-winglet. The V-tail is used to decrease flow interference between the normal horizontal and vertical surface of conventional tail configuration. This will also help reduce weight by reducing the number of needed control surfaces. The use of a C-winglet is an innovative take on the boxed winglet utilized in early concepts. Figure 2.3 is a picture of an early BWB concept with C-winglet.

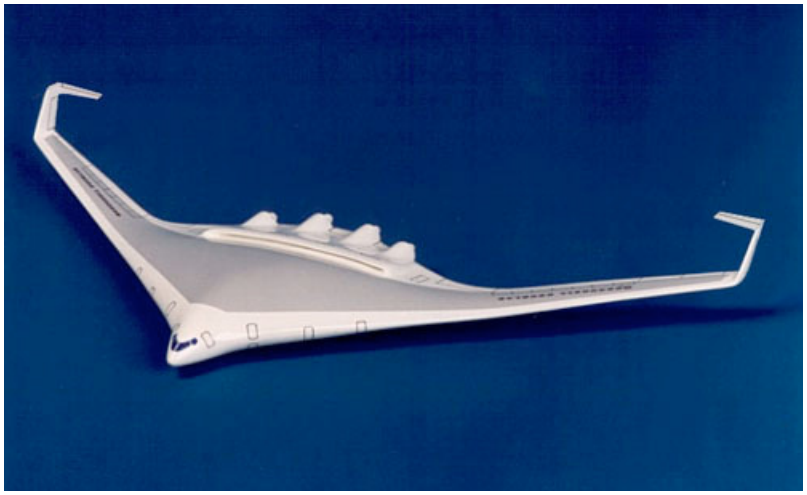


Figure 2.3: BWB with C-wing[10]

The purpose of the C-winglet is similar to that of the winglet originally developed by Richard Whitcomb. Planar wings tend to have high pressure airflow from the bottom circulate around the wing tip to the low pressure region above the wing. This generates a loss of lift at the wingtip. The purpose of the winglet is to block the three-dimensional effects of high pressure flow around the wingtips. The span-wise loading distribution is represented by the Oswald efficiency factor. A planar wing with an elliptical loading distribution has an efficiency of 1. Through the use of

winglets and C-winglets, the efficiency can greatly increase. Figure 2.4 shows the span efficiency for various wing shapes[10].

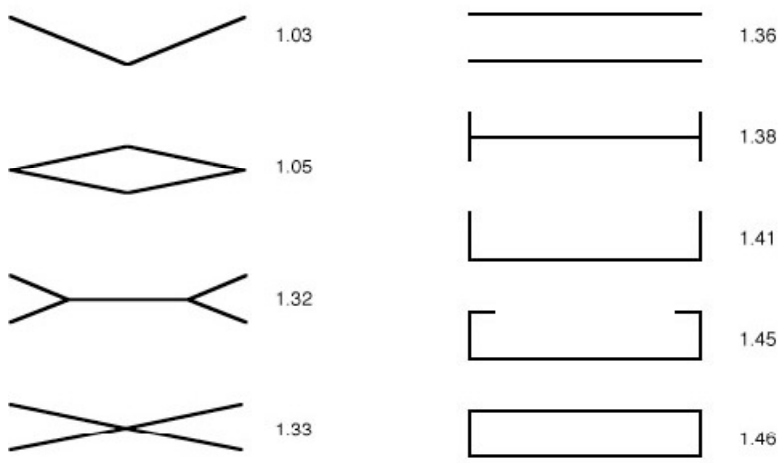


Figure 2.4: Comparison of Span Efficiency for Various Wing Types[10]

The C-winglet is depicted with an efficiency of 1.45 while a full box wing has an efficiency of about 1.46. It can achieve an efficiency near that of a box wing without the additional weight. This is the main motivation. However, some negatives such as the additional root wing bending moment and aeroelastic effects can lead to increased structural weight[10].

The pros and cons of the Tube and Wing design are presented below in Table 2.3. Many positives are results of the design's similarity to current aircraft. Besides the C-wing and the V-tail, many of the current aircraft technologies and analysis can be applied to this design. Its similarity with Tube and Wing aircraft will also help reduce manufacturing costs as current Tube and Wing assembly facilities will be able to accommodate this design. Another important consideration is aircraft family expansion. If additional larger or smaller models are desired the seating capacity can be changed by simply manipulating the fuselage length. However, the design is weak in some areas. The thin wings reduce storage capacity for high lift systems and

biofuels when compared to the previous mentioned design. The V-tail's ruddervators combine the pitch and yaw forces. This significantly increases the difficulty of stability analysis. The C-wing's thin complex shape can lead to aeroelastic issues such as flutter and increased structural weight due to generation of a large bending moment. Most of these cons can be overcome using advanced control systems making this concept a viable replacement for current aircraft.

Table 2.3: Pros-Cons of Tube and Wing Design

Pros	Cons
• Optimized use of fuselage area • Simple, familiar Fuselage and Wing design • Low manufacturing costs • Simple Family Expansion • C-wing greatly increases span efficiency	• V-tail creates combined rudder and elevator forces • C-wing has issues with aeroelasticity and bending moment generation

The Tube and Wing design is shown below in Figure 2.5. With a span of 121 feet and length of 130 feet, the concept is very similar to the current Boeing 737 and A320. The maximum span was limited assuming the new aircraft will be more accessible if it fit into the same gates as comparable aircraft. The fuselage length was designed to provide the space for the RFP's required 175 passengers.

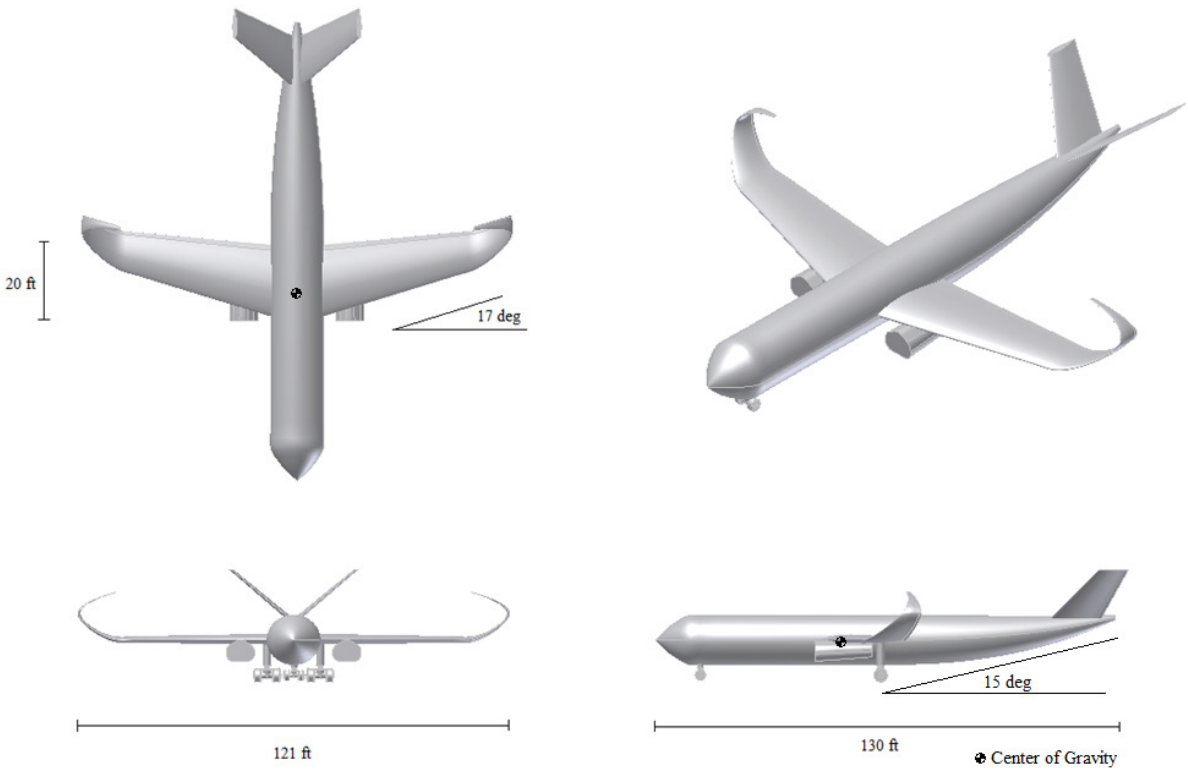


Figure 2.5: Tube and Wing Design

To create the T/W vs. W/S graph the same method was used as with the HWB. This is shown in figure 2.6 and indicates the aircraft design point.

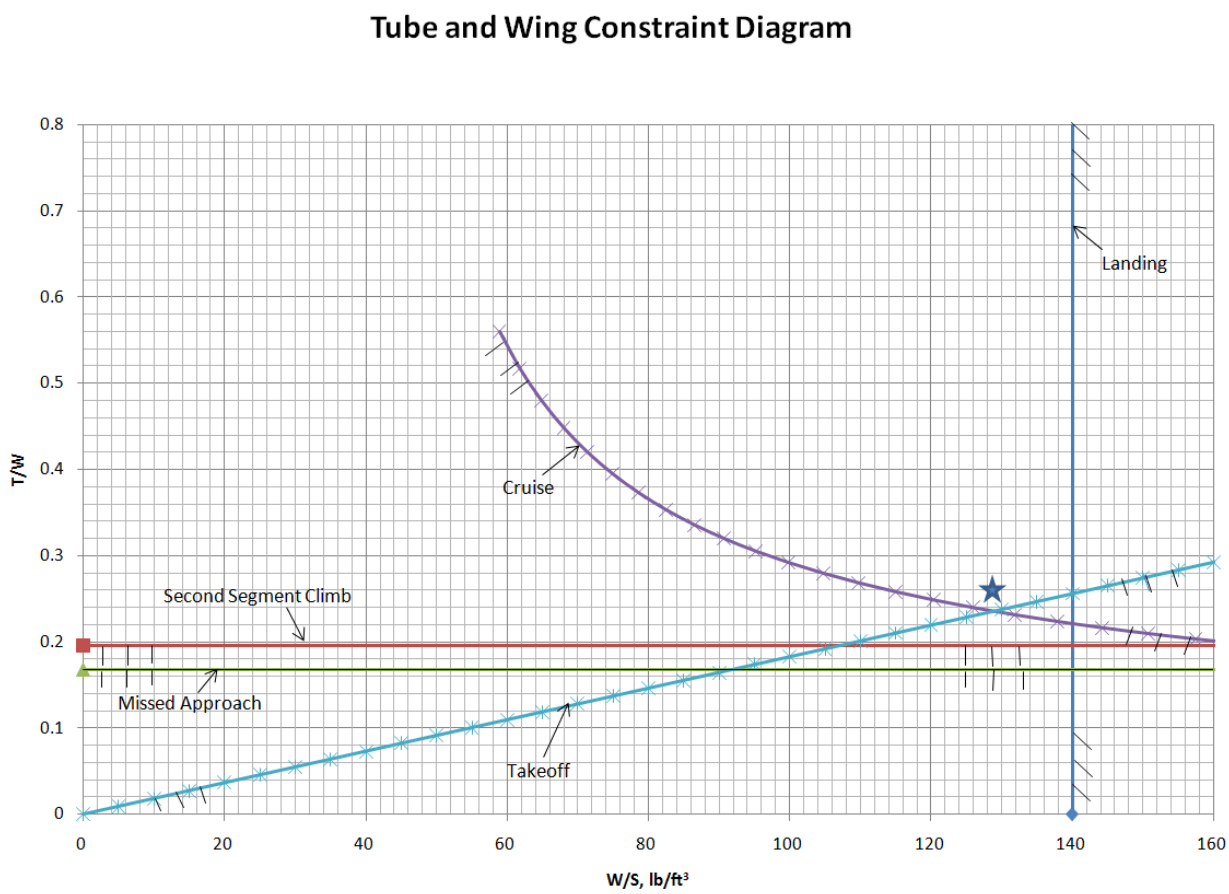


Figure 2.6: Tube and Wing Sizing Optimization

The design point for this concept was selected at a W/S of 129 lb/ft^2 and a T/W of 0.26. This is used to determine the thrust and wing area needed to fly all parts of the aircraft's mission profile.

To determine the maximum takeoff weight for the Tube and Wing aircraft, Nicolai's sizing program was again used[9]. The inputs used were gathered in the same manner as for the Hybrid Wing Body. The program gave a maximum takeoff weight of 122,500 lbs and a fuel weight of 25,500 lbs.

2.4 Design Selection

Both the HWB and the Tube and Wing concepts where compared to determine the better final design. These designs are also compared to the Boeing 737 in an effort to insure the final design is an improvement over the replaced aircraft. Table 2.4 is a decision matrix used for comparison.

Table 2.4: Design Selection Decision Matrix

	Comparison Factors					
	Weight	Aerodynamics	Stability and Control	Manufacturing Cost	Biofuel Storage Capacity	Total
HWB	0.8	1	0.5	0.3	1	0.705
Tube and Wing	1	0.8	0.7	0.8	0.8	0.8
Boeing 737	0.3	0.6	0.7	0.7	0.5	0.59
Factor weight:	0.1	0.2	0.2	0.25	0.25	1

The table above compares the HWB, the Tube and Wing, and the Boeing 737 using five comparison factors: weight, aerodynamics, stability and control, manufacturing cost, and biofuel storage capacity. Each of the criteria are assigned a weight. The aircraft are scored based on their ability to minimize weight, maximize aerodynamic efficiency, maximize stability and control, minimize manufacturing cost and to maximize biofuel storage capacity. The aircraft are given a value between 0 and 1 for each of the factors with 1 as the best. The aircraft scores are computed by summing the scores and multiplying by the factor weight. According to the table, the Tube and Wing is the best design solution and exhibits sufficient improvements over the current Boeing 737.

Through in-depth analysis of the Tube and Wing concept, it was determined that the C-wing was not necessary to obtain the performance specifications required by the RFP. Thus, the design will utilize standard blended winglets instead. From Figure 2.4, the winglet achieves an Oswald efficiency factor near that of the C-wing of about 1.41. The design is also simpler

allowing more straight forward analysis methods. Table 2.8 below discusses the advantages and disadvantages of the final design when compared to the former concepts.

Table 2.5: Pros and Cons of Final Tube and Wing Design

Pros	Cons
• Optimized use of fuselage area • Simple, familiar Fuselage and Wing design • Low manufacturing costs • Simple Family Expansion • Winglets greatly increases span efficiency	• V-tail creates combined rudder and elevator forces

A constraint diagram was created for the final design using methods previously discussed.

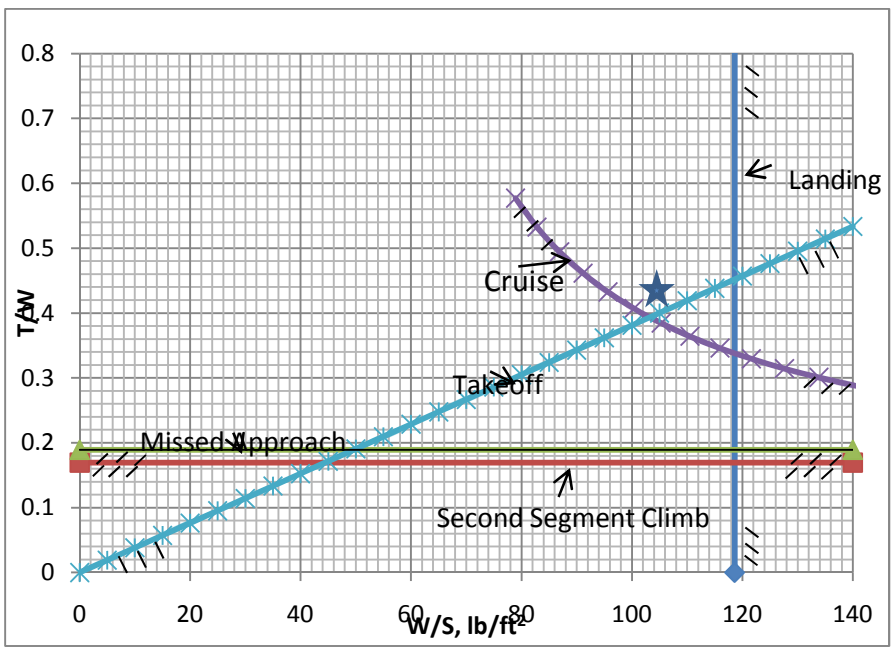


Figure 2.7: Final Design Constraint Diagram

The design point is at a T/W of .42 and a 103 lb/ft^2. This is subject to change depending on the engine selection.

3. Biofuels

In an effort to design the most environmentally friendly aircraft, the fuel type becomes very important. A significant requirement of the RFP includes the use of biofuels as a replacement to current petroleum-based fuels. Biofuels consist of any fuel sources derived from plant matter. Biofuels can be produced on large farming facilities reducing the dependence on foreign fossil fuels. The growing of these plants consumes carbon dioxide which is a major greenhouse gas. However, many biofuels such as Ethanol and Soybean-based Biodiesel require large amounts of land to grow [11]. Most biofuels also have lower densities and energy contents than current jet fuels such as Jet-A resulting in larger fuel tanks.

3.1 Biofuel Selection

A trade study was performed in order to select the optimum fuel source for the BC-175. Table 3.1 is a comparison of biofuels with hydrogen, Jet-A, and Fischer-Tropsch Fuel (a synthetic petroleum derived from coal). The comparison includes density, energy content, energy density, and energy per Boeing 737-400 tank.

Table 3.1: Energy Content Comparison

Fuel	Density (lb/ft^3)	Energy Content ($Btu/lb*10^3$)	Energy Density (Btu/ft^3)	Energy per Flight ($Btu*10^6$) for 737-400 Tank Size
Jet A	50.2	18.6	1280	770
FT-Gasoline	49.8	18.6	1280	760
Biodiesel(Methyl Ester)	55.4	16.1	1230	730
Algae	50.0	17.2	1190	700
Ethanol	49.3	13.4	910	540
Methanol(Liquid)	49.6	9.8	670	400
Soybeans	48.1	9.0	600	360
Hydrogen (Liquid)	4.4	61.0	370	220
Methane(Gas)	3.5	23.9	110	68
Hydrogen (Gas)	0.051	61	0.43	0.26

Results show that the current Jet-A, petroleum-based fuel, has the highest energy content. The next closest biofuel is algae. With a tank energy approximately 9% less than Jet-A, fuel tanks only need to be slightly larger for the same aircraft. This means little modification to current aircraft and concepts. In addition, Algae can be grown in many places and the amount of land required can be decreased as algae can be grown vertically. Figure 3.1 is a comparison of different plant resources and their land and growing requirements[12].

Fuel Sources			Use of resources during growing, harvesting and refining of fuel					
Crop	**Used to Produce**	**Greenhouse Gas Emissions*** (Kg of C02 created per mega joule of energy produced)	Water	Fertilizer	Pesticide	Energy	**Percent of existing U.S. crop land needed to produce enough fuel to meet half of U.S. demand**	**Pros and Cons**
Corn	Ethanol	81-85	high	high	high	high	157%-262%	Technology ready and relatively cheap, reduces food supply
Sugar cane	Ethanol	4-12	high	high	med	med	46-57	Technology ready, limited as to where will grow
Switch grass	Ethanol	-24	med-low	low	low	low	60-108	Won't compete with food crops, technology not ready
Wood residue	Ethanol, biodiesel	N/A	med	low	low	low	150-250	Uses timber waste and other debris, technology not fully ready
Soybeans	Biodiesel	49	high	low-med	med	med-low	180-240	Technology ready, reduces food supply
Rapeseed, canola	Biodiesel	37	high	med	med	med-low	30	Technology ready, reduces food supply
Algae	Biodiesel	-183	med	low	low	high	1-2	Potential for huge production levels, technology not ready

*Emissions produced during the growing, harvesting, refining and burning of fuel. Gasoline is 94, diesel is 83.

Figure 3.1: Comparison of Biofuel Plant Resources[12]

The figure shows that, although Algae requires the most energy to grow and refine, it requires the least amount of land and its refinement produces the least amount of greenhouse gas. In conclusion, algae is the most viable biofuel for the BC-175.

An advantage to using an algae based biofuel is they do not require good soil or precipitation. All they need is sunlight and saline water in which to grow. In order to produce high yields of oil, algae needs large amounts of carbon dioxide and what better place to get the gas other than a coal burning power plant. Using this system, a 1000 megawatt power plant can produce more than 40 million gallons of biodiesel and 50 million gallons of ethanol a year, requiring 2,000 acres of algae farm land. There are nearly 1,000 power plants nationwide with enough space to grow algae[13].

According to Dr. Michael Pacheco, Director of the National Bioenergy Center, current technology is capable of producing 1,000 to 1,200 gallons of algae oil per acre suitable for jet fuel refining. Currently, this requires 6,500 square miles of land. With the research plan of the

National Renewable Energy Laboratory the land required will shrink to 830 square miles and produce as much as 10 to 15 thousand gallons per acre as shown in the figure below relating to state of Arizona.

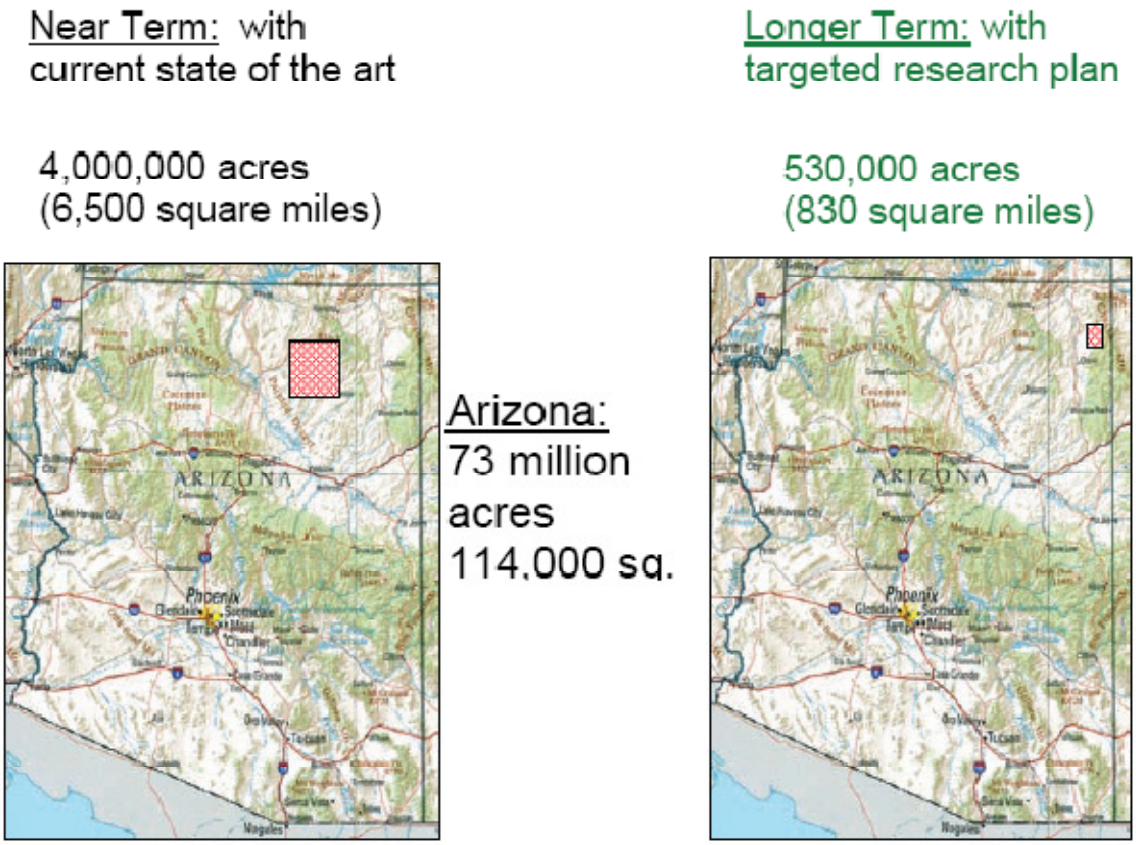


Figure 3.2: Algae Oil Needed for Five Billion Gal/yr Jet Fuel[14]

Current algae cost is around 30 dollars per gallon. This extremely high price is due to the large amounts of energy required to create the fuel. However, some companies such as Solix project cost reductions of around 90% in the near future [15]. This will greatly encourage Algae use. In early 2010, Continental Airways flight 516 used a 50-50 blend of Jet-A and biofuels which included 600 gallons of algae fuel[16]. The flight was successful proving the viability of algae as an aviation fuel in the future.

4. AERODYNAMICS

The RFP requires a 25% increase in lift-to-drag ratio over the current aircraft in this passenger class. Achieving this requires a wing design that has both low frictional and wave drag characteristics. Minimizing weight through composite structural design allows for a standard wing loading on an otherwise smaller area wing, when compared to aircraft such as the 737 and A320. The resultant increase in aspect ratio provides the prescribed increase in lift-to-drag ratio, while a supercritical airfoil section reduces the wave drag penalty at the transonic cruise speed of Mach 0.8. These traits paired with a set of tip devices that further increase *L/D* and span loading efficiency prove the feasibility of operation on biofuels.

4.1Wing Design

To fit into the unmodified terminal gates that accept the 737 and A320, the wing has a similar span of 117 feet. The wing area was selected by adopting a design wing loading (*W/S*) that is similar to current aircraft in this class. At roughly 100 pounds per square foot based on the initial cruise weight of 120,453 pounds the wing area as designed is 1181 square feet giving a thrust-to-weight (*T/W*) of 0.46 at this flight condition. To achieve the maximum possible extent of natural laminar flow, the leading edge sweep is designed to keep the transitional Reynolds number beyond that which the wing experiences during all normal flight conditions. As greatly swept wings promote spanwise disturbance growth and separation, leading edge sweep was chosen to be 17 degrees using Figure 4.1 below, from Braslow[17]. According to the figure, this sweep gives a transitional Reynolds number of roughly 22 million corresponding to a characteristic length of 14.4 feet. This length is well beyond the chord location where the adverse

pressure gradient will cause transition. A root chord of 17 feet was chosen in correspondence with the wing area to give a historically similar taper ratio of 0.235 and a tip chord of 4 feet.

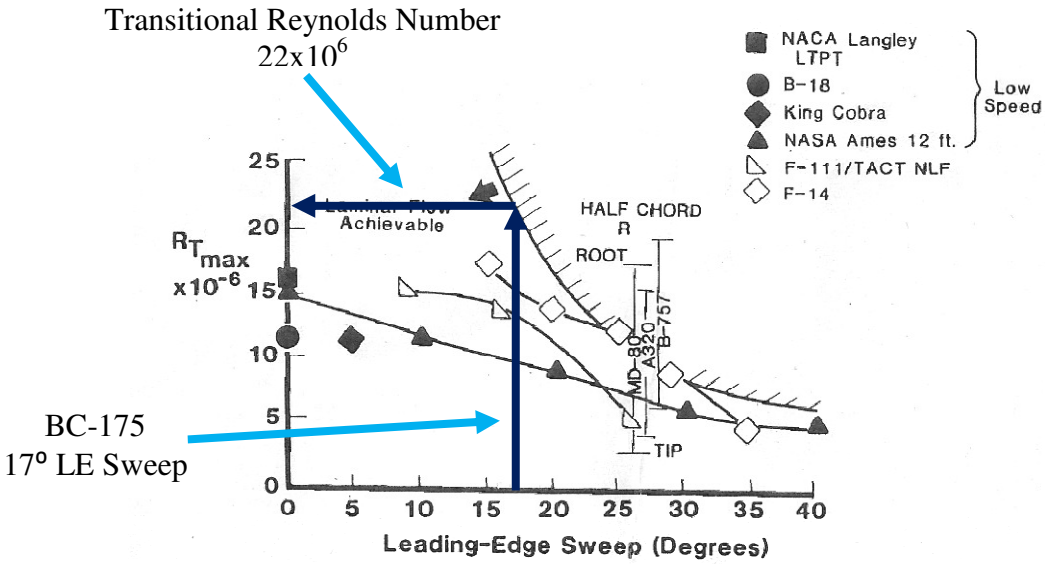


Figure 4.1: Experimental data, transitional Reynolds number with leading edge sweep Modified from Braslow[17]

Airfoil selection is a crucial part of this design considering the challenges of flying more efficiently at transonic cruise velocities than the 737 and A320. Wave drag can severely inhibit the performance of a wing in this flight regime, therefore the wing section chosen is designed to greatly reduce this risk. The use of a supercritical section over the entire wing delays sonic conditions and raises the drag divergence Mach number until beyond the cruise velocity. These airfoil shapes produce lift more evenly across the chord length of their upper surface as compared to standard airfoils. On a non-supercritical section the favorable pressure gradient around the first quarter of the chord length is stronger, produces the majority of the lift and would likely accelerate the flow to sonic conditions at the cruise condition of Mach 0.8. The type of airfoil used has an extended and weaker pressure gradient that delays shocks from forming on the wing and therefore reduces the wave drag. Figure 4.2 below, shows the supercritical airfoil

section that has been selected. The NASA SC(2)-0412 airfoil has a 12% thickness-to-chord and 1.3% camber.

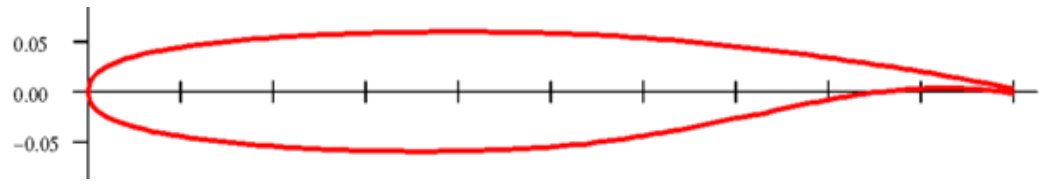


Figure 4.2: NASA SC(2)-0412[18]

The airfoil was analyzed using *XFoil* at the takeoff velocity of Mach 0.2 at sea level. The results shown in Figure 4.3 include the data as computed and data corrected by a factor of 22 percent. The correction was implemented from an article by Peter Garison[19] where he compares XFoil estimations to actual flight test data. The corrected airfoil prediction shows a maximum lift coefficient of 1.82 at 16.1 degrees angle of attack.

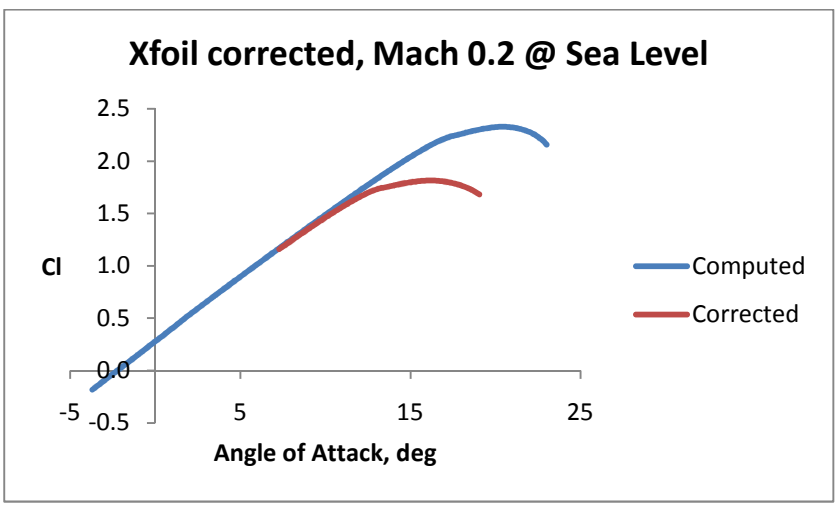


Figure 4.3: XFoil lift coefficient versus angle of attack computation and correction for NASA SC(2)-0412

The modified Korn equation from Mason[20] with simple sweep theory is used to estimate the drag divergence Mach number based on the selected design parameters:

$$M_{DD} = \frac{\kappa_A}{cos\Lambda} - \frac{(t/c)}{cos^2\Lambda} - \frac{c_l}{10cos^3\Lambda} \tag{4.1}$$

where M_{DD}, C_l, t/c, Λ and κ_A represent drag divergence Mach number, lift coefficient, thickness to chord ratio, leading edge sweep and airfoil technology factor, respectively. The technology factor will remain a constant 0.95 representing a supercritical section.

Based on the modified Korn equation and the empirically-derived shape of the drag rise[20], the critical Mach number is 0.69 and the drag divergence Mach number is 0.79. This calculation was based on the cruise condition lift coefficient at maximum takeoff weight. As the plane will actually be flying lighter than in this conservative estimate, it will require less lift and have higher actual drag divergence and critical Mach numbers. Designing the drag divergence Mach number to be right at the cruise velocity in this fashion insures wave drag will not be an issue.

The winglet plays a large role in meeting RFP requirements. The advantages include nearly 6% decrease in fuel consumption by producing a forward thrust component and thus reducing the total drag. This also reduces emissions and noise since the engine is run at lower thrust settings. The winglet design geometry is adopted from those that have been retrofitted on most 737's that fly today. At 10 feet tall and 2.25 feet wide they increase span loading efficiency *e,* to 1.2 at the cruise condition, as computed by a Trepz plane induced drag calculation.

4.2 High Lift Devices

The BC-175 needs to achieve a lift coefficient of 2.1, corresponding to the landing conditions discussed in *Section 7.5 Landing*. High lift devices will be required as the maximum clean wing lift coefficient is computed as 1.38 at 11 degrees angle of attack, limited by the tail scrape angle. Using a high lift analysis from Raymer[8] and the maximum lift coefficient, double slotted flaps are used over half of the reference area on the inboard sections. The required

extension in chord length is 15% for the landing condition equating to a 56% flap extension. The high lift device configuration is illustrated in Figure 4.4, below.

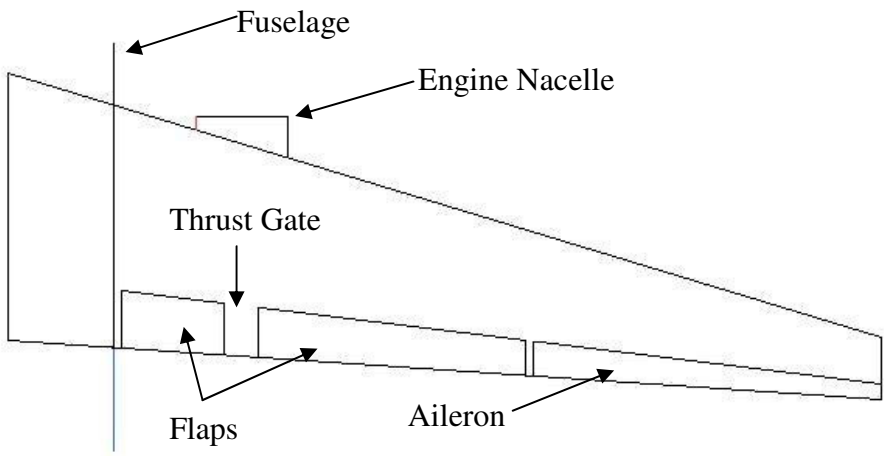


Figure 4.4: High Lift Device Configuration

The conservative design will allow for landing at altitudes higher than sea level while still having space further outboard for aileron placement. Landing and takeoff are designed to be achieved without leading edge devices because they often cause transitional effects to the boundary layer even when retracted due to small gaps in the section. To achieve maximum laminar flow across the wing, the double slotted Fowler style flap is the sole high lift device used on this aircraft. By sufficiently increasing wing area and airfoil camber using these high lift devices, the wing loading is low enough to achieve the takeoff and landing requirements.

4.3 Drag Analysis

Since the BC-175 will be flying at transonic velocities, wave drag is considered along with the standard parasitic and induced drags. A program, TBWwrapper, an Aerodynamic Estimation Framework for Air Vehicle Conceptual Design written by Gur[21], was used for

further aerodynamic analysis. The program considers multiple drag estimations and design conditions as defined by the user. As it considers all parts of the aircraft and their orientation with one another, an estimation of interference drag is produced. A complete consideration of the drag breakdown is shown below in Figure 4.5 from Gur[21]

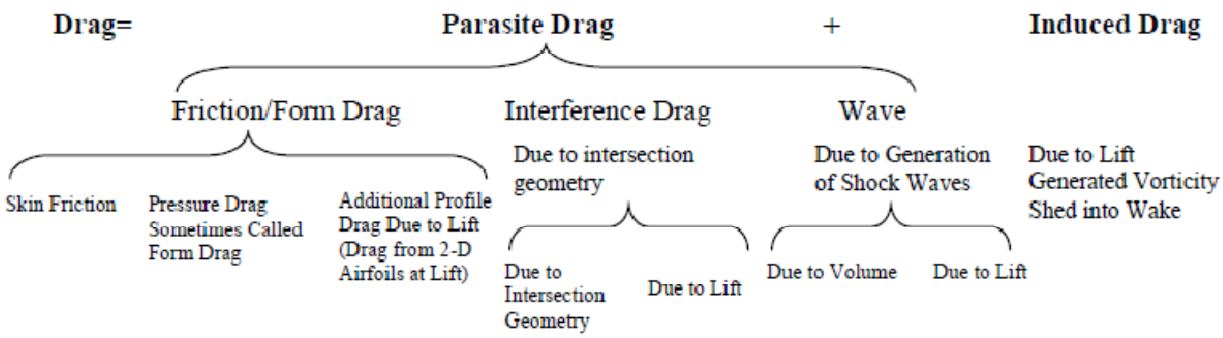
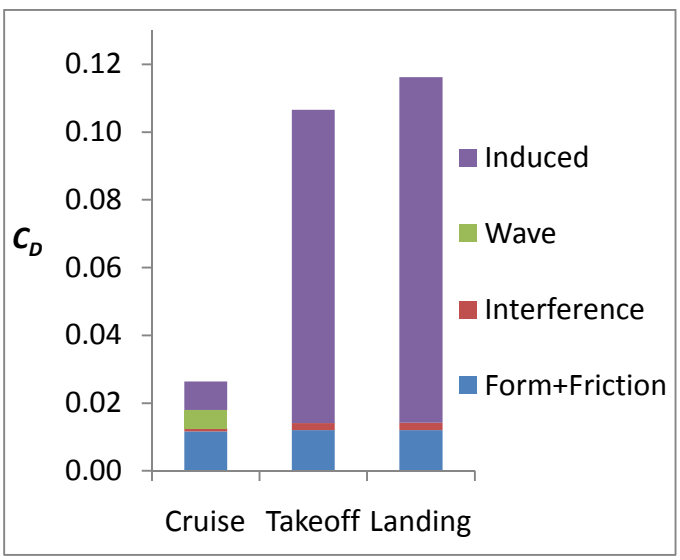


Figure 4.5: Drag Breakdown[21]

Each of these drag contributions is estimated and summed together for the drag build up at takeoff, cruise and landing in Figure 4.6 below.



	C_{Df} & C_{Dform}	C_{Di}	C_{Dint}	C_{Dw}	C_D
Takeoff	0.0120	0.0925	0.0021	0.0000	0.1066
Cruise	0.0117	0.0084	0.0009	0.0054	0.0270
Landing	0.0120	0.1020	0.0022	0.0000	0.1162

Figure 4.6: Drag Buildup

Lift coefficients with lift-to-drag ratio at each cruise altitude and the cruise velocity are shown in Figure 4.7 below. The two different data sets represent weight conditions at initial and final

cruise. Early in cruise, the maximum *L/D* is 21.6 which slightly falls to 21.5 before descent. After a short time in cruise, the L/D_{max} is achieved at the cruise altitude as shown by the slight peak in the initial cruise weight data below.

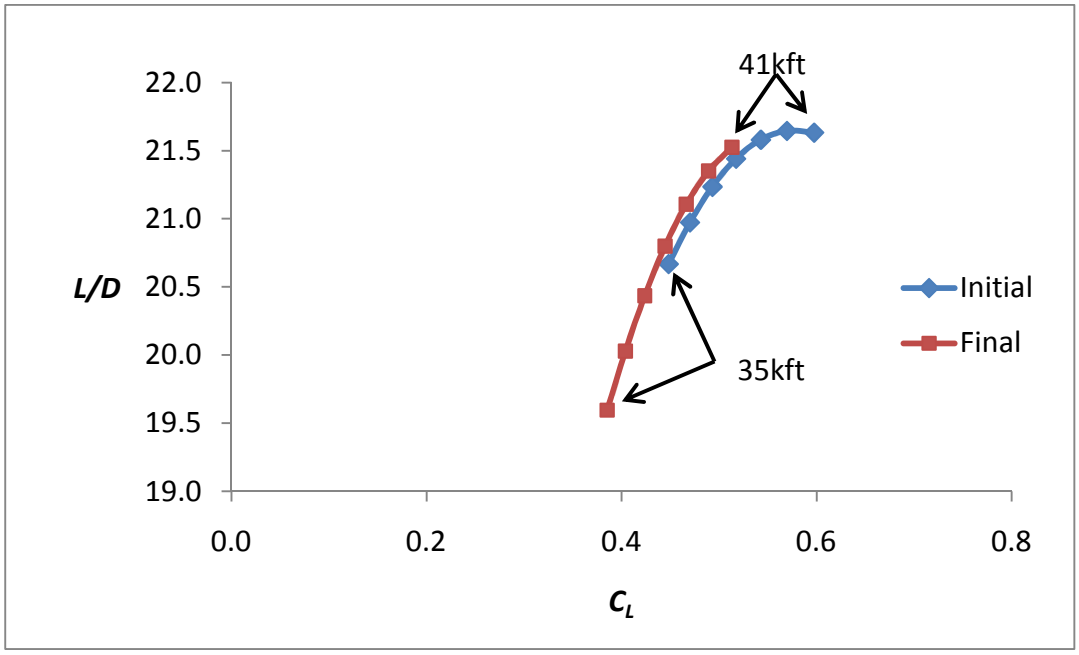


Figure 4.7: Trimmed cruise lift-to-drag ratio analysis 0.8 M, 41000 feet

Trim drag must also be considered for cruising flight. An analysis that shows how drag on the BC-175 changes with the additional drag accompanied by the trim setting is shown below, to the right, in Figure 4.8. On the left of the figure, a range for cruising lift coefficients is also shown.

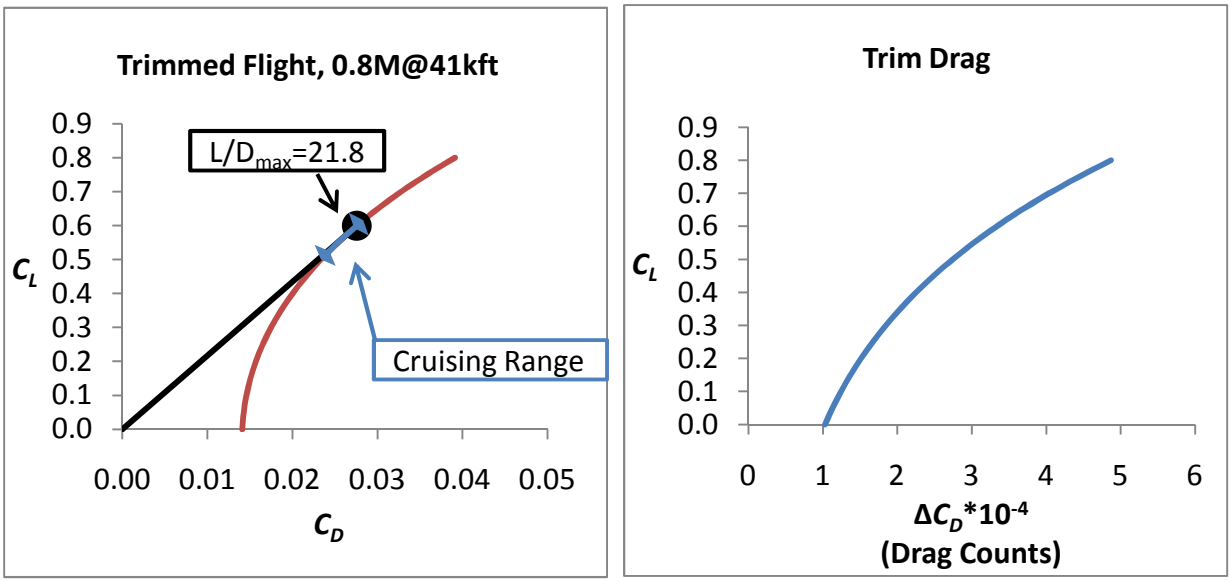


Figure 4.8: Cruise Trim Drag Analysis 0.8 M, 41000 feet

5. Propulsion

Based on the criteria given by the RFP, it was decided that turbofan engines be used for our concepts. There were three different types of engines to choose from: propfan, turbojet and turbofan. A propfan engine was not selected because of its inefficiency in noise level which was part of the RFP requirement. A turbojet engine creates lots of noise and it is very inefficient when flying in subsonic range. Therefore a turbofan engine is more feasible for our requirement.

Various turbofan engines were compared as shown below in Table 5.1. Out of these, the PW1000G was chosen for our concept based on the specification below. The PW1000G was chosen for its efficiency and the new technologies associated with it which help meet the RFP requirements.

Table 5.1: Various engine specifications. [22]

ENGINE	CFM56-5A1 used in A320-211/-311	CFM56-5B3 used in A321	CFM56-5C4 used in A340	PW2037 used in B757	PW1000G used in Irkut MS-21
Thrust(lb)	25000	32000	34000	36600	28000
SFC	0.33	0.36	0.33	0.335	0.29
Airflow(lb/s)	852	956	1065	1210	-
BPR	6	5.4	6.4	5.8	12
Thrust_cruise (lb)	5000	5840	7100	6500	-
SFC_cruise	0.596	0.545	0.545	0.582	-
Fan dia. (in)	68.3	68.3	72	78.5	74
Dry weight (lb)	4995	5250	5700	7185	-

The PW1000G uses a gear box to decouple and slow down the rotation speed of the fan from that of the low-pressure spool which allows both the fan and the low pressure turbine to run at a more efficient speed. The fan is rotating 30% slower than a conventional turbofan which means that the blade-tip speed is subsonic and there is no adverse shock wave effect.

The slower rotation speed of the fan and the large fan diameter gives two advantages: up to a 14% improvement in fuel efficiency (compared to current turbofan engine) and lower noise levels. The bypass ratio is so high that the cold bypass air mixes with the hot exhaust air covering the noise produced by the exhaust air. Also, the shock wave noise is eliminated due to subsonic rotation speed of the fan-blade tips. To further reduce noise levels, PW1000G will have a cut-off nacelle design.

In order to cut down on NOx level, the combustor in PW1000G uses latest TALON-X (Technology for Advanced Low NOx) design. As the engine heats up and cools down, the inner-lining panels expand and contract independently reducing wear and therefore the amount of

maintenance required on the engine. Using TALON-X, PW1000G is able to reduce NOx emission by 50% compared to CAEP 6[23].

PW1000G promises reduction in operating cost, reduction in fuel burn by 14%, 50% lower noise level compared to current turbofan engines and fewer moving parts which means lower maintenance cost [24]. Although the current maximum thrust required for our aircraft is 28,000 lbs per engine, therefore we can use the Pratt and Whitney engines that will be used on Irkut MS-21 which produces 25,000-32,000 lbs of thrust.

To calculate the thrust available at different altitude for PW1000G the following equation was used:

$$TA = \tau_{SL} * \left(\frac{P}{P_{SL}}\right) * \sqrt{\frac{T_{SL}}{T}} \tag{5.1}$$

where τ_{SL} is thrust at sea level, P_{SL} is pressure at sea level and T_{SL} is the temperature at sea level[25]. Using the equation above, a thrust vs. altitude graph was created as shown in Figure 5.1 below.

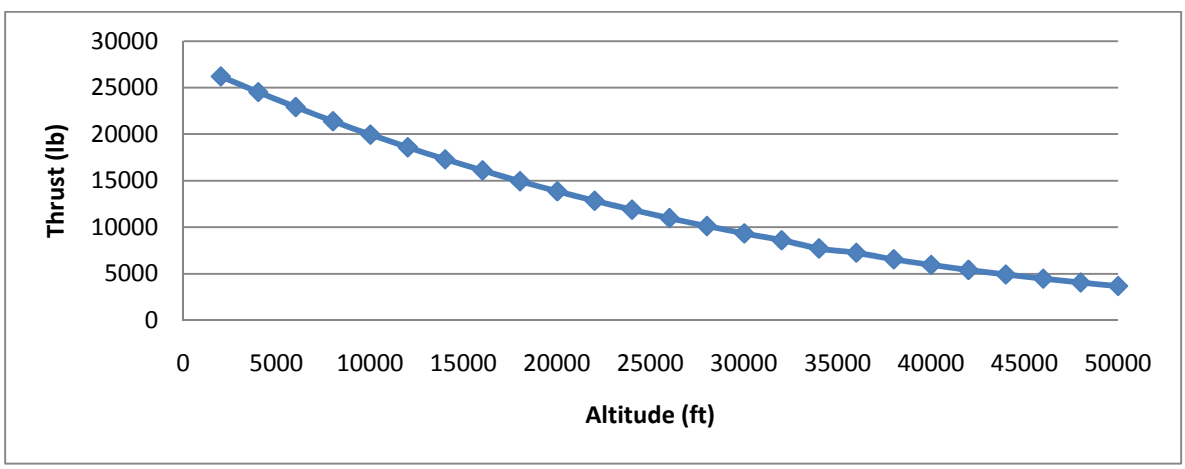


Figure 5.1: Thrust Available vs. Altitude for PW1000G

6. Weights

6.1 Final Weights

The weight of the BC-175 was determined with the estimation methods from Jan Roskam[26]. Each component was estimated using the equations provided in the text, unless actual values were available. As some of these equations are dependent on the TOGW, an iterative process was used to calculate the final TOGW. The initial weight for the iteration was calculated using *Nicolai's* aircraft sizing algorithm[8]. The weight values from the iteration process are shown in Table 6.1.

Table 6.1: Iteration of TOGW for the BC-175

Iteration Process (lbs)						
	Nicolai Initial	**Iteration 1**	**Iteration 2**	**Iteration 3**	**Iteration 4**	**Iteration 5**
TOGW	122589	124652	124964	125011	125018	125019
Wempty	60018	56577	56889	56936	56943	56944
Zero fuel	91514	93577	93889	93936	93943	93944

This process was run for a total of five iterations and led to the final weight value of each component in the TOGW, shown in Table 6.2.

Table 6.2: Aircraft Component Weight Breakdown

Component	Weight (lbs)	Location (ft)	Moment (ft-lbs)
Payload	37000	57	2109000
Fuel Weight	31075	50	1553750
Wing	11814	54	637956
Tail	408	116	47355
Fuselage	7025	55	383561
Nacelle	4160	50	208000
Main Gear	4142	57	236103
Nose Gear	773	12	9279
Engine Weight	10000	50	500000
Fuel System	590	53	31253
Propulsion System	464	50	23192
Flight Control System	1600	67	107210
Hydraulic and Pneumatic	1000	62	62009
Electrical System	1550	50	77475
Instruments Electronics Avionics	1869	18	33642
AC, Anti-icing	3429	70	240021
Oxygen System	240	50	12000
APU	875	116	101514
Furnishings	7005	57	399282
TOGW	**125019**	**54.17**	**6772602**
Wempty	**56944**	**54.65**	**3111721**
Zero fuel	**93944**	**55.55**	**5218852**

Table 6.3 compares these weights to those of existing aircraft.

Table 6.3: Weight comparison of BC-175

	BC-175	737-700	A320-200
TOGW	125019	154,500	170,000
Wempty	56944	84,100	93,000
Zero Fuel	93944	110,035	119,293

This table shows that our aircraft is significantly lighter than current aircraft.

6.2 Center of Gravity

The aircraft center of gravity was determined by using the full list of components that affect the TOGW. This was calculated by summing the moments of each component around the nose of the aircraft and dividing by the TOGW. These can be seen in table 6.2 and indicates that the center of gravity is furthest forward when the aircraft is fully loaded, and furthest aft when the aircraft has no fuel aboard. Figure 6.1 shows that cg travel as the aircraft weight is varied.

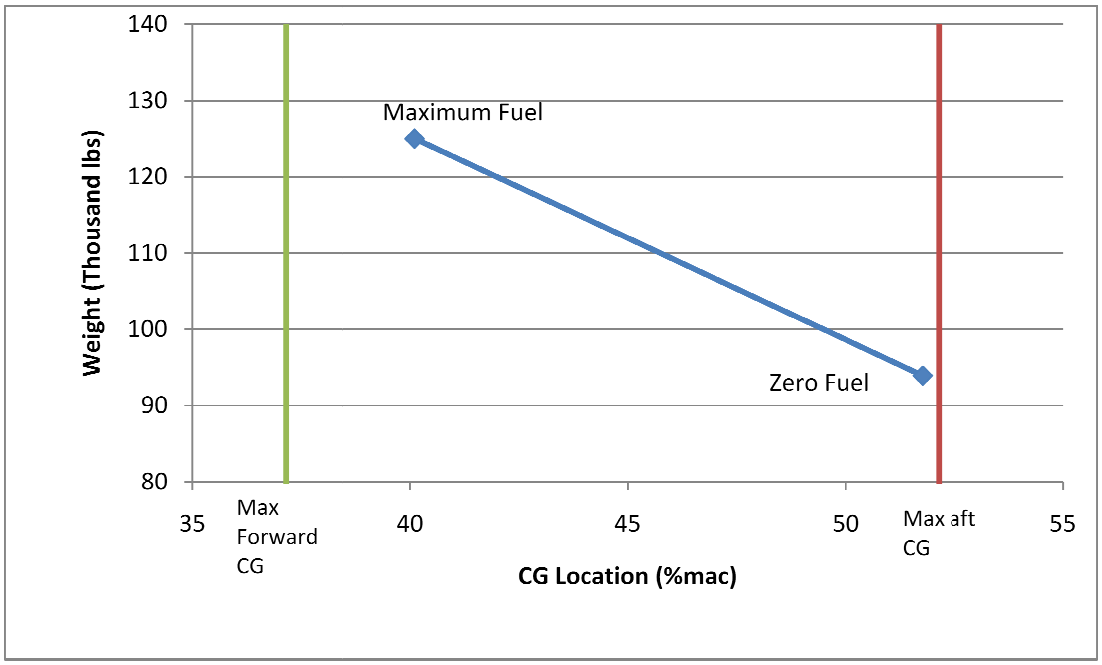


Figure 6.1: CG movement with weight variation

This shows that the cg of the aircraft remains in an acceptable region in all weight conditions.

7. Performance

The RFP requires the aircraft replacing the A320 and Boeing 737 to have better overall performance than its predecessors and to meet some additional requirements dealing with field performance and mission performance. The specific RFP requirements are shown in Section 1.1.

The BC-175 was analyzed using formulas from Raymer[8], Anderson[27], and Marchman[28] to ensure each performance qualification was met. Specifically, the mission flight was broken into takeoff, climbing flight, cruise, descent, and landing for analysis. Within each section general performance was evaluated along with the parameters specified within the RFP. An overall mission profile was then constructed merging the analysis of each individual flight segment into a composite.

7.1 Takeoff

The main takeoff parameter used to gauge performance in an aircraft destined for operation under FAR Part 121[30] is balanced field length. Balanced field length is the total takeoff distance including obstacle clearance when an engine fails at the decision point, the speed at which, upon an engine failure, the aircraft can either brake to a halt or continue the takeoff in the same total distance. If the engine fails before decision speed, the pilot can easily brake to a halt. If the engine fails after decision speed, the pilot must complete the takeoff[8]. The obstacle height included for a commercial aircraft is 35 ft[30]. To meet the RFP, the BC-175 must have a maximum balanced field length of 8,200 ft. The balanced field length was analyzed at density altitudes from zero to 5,000 ft to provide more information for various airport elevations. The results of the Balanced Field Length analysis are shown below.

Table 7.1: Takeoff Performance for BC-175

Takeoff Performance					
Density Altitude (ft)	BFL (ft)	RFP Req. - 8200ft	Ground Roll (ft)	Takeoff Speed (knots)	CL
0	6177	OK	4056	137	2
1000	6586	OK	4297	139	2
2000	7021	OK	4551	141	2
3000	7495	OK	4826	143	2
4000	8002	OK	5119	145	2
5000	8200	OK	5440	147	2

Each takeoff case assumes the runway to be dry asphalt and the aircraft is at maximum takeoff ground weight. It does not have to be a standard temperature day since the altitudes given are density altitudes. In actual operations, the BC-175 can obtain a substantial performance gain when operating at reduced gross weights. The takeoff thrust can be reduced, reducing the amount of fuel required so the takeoff distances remain the same as when carrying the maximum weight. This will conserve fuel on takeoff since less thrust is being used. However, the pilot will still be able to use the full thrust available in case of an emergency were more thrust is required. The BC-175 meets the balanced field length requirement set forth by the RFP.

7.2 Climbing Flight

The only climbing flight parameter required by the RFP is climb to the initial cruise altitude. The RFP requires the aircraft to reach an altitude of 35,000 ft without the use of step climbing. The BC-175 is equipped with two PW1000G engines which provide 28,000 lbs of thrust at sea level. The climbing characteristics for the BC-175 are shown below.

Table 7.2: Climbing Flight Performance for BC-175

Climbing Flight			
Density Altitude (ft)	Climb Angle (deg)	Rate of Climb (fpm)	Indicated Airspeed (knots)
0 - 10000	5.0	2207	250
10000 - 35000	4.5	2196	275
35000 - 41000	2.6	1257	275

The first climb from 0 to 10,000 ft is constrained by the FAA regulation which implements a speed limit of 250 knots under 10,000 ft. The second climb stage is designed around the best rate of climb. According to Aircraft Performance Engineering[31] and Optimizing Jet Transport Efficiency[32], airliners typically climb at a speed slightly faster than the speed for best rate of climb. This allows the aircraft to travel a farther distance on the same amount of fuel and lose only a slight rate of climb. For the BC-175 that speed is 275 knots and it results in a normal climb rate of about 2,000 fpm. To complete the climb to 41,000 ft, the same indicated airspeed is used. However, the higher altitude results in lower excess thrust to climb with. With less thrust available a lower climb angle is required to maintain the same indicated airspeed. This results in a lower climb rate.

Although some aircraft require the use of a level segment at an initial cruise altitude to reduce weight through fuel burn before having the climb capability of reaching a final cruise altitude (step climb), the BC-175 has sufficient power available to climb directly to 41,000 ft after a maximum gross weight takeoff without the need for an intermediate level off. Additional information about the climb profile of the BC-175 is provided in Section 7.6.

7.3 Range

The RFP sets out three significant requirements for the cruise portion of the mission profile. These are

- Cruise altitude selected must be between FL 35,000 ft and FL 41,000 ft.
- Cruise speed must be at least Mach 0.8 but is limited to a maximum of Mach 0.83 or 340 KCAS (knots calibrated airspeed), and
- The aircraft must have a nominal operational range of 1,200 nautical miles and a maximum operational range of 3,500 nautical miles.

The cruise data for the BC-175 is shown below.

Table 7.3: Cruise Performance for BC-175

Cruise Values Not Including Climbing and Descending Range						
Density Altitude (ft)	Mach	Speed (knots)	Speed (KCAS)	Speed Check	L/D	Range (nmi)
35000	0.8	461	255	OK	20.67	3221
36000	0.8	459	249	OK	20.97	3253
37000	0.8	459	244	OK	21.23	3291
38000	0.8	459	238	OK	21.44	3323
39000	0.8	459	232	OK	21.58	3345
40000	0.8	459	227	OK	21.63	3353
41000	0.8	459	222	OK	21.74	3370

The values above are shown with the aircraft at gross weight. The chart below shows the thrust required to meet the required airspeed numbers for flight at 41,000 ft for the BC-175 and demonstrates that the required thrust is available to meet the RFP requirements.

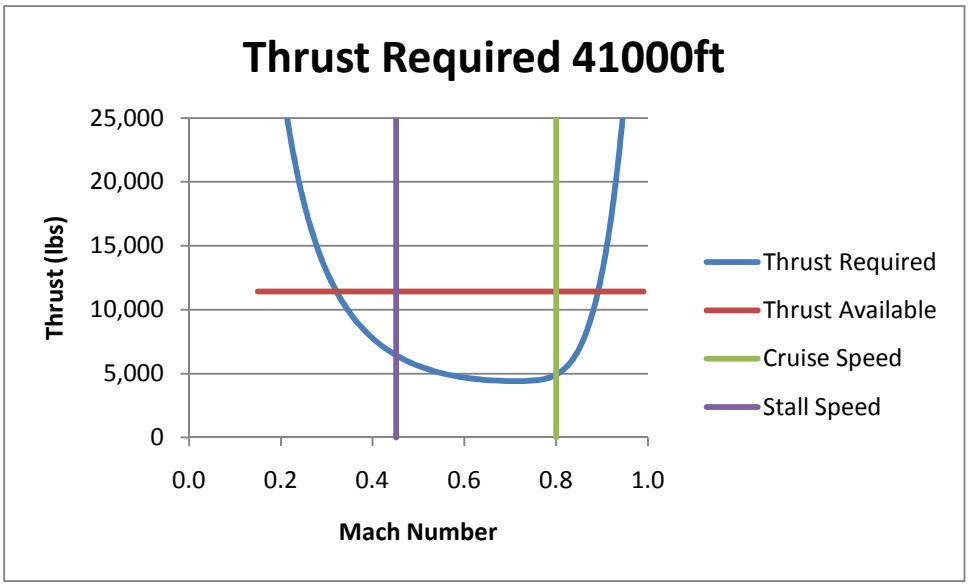


Figure 7.1: Thrust Required at 41,000 ft for BC-175

This graph shows the BC-175 will be able to maintain level flight at a cruise altitude of 41,000 ft. It also shows the excess thrust that enables the aircraft to climb directly to 41,000 ft instead of having to step climb after a significant fuel burn.

The BC-175 has been designed to optimize performance in the altitudes required by the RFP. This optimization provides for efficient flight and significant range profiles for the BC-175. The following charts display the specific range of the BC-175 at different Mach numbers and altitudes.

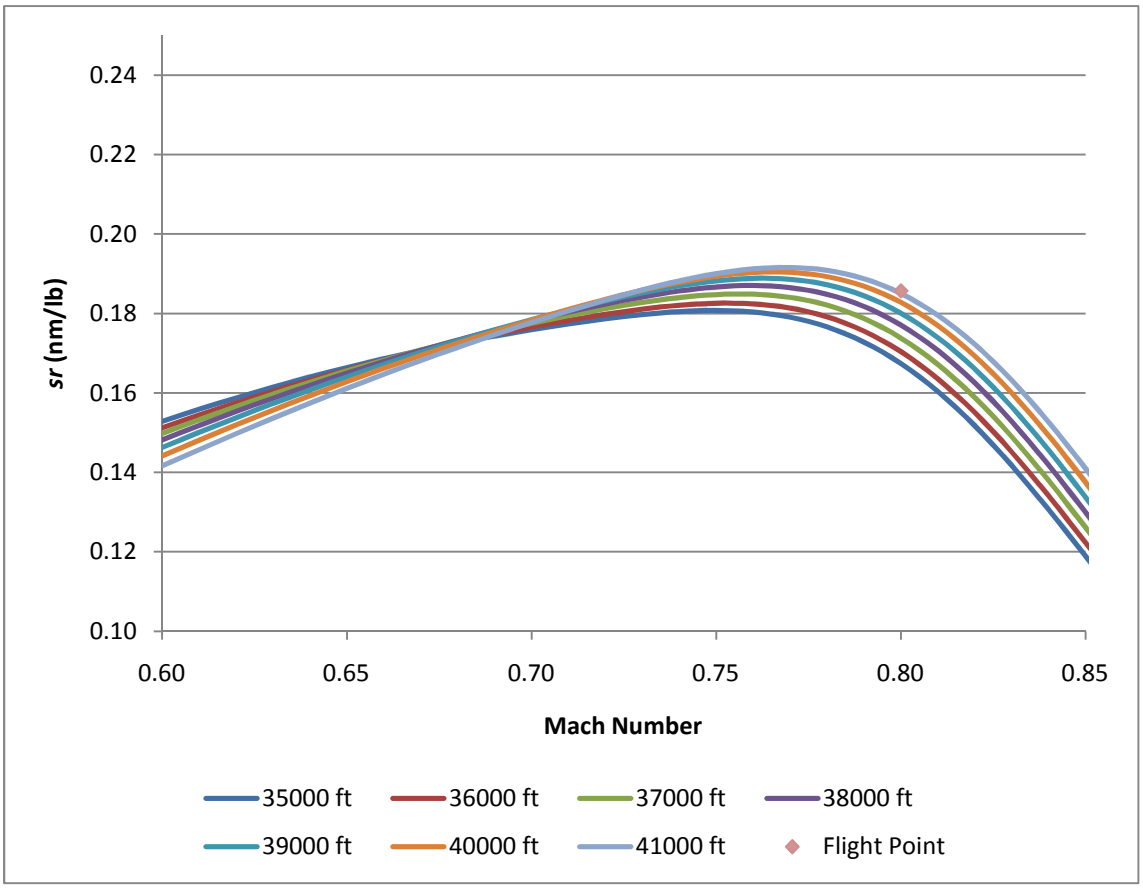


Figure 7.2: Specific Range including drag rise for BC-175

This graph takes into account the drag rise caused by the increased wave drag encountered by local supersonic flow over a wing when still flying at subsonic speeds. This increase in drag occurs when flying at speeds at or above the critical Mach number for an aircraft. Sweeping a wing will increase the critical Mach number and thereby delay the onset of the drag rise. The critical Mach number for the BC-175 is 0.68.

Examining the graph shows the design of the BC-175 has been optimized for the flight conditions set by the RFP. The flight point should optimally occur slightly to the right of the peak of the graph. By having the point to the right of the peak, the aircraft will be able to fly at a higher speed with only a minimal loss in specific range. This is more efficient than flying slower

at a slightly higher specific range. The chosen flight conditions of 41,000 ft and Mach 0.8 occur at the optimum location. This shows the aircraft will be flying at the most favorable conditions. Since the line graph can sometimes be hard to read, a contour plot of the specific range is shown below.

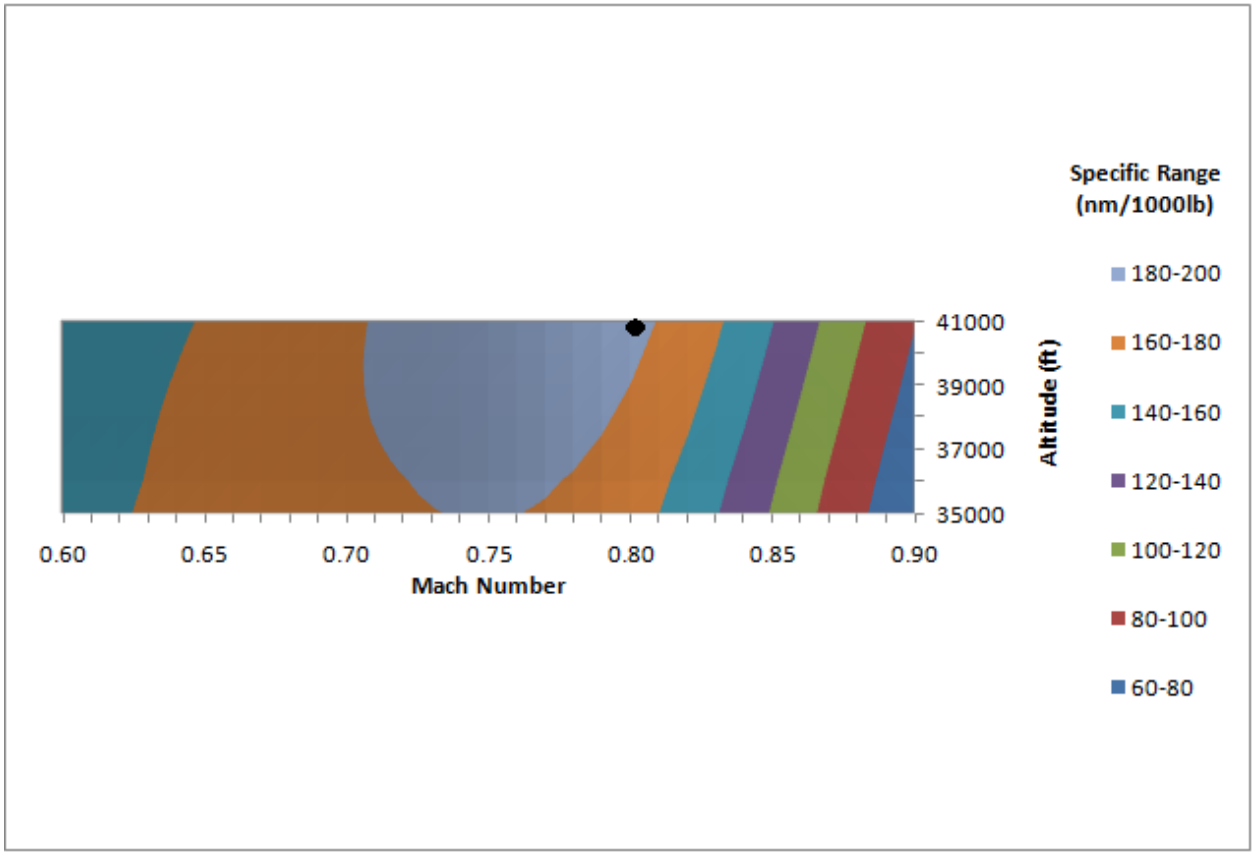


Figure 7.3: Contour Plot of Specific Range for BC-175

The contour plot shows the flight conditions of 41,000 ft and Mach 0.8 (represented by the black diamond) will be the most efficient. This is again because the flight point should be just slightly right of the area for best specific range and cruise speed. These graphs show the BC-175 is designed optimally for the conditions set forth by the RFP.

The analysis shown above demonstrates that the BC-175 can cruise at FL 41,000 ft at Mach 0.8 and have a range of 3,500 nautical miles. Therefore, the BC-175 passes all three RFP conditions for cruising flight.

7.4 Descent

There are no specific requirements in the RFP for descending flight. The descent segment was determined using requirements from Notes on Airline Climb and Descent[29]. The two constraints on descent are the cabin pressure cannot descend faster than 300 ft/min and the aircraft generally descends at the flight idle engine setting. The BC-175 cabin is pressurized to 8,000 ft which requires about 27 minutes minimum for the descent. The descent from 41,000 ft will take about 32 minutes as shown in Section 6.6 which meets the minimum required time. Flight idle for the aircraft is 60% of maximum thrust available. This flight idle setting will allow for the aircraft to decrease its speed as it descends with the assistance of speed brakes.

7.5 Landing

The only landing requirement set forth by the RFP is the aircraft must have a landing speed lower than 140 KCAS. Along with landing speed, the FAR field lengths were also determined to provide an idea of the required landing distance. The FAR field length is defined as the total approach distance over a 35 ft obstacle and the total ground roll required to stop multiplied by 1.666 to allow for pilot technique[8]. Similar to takeoff, the landing performance values were evaluated at density altitudes of zero to 5,000 ft. The analysis is shown below.

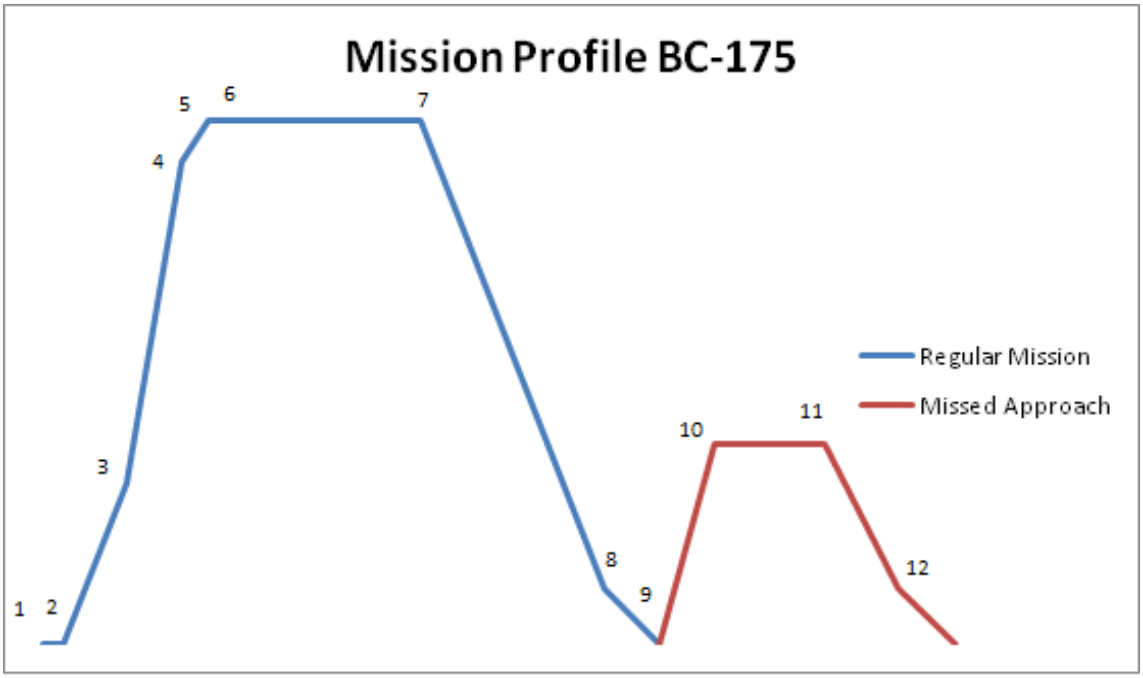
Table 7.4: Landing Performance for BC-175

Landing Performance						
Density Altitude (ft)	Landing Speed (knots)	RFP Req. < 140kts	Total Ground Roll (ft)	Total Approach (ft)	FAR Field Length (ft)	CL
0	125	OK	2900	3778	6293	2.1
1000	127	OK	2935	3818	6361	2.1
2000	128	OK	2973	3863	6435	2.1
3000	130	OK	3014	3910	6514	2.1
4000	132	OK	3058	3961	6599	2.1
5000	134	OK	3104	4014	6688	2.1

Each case assumes the runway is dry asphalt and uses the landing weight determined from the mission profile in Section 7.6 of 99,200 lbs. This is the maximum landing weight which is the maximum zero fuel weight plus fuel reserves for maximum range. The landing analysis conducted assumes using only landing gear brakes to bring the aircraft to a stop. Also it is assumed that there is a three second period between when the aircraft touches down and when the brakes are applied. Several features including reverse thrust, auto brakes, and auto spoiler deployment were not considered in these calculations. If these were to be included, the operational performance would be significantly better than calculated. It should be noted that the landing distance is less than the balanced field length. Therefore, the aircraft can safely arrive at any airport that it is capable of departing. The BC-175 meets the landing speed requirements set by the RFP.

7.6 Mission Profile

By combining the previous sections a complete mission profile for the BC-175 can be constructed. The mission profile, which details each flight stage for a maximum range flight, is shown below.



Mission Profile						
Mission Segment	Mach	Altitude (ft)	L/D	Time (min)	Fuel (lbs)	Distance (nmi)
1. Taxi/Takeoff	0 - 0.23	SL	-	15.0	2041	0
2. First Climb Stage	0.23 - 0.37	0 - 10000	-	4.5	551	19
3. Second Climb Stage	0.37 - 0.48	10000 - 35000	-	12.1	1472	55
4. Third Climb Stage	0.48	35000 - 41000	-	3.8	409	17
5. Acceleration to Cruise	0.48 - 0.8	41000	-	1.0	93	6
6. Cruise	0.8	41000	21.74	442.2	18219	3370
7. Descent	0.8 - 0.25	41000 - 1500	-	31.6	2509	74
8. Landing	0.25 - 0	1500 - SL	-	5.0	680	0
Totals				515.3	25974	3541
Missed Approach						
9. Climb	0 - 0.37	0 - 15000	-	6.8	826	28
10. Cruise	0.37 - 0.4	15000	27.73	28.1	825	117
11. Descent	0.4 - 0.25	15000 - 1500	-	27.0	765	56
12. Landing	0.25 - 0	1500 - 0	-	5.0	680	0
Totals				66.9	3097	202

Figure 7.4: Mission Profile for BC-175

Segments 1 through 8 represent a regular flight for maximum range. For shorter flights the cruise segment will be shortened. Segments 9 through 12 represent a missed approach and if needed a cruise to another airport 200 nautical miles away.

The entire mission uses 29,070 lbs of fuel and the BC-175 carries 31,070 lbs of fuel. This leaves a small window for changing the mission profile if required. While many portions of this profile can be modified, this outlines a regular flight for the BC-175.

7.7 Comparison of Performance

The BC-175 satisfies every performance requirement established by the RFP however, the BC-175 does not qualify as a legitimate replacement for the existing aircraft unless it out performs its predecessors. A chart below compares the performance of the BC-175 to the A320 and the Boeing 737-800.

Table 7.5: Comparison of Performance Characteristics[3][4]

	Boeing 737-800	Airbus A320	BC-175
Max Take-off Weight (lbs)	174200	170000	124500
Balanced Field Length (ft)	8000-8300	6900	6200
Service Ceiling (ft)	41000	39000	41000
Cruise Speed (Mach/mph)	.78/511	0.78/511	0.8/530
Max Range (nmi)	3060	3200	3500
L/D Max	19	20	27
Landing Speed (knots)	150	134	125

This chart shows the BC-175 is a significant step up from both the Boeing 737 and the A320. The most notable comparison is the lift to drag ratios in which the BC-175 is required to have a 25% increase over both the Boeing 737 and A320. Also, the BC-175 is significantly lighter than both the Boeing 737 and the A320. The above data shows the BC-175 will be a viable replacement for the Boeing 737 and the A320.

The RFP requirements for performance and the BC-175's capabilities are shown below.

Table 7.6: RFP Performance Requirements for BC-175

RFP Requirements		
RFP	BC-175	Check
Balanced Field Length - 8200ft	6200	GOOD
Cruise Altitude FL 350 – 410	FL 410	GOOD
Range (nmi) Nominal 1200, Max 3500	3500	GOOD
Landing Speed < 140 KCAS	125	GOOD
L/D Max 23+	27	GOOD

The BC-175 fulfills all of the performance requirements of the RFP and will be able to replace the Boeing 737 and the A320 as a superior short and long range carrier.

8. Structures and Materials

The BC-175 is constructed with an assortment of materials combined with efficient placement of load bearing structural supports to accommodate the requirements given in the RFP as well as reduce overall weight and cost. A special consideration for this project is the integration of improved composite materials that not only reduce weight but provide for strong structural components. In addition, the advantage to reducing overall weight can provide for more emphasis on implementation of newer technologies in control surfaces and other systems.

8.1 Material Comparison

An important aspect to fully understand before discussing structural design is the overview of the different materials considered for the aircraft. Considering the importance of integration of composite materials one must understand the advantages and disadvantages when

compared to previously used materials. Table 8.1 below shows a simple comparison of the different materials considered for the two designs. The two CFRPs shown in the Table below are developed by Toray Carbon Fiber. They utilize new technology such as "applied thermoplastic particles" which toughens the material and helps stop crack propagation[33]. The T1000 composite has the highest tensile strength in the world and was designed specifically for pressure vessel applications such as a aircraft cabin[33].

Table 8.1: Material Comparison[34][35][36][37][38]

	Alum. 2024-T0	Alum. 7075-0	AISI 1050 Steel Alloy	AMS 4914 Tit. Alloy	CFRP T800-S	CFRP T1000
Cost ($/lb)	~1.50	~1.50	~7.00	~40.00	~30.00	~50.00
Density (lb/ft^3)	170	175	490	300	75	112
Yield Strength (ksi)	11	21	180	110	415	~420
Tensile Strength (ksi)	32	40	220	140	430	440
Therm Cond. (BTU_{IT} /(hr*ft*^{o}F)	~110	~75	~17	~5	~20	~19

8.2 V-N Diagrams

To determine the materials to use to account for the larger structural loading cases, a V-n diagram is essential. At low speeds the maximum load factor is constrained by aircraft maximum lift coefficient. At higher speeds the maneuver load factor may be restricted as specified by FAR Part 25.337[30]. This gives a maximum load factor of about 2.5 and a minimum of about -1.0[30]. Gust loads are also added to show how wind gusts effect the loads on the aircraft surfaces[39]. Figure 8.1 below shows the V-n diagram for the BC-175.

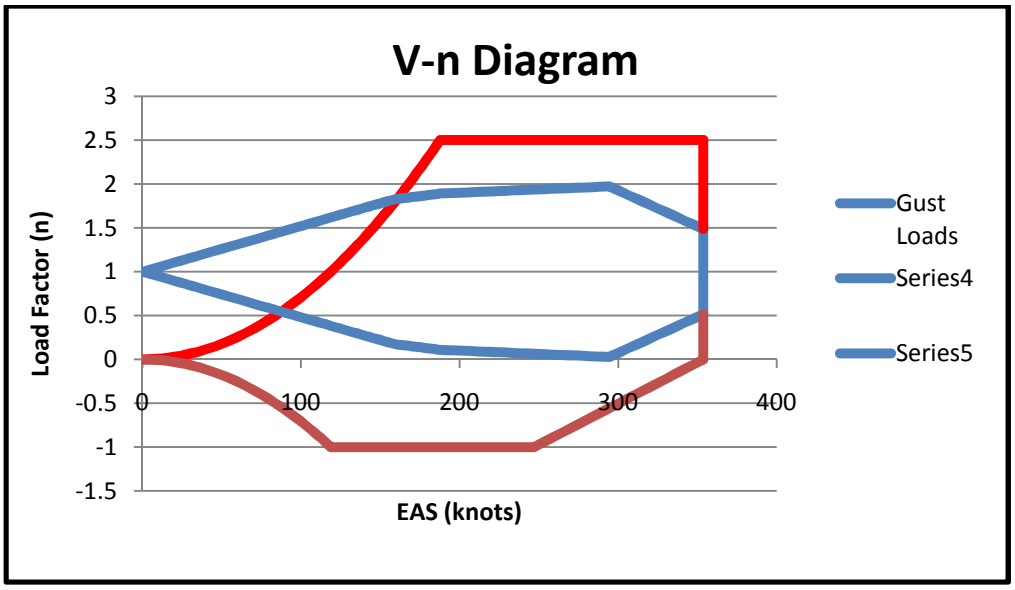


Figure 8.1: V-n Diagram

8.3 Wing Design

Wing structure design is important to maximize the efficiency of an aircraft's performance. For the BC-175, a standard setup with two spar with a wing box is utilized. The two spars, I-beam in design, will be placed at 15% chord aft of the leading edge and 34% chord forward of the trailing edge flaps. This placement is chosen to ensure structural stability as well as maximize volume inside the wing for fuel tank space. AMS 4914 Titanium Alloy is chosen for the spars due to its low weight, high strength and somewhat lower cost shown in Table 8.1. The spar accommodates for vertical deflections in flight and on the ground. The overall bending moment and ultimate strength of the spar is determined by the limits given on the V-n diagram, Figure 8.1, above. The wing box, which includes the ribs and the stringers, is constructed out of T800-S composite. Because of its incredibly light weight, high strength, and thermo conductivity properties, T800-S is a perfect fit to accommodate the structural demands needed with the wing box. A few other benefits include no fatigue due to repeated stress, no crack

propagation, and no corrosion[40]. The composite also requires little to no maintenance which will reduce the lifetime cost of the aircraft.

8.4 Control Surfaces

Control surfaces are a perfect place to utilize composite materials and were one of the first components of aircraft in which composites were used[40]. There are many benefits of using composite materials on control surfaces. Considering that much of the maintenance that aircrafts undergo is due to the stress on the control surfaces and their supporting structures, applying composites are very beneficial. Due to low corrosive properties and absence of fatigue potential, lifetime maintenance on control surfaces drops dramatically. Because of the low weight aspect of composites the controls surfaces are lighter which decreases the need for stronger structural support to hold them. T800-S is used for the skin, and a combination of the composite with Aluminum 2024 is used to construct the structure box. Aluminum is used because of its high thermal conductivity which is useful for de-icing and relatively low weight. Titanium alloy is used at where the control surfaces touch the spars on the wing and tail to support the structural loads.

8.5 Skin and Pressure Vessel

The most significant change in aircraft structural design in the past five years is the complete implementation of composite materials to the skin of the aircraft. In previous years it was determined the composites were not strong enough to account for the pressure difference required in the cabin. With the production of strong composites such as T1000, this is now possible. With the BC-175 , T1000 is utilized for the skin as well at the forward and aft pressure

vessel caps. Because of its incredible tensile strength, the skin can be very thin and still provide the strength needed to hold aerodynamic shape and accommodate for pressure differences at any altitude[34]. This application dramatically reduces the weight and required lifetime maintenance of the aircraft. For the BC-175 the cabin will be pressurized to 8,000 feet. At the intersection points of the wing and tail, Titanium alloy is used to provide the structural support.

8.6 Engine Nacelle

The engine nacelle is another component in which composite materials have been used for decades[40]. The skin of the nacelle is constructed with T1000 composite because of the local exposure to heat from the engine as well as the load from the thrust. Titanium alloy is used at the connection to the engine pylon to handle the large point load applied at that location.

8.7 Miscellaneous

A few other important components are explained in the following paragraph. First, the nose cone of the BC-175 is constructed with KFRP with Aluminum 2024. This is to allow the radar to work appropriately and to prevent damage in the event of a collision with small particles or birds[41]. The landing gear is housed in a pod when retracted which is constructed with T800-S composite.

8.8 Manufacturing and Maintenance

A large portion of the cost of a new aircraft is incorporating the associated manufacturing costs. Considering the relative size and design of the aircraft, manufacturing facility costs will be significantly cheaper because the size and equipment used in existing facilities can be utilized. Many of the main structural components of the design are similar to existing aircraft which will

also reduce the cost of manufacturing. The integration of composite materials will call of an increase in cost due to the relatively higher material cost. However, these expenses are countered by the waste-free production and molding of these materials. When composite material is molded to a new shape, all excess material is saved and reused. Another significant fact is the overall decrease in parts needed when composites are used as replacements. For example, when Airbus built their vertical fin box out of composite materials, they reduced the overall fastener count from 2,076 to only 95 parts[40]. This saves manufacturing, labor, and maintenance. Aluminum and titanium molding and carving facilities are expensive and require routine maintenance but are essential to both designs.

The lifetime costs of the BC-175 will be significantly cheaper than other modern aircraft. As discussed in previous sections, the extensive implementation of composite materials reduces the need for regular maintenance everywhere its applied. It is estimated that "associated costs with maintenance and operation will be at least two to three times greater than initial purchase values"[41]. Although, it is important to note if a composite structure is damaged the repair cost can be up to twice of what it would be with regular metallic structures[41]. However, the technology required to effectively repair composite damage should be sufficient in the next few years.

8.9 Overview and Cad Drawings

The other basic structural components are described in the following section. Bulk head placement, along with ribs, stringers, and longerons are determined through proven structural design. Due to the usage of strong composites such as T800-S and T1000 on the skin of the aircraft, a semi-monocoque construction is used. This transfers loads from the wing through the

skin which is then absorbed by the stronger load bearing members such as the bulk heads and spars. Longerons and stringers help support the longitudinal loads and bulkheads help support the transverse loads on the fuselage. Larger bulkheads are placed near where the wing attaches to the fuselage to absorb the forces and moments created by the aerodynamic forces on the wing. Figure 8.2 below shows the basic layout of the aircraft.

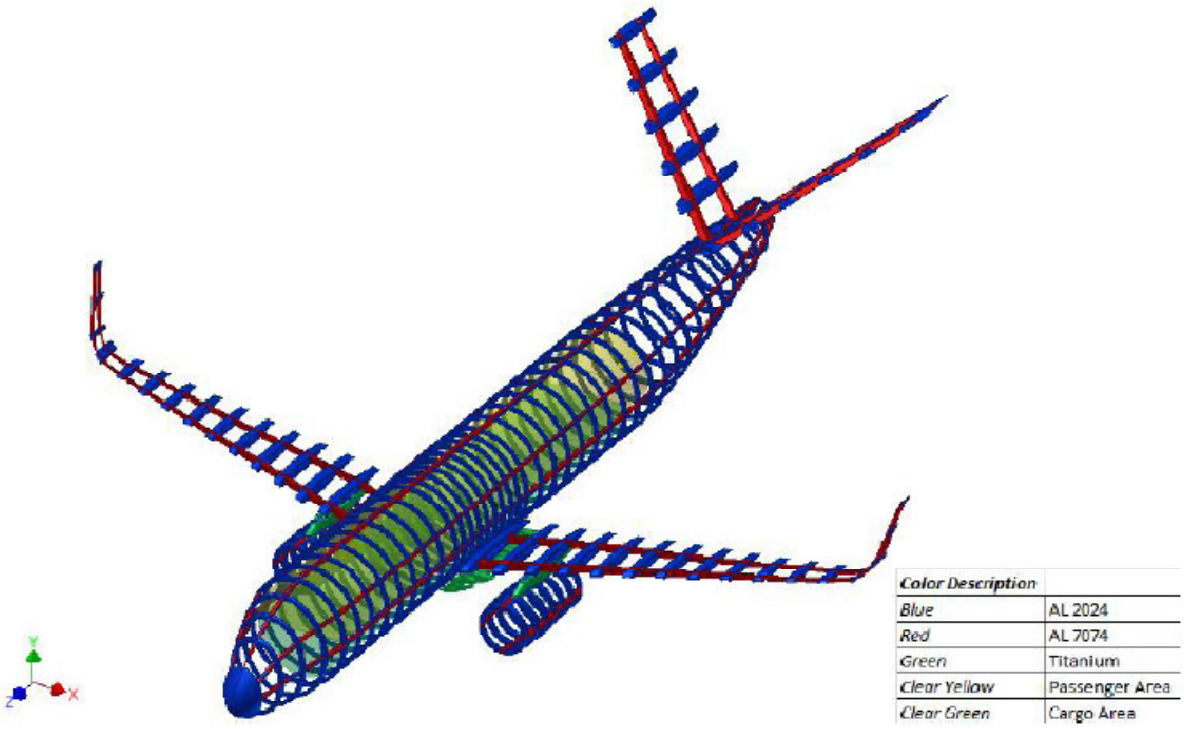


Figure 8.2: Structural Diagram

The ribs of the fuselage, designed with Aluminum 2024-T0, are spaced about three feet about the whole way down the aircraft. Larger ribs are placed more frequently, about every foot and a half, where the wing connects to the fuselage. These are constructed with Aluminum 7075-0. Bulkheads are placed forward of the first entrance, two are placed where the wing starts and ends on the fuselage, and one is placed aft of the rear entrance. Longerons are placed at 0°, 90°,

180°, and 270° around the fuselage. Bulkheads, longerons, and stringers are all constructed with Aluminum 2024-T0. In the two tails there are small spars located forward of the control surface at about 36% chord and ribs are placed every two feet. In the wing, the ribs are placed every foot and a half. These ribs are shaped to provide enough volume for the fuel tanks.

9. Stability and Control

The BC-175 is a class III aircraft which satisfies the requirements set by the RFP and FAR. The design utilizes a V-tail to reduce wetted area as well as traditional control surfaces to ensure safe operation under all conditions. Analysis to determine the neutral point, the control surface sizing, and the dynamic flight qualities was done using various methods and programs. These programs included *Tornado* Vortex Lattice Method (VLM)[42], *LDstab* (Lateral Directional Stability)[43], and a VPI-NASA Excel spreadsheet[44]. *Tornado* was used to determine the stability derivatives, the control derivatives, the static margin and the neutral point. *LDstab* was used for some preliminary engine out analysis, while the VPI-NASA Excel spreadsheet was used for the final engine out analysis. The VPI-NASA Excel spreadsheet was developed by Virginia Tech and was also used for aileron and ruddervator sizing calculations.

9.1 Tail Sizing

Two tail configurations were considered for the BC-175: a V-Tail configuration and a conventional tail. Both configurations were analyzed and sized for the minimum static margin, engine out criteria, and nose wheel lift off. Ultimately the V-tail was found to reduce tail area by 87.1 square feet (21.0%) over the conventional tail. The static margin was evaluated at cruise and maximum altitude. The engine out criteria was evaluated under takeoff at sea level conditions.

The V-tail has a root chord of 11.0 feet, a tip chord of 8.0 feet, and a total area of 323.7 square feet. It has a dihedral angle of 42.76° and is 73.4 feet from the wing apex to the tail apex.

The engine out condition requires that the available yawing moment coefficient exceeds the yawing moment coefficient required to maintain steady flight with one failed engine at $1.2V_{stall}$ as required under FAR 25.149[30]. The remaining engine must be able to maintain full thrust of 28,000 lbs without the bank angle exceeding 5°. The aforementioned VPI-NASA Excel spreadsheet was used to complete the analysis. The engine out parameters are shown in Table 9.1.

Table 9.1: Engine Out Analysis

Engine Out Analysis	
B	2.55
Φ	4
Δa	1.24
Δr	20
C_{navail}	0.0489
$C_{nrequired}$	0.0299

9.2 Static Margin

The minimum static margin was found to be 10% using the *Tornado* Vortex Lattice Method Matlab code. The *Tornado* model can be seen in Figure 9.1. The center of gravity location ranges from 39.5% MAC when the aircraft is fully loaded to 51.3% MAC at the zero fuel weight.

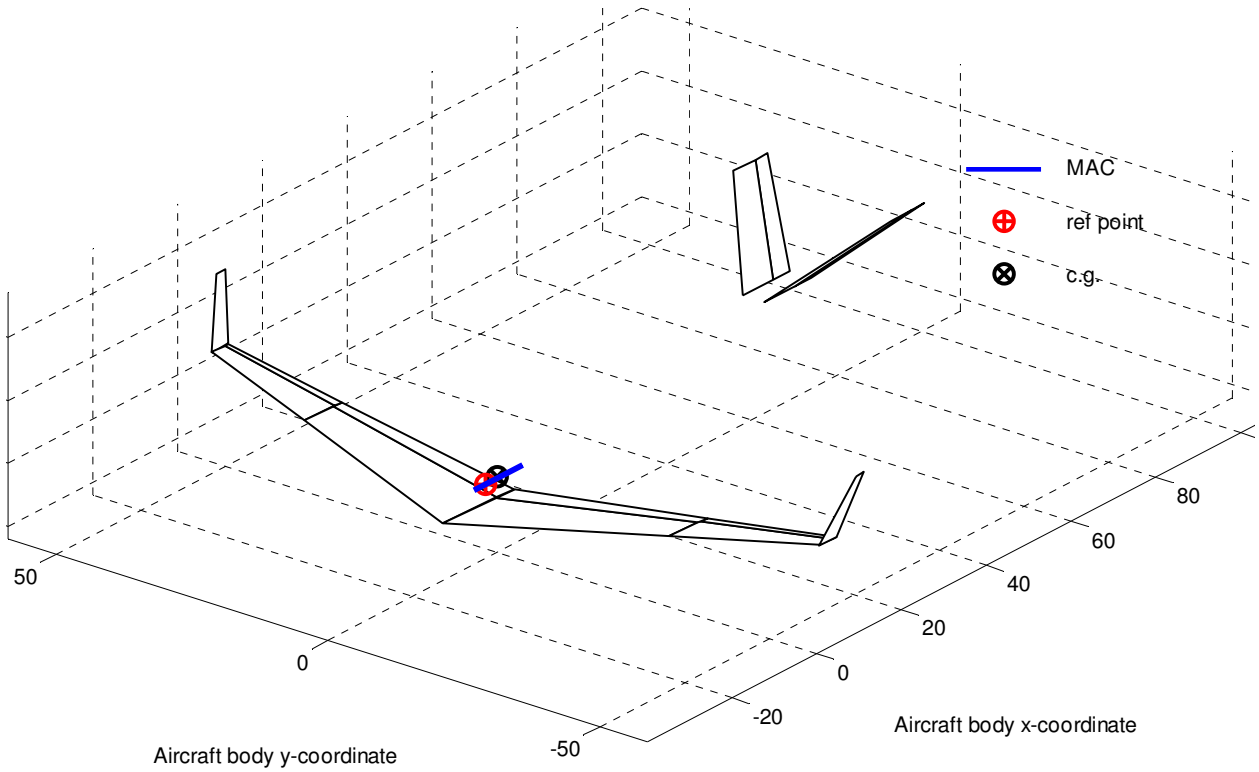


Figure 9.1: Tornado Model

9.3 Control Surface Sizing

The BC-175 utilizes ailerons, spoilers, and ruddervators to complete all necessary in flight maneuvers. The ruddervators are sized to meet engine out criteria as well as nose wheel lift off during takeoff. The ruddervators are 35% of the tail chord and have a total area of 113.3 square feet. The ruddervators are capable of lifting the nose off the ground at a speed lower than the calculated lift-off speed. Section 4.2.7.3 of MIL-STD-1797 states that at $0.9V_{min}$ the aircraft must be able to achieve the pitch attitude required for take-off at V_{min} for dry runways. The BC-175 is capable of achieving a pitch angle of 11.5° at $0.9V_{min}$,which exceeds the 11° pitch angle required for take-off at V_{min}. Figure 9.2 shows the relationship between the pitch angle and the lift-off velocity.

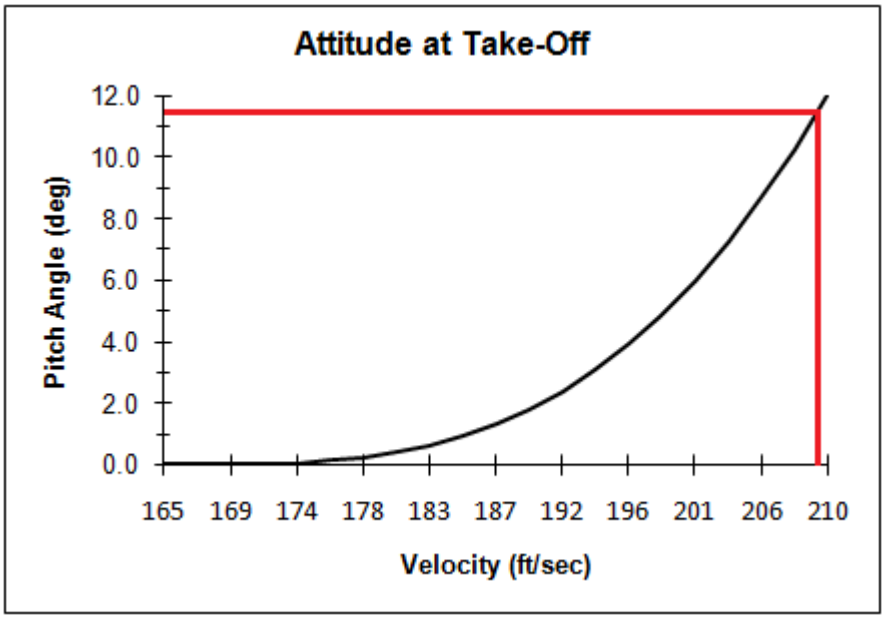


Figure 9.2: Pitch Angle vs. Velocity Required for Nose-Wheel Lift-off

The ailerons were sized for a Level 1 flight rating as defined by MIL-F 8785B roll performance specifications. The requirement is that the plane must be able to roll 30° in 1.5 seconds. The BC-175 takes 1.00 seconds to roll 30°. Figure 9.3 shows the roll response of the BC-175. The ailerons run to the base of the winglets taking up 40% of the wing span and 25% of the wing chord. All control surfaces were sized using stability derivatives found by the *Tornado* VLM program. Tables 9.2 and 9.3 show the stability and control derivatives.

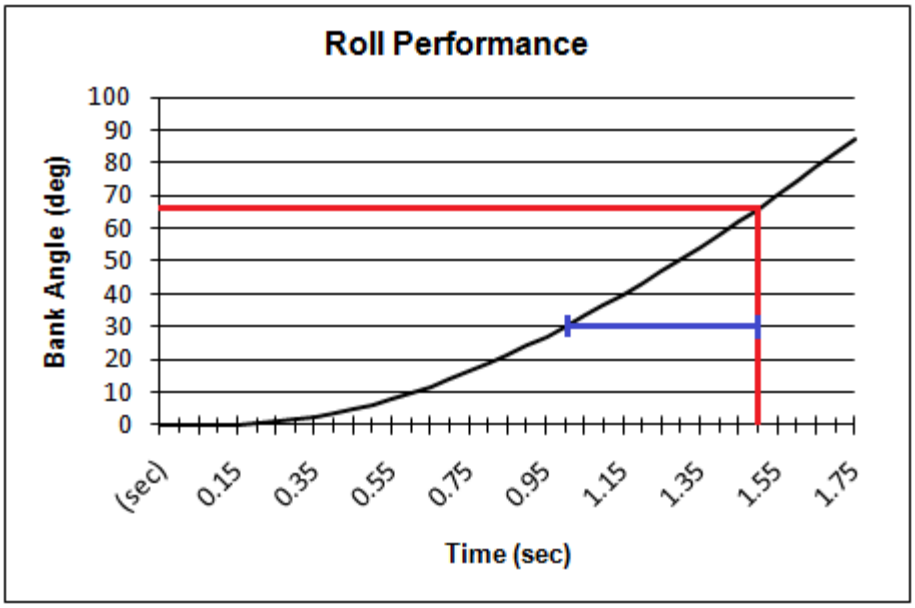


Figure 9.3: Roll Performance Capability with Sized Ailerons

Table 9.2: Longitudinal Stability Derivatives

Derivative	BC-175
$C_{m\alpha}$	-1.722
C_{mq}	-30.333
$C_{L\alpha}$	5.165
C_{Lq}	7.282
C_{Ldr}	0.297
C_{Ddr}	0.001
C_{mdr}	-1.905

Table 9.3: Lateral-Directional Stability Derivatives

Derivative	BC-175
$C_{l\beta}$	0.174
C_{lp}	-0.385
C_{lr}	0.08
$C_{n\beta}$	-0.144
C_{np}	0.042
C_{nr}	-0.156
$C_{y\beta}$	-0.479
C_{yp}	0.319
C_{yr}	-0.321
C_{yda}	-0.096
C_{lda}	0.196
C_{nda}	0.005
C_{ydr}	-0.233
C_{ldr}	0.034
C_{ndr}	-0.131

9.4 Dynamic Analysis

Dynamic analysis was done using the approximate methods of estimation from Roskam[45] with derivatives found from the *Tornado* VLM. Evaluation of the dynamic qualities was done for the cruise case at a Mach number of 0.8 and at an altitude of 41,000 feet on a standard day. The dynamic qualities for the phugoid, short period, and dutch roll modes were compared with the requirements for MIL-STD Class I Category B flight. Table 9.4 compares the Class I requirements with the dynamic values estimated for the BC-175.

The preliminary analysis reveals that both the short period mode and the dutch roll mode are under-damped. To bring these modes up to a Level 1 flight rating, the BC-175 is equipped with a flight control system consisting of feedback gain for both the pitch rate and the yaw rate.

By implementing such a flight control system it is possible to bring the damping ratios of the short period and dutch roll modes up to Level 1 requirements.

Table 9.4: BC-175 Dynamic Modes and Level 1 Requirements (no control system)

	Damping		Frequency	
	Requirement	**BC-175**	**Requirement**	**BC-175**
Phugoid	$\xi_{PH} > 0.04$	0.042	NA	NA
Short Period	$0.3 < \xi_{sp} < 2.0$	0.253	$0.8\text{rad/s} < \omega_{nsp} < 2$	1.565
Dutch Roll	$\xi_D > 0.19$	0.065	$\omega_{nD} > 0.4$	1.202

10. Systems

The BC-175 will incorporate advanced systems in an effort to improve flight performance and efficiency. Many different systems come to play when designing an aircraft; however, there are some especially significant systems to discuss.

10.1 Aircraft Cabin Layout

The aircraft cabin is designed to RFP and FAA specifications. The aircraft seats 177 passengers in a single class configuration and the cabin must be at least 12.5 feet wide and 7.25 feet tall. Current Boeing 737 and A320 configurations use a single aisle with 6 seats per row. This configuration will be used for the BC-175. The cabin sizing was determined using a code located on the Stanford website[46]. The figure below shows the passenger cabin cross-section.

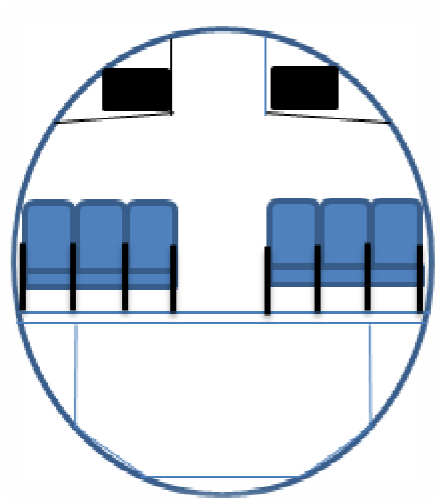


Figure 10.1: Cabin Cross-section

The seats are 20 inches wide compared to the standard 17.2 inches adding to passenger comfort. The aisle width was increased to 24 inches compared to the standard 18 inches increasing passenger mobility during cabin travel or emergency evacuations. The pitch, or the distance from a point on one seat to the same point on the next seat, is 32 inches. The figure below shows the general location of crew stations, galleys, lavatories, and emergency exits.

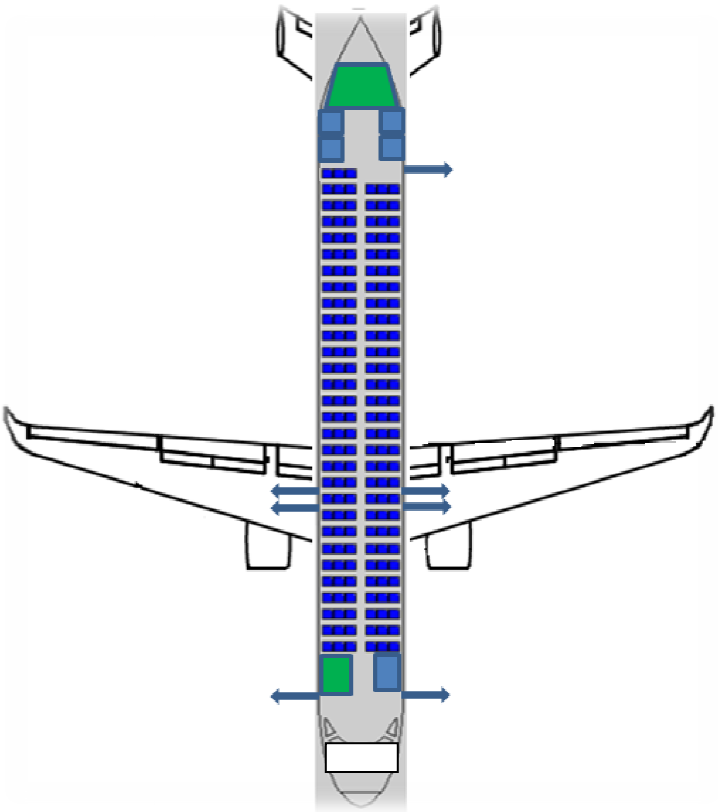


Figure 10.2: Cabin Arrangement

This layout insures passenger comfort and safety. There are two general galley locations with one located at the front and rear of the cabin. There are also four standard lavatories at the rear of the aircraft and one handicap-accessible lavatory at the front of the aircraft. For passenger safety, there are numerous emergency exits including three floor level Type A exit doors and four mid-cabin over the wing Type III exit doors. This exceeds the FAR 25.807 requirement for emergency exits[30]. The crew station is located in the white section above. Flight attendants have personal folding seats in each galley.

There are a number of environmental systems to consider when designing an aircraft cabin. B/E Aerospace provided many of the cabin systems used on the Boeing 787. These were used as a basis for the selection of cabin systems for the BC-175.

The B/E Aerospace seating systems are a low cost, lightweight, and safe solution. A three seat group is pictured below.

Figure 10.3: B/E Aerospace Three Seat Cluster[47]

The seats make use of lightweight, strong aluminum alloys, and a fabric suspension system to reduce weight while maintaining durability.

Another important system to consider is the oxygen system. B/E Aerospace produces an innovative oxygen delivery mechanism called the Pulse Passenger Oxygen System[48]. The oxygen is stored in a pressurized tank and activated only when required. It is dispersed to the passenger based on their breathing patterns helping preserve oxygen. This system, pictured below, is powered off during normal operating conditions resulting in zero energy consumption.

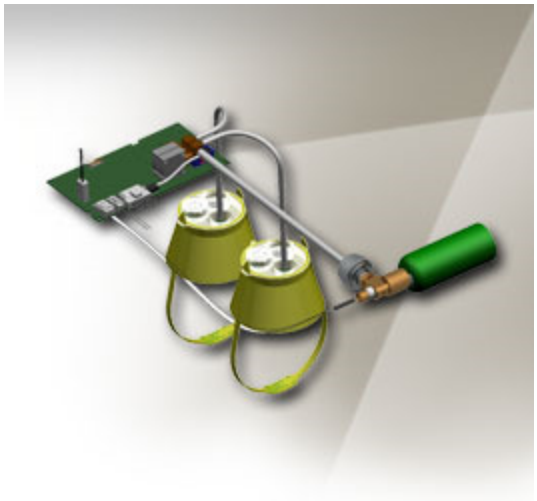


Figure 10.4: B/E Aerospace Pulse Oxygen Delivery System[48]

B/E Aerospace also produces a similar portable system for individual cases of oxygen deprivation. The small single lever design allows simple operation and only requires three AA batteries.

The BC-175 utilizes LED, or light emitting diode systems rely on large quantities of small bulbs to provide versatile lighting schemes. With the incorporation of B/E Aerospace's Mood Lighting System[49], interior cabin lighting will be able to achieve twice the brightness of current fluorescent systems with a choice of 16.7 million colors. Lighting color variation can be used to calm passengers, helping to relieve symptoms of jet lag. LED's also consume less energy compared to current lighting systems. The figure below pictures a cabin with the Mood Lighting System.

Figure 10.5: Boeing 787 Mood Lighting System[49]

10.2 Cockpit Layout

Modern aircraft are utilizing more digital technologies and replacing or replicating many analog buttons and instruments. An example is the Rockwell Collins MFD-2912 digital display pictured below.

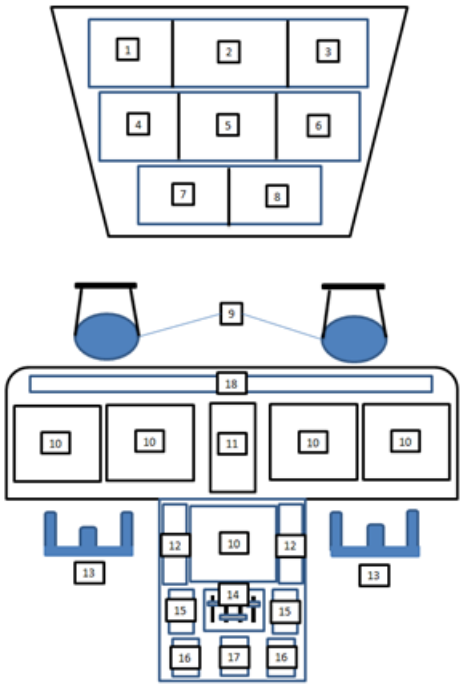
Figure 10.6: Rockwell-Collins MFD 2912 Digital Display[50]

This display can be used to view any aircraft data from control deflections to three dimensional weather patterns. Five of these will be incorporated into the BC-175 cockpit. Each pilot will have two monitors and a center console display allowing the monitoring of many different flight

systems simultaneously. In addition, the Rockwell Collins HGS-4000 will be installed[51]. The HGS or heads-up guidance system is a small transparent display that is situated between the pilot and the windshield. It displays vital information in the pilot's forward field of view. The figure below shows a Boeing 787 cockpit with the HGS and a similar five monitor set-up.

Figure 10.7: Boeing 787 Cockpit[52]

The following figure is a two-dimensional profile of the main instrument panel and center console. The majority of the analog controls have been incorporated into digital display system.



1	Electrical Controls
2	Hydraulic Controls
3	Fuel Controls
4	Pressurization Controls
5	Anti-Ice Controls
6	Cabin Controls
7	Air System Controls
8	Interior & Exterior Lights
9	Rockwell-Collins HGS
10	Rockwell-Collins MFR 2912
11	HGS Controls
12	Monitor Controls
13	Yoke
14	Power Levers
15	Flap & Spoiler Controls
16	Flight Management System Input
17	Engine Controls
18	Autopilot /Master Caution

Figure 10.8: BC-175 Cockpit Layout[53]

Controls such as throttle, autopilot, and deicing are in an optimum position for either pilot to monitor. The overhead instrument panel consists of storage area for manuals and remaining emergency, lighting, and cabin warning controls.

10.3 Flight Control Systems

The BC-175 control system is comprised of many new improvements over current aircraft. Current aircraft like the Boeing 737 or A320 use mostly hydraulics for control surface deflection. For the BC-175 electro-mechanical systems are used to deflect control surfaces using electric motors. These are lighter and require less maintenance than hydraulic controls. This results in an overall improvement in control reliability.

Other improvements include a new system for control signal transfer. As a modern adaptation of the fly-by-wire systems, fly-by-light relies on the same principles with enhanced

performance. Fly-by-wire is used in current aircraft where wires transmit signals from the flight controls, through the flight control computer, to the actuators. Wires can only transfer one way signals so an abundance of wires are necessary. Fly-by-light systems use fiber optic cables to transmit multiple signals through the same cable. The signals in a fly-by-light system are transferred by light waves which travel faster than electrical signals. Each cable is connected to an inline signal concentrator to condense thousands of electrical signals for optical conversion. Each conversion also produces redundant signals to ensure system integrity. Although an electrical to optical signal converter is required, the overall savings in weight are significant. Recent testing of fly-by-light was completed by Gulfstream, a subsidiary of General Dynamics[54]. The system replaced a wire bundle with only four fiber optic cables. By utilizing this system, the BC-175 will be safer and lighter than aircraft using fly-by-wire.

10.4 Electrical Systems

The electrical system of an aircraft provides electricity to all other aircraft systems. Several large components of the electrical infrastructure are discussed below.

The auxiliary power unit or APU is a central part of the modern aircraft. The APU is a small engine often used to power preflight systems and to start main aircraft engines. It can be used to supplement control power during flight or operate aircraft emergency systems during engine failure. In an effort to reduce system complexity, the BC-175 utilizes an APU system similar to that of the Boeing 787, using electrical controls rather than the common additional pneumatic load compressor.

The APU is a small turbine engine located in the tail of the BC-175. The APU will have an upper fuselage inlet and an exhaust out the tail. There will be two variable frequency electric

generators attached to the APU to be used for starting engines and electric power generation. The generators will also have to generate more electricity throughout the flight than the Boeing 737 or A 320 as a no bleed air system, the Hamilton Sundstrand APS5000, will be used. This APU produces about 1,100 horsepower. This will be used with the 6 electrical generators(two for each engine and two for the APU) which are rated at 225kVA. The system will use a 115/200v, 400Hz alternating current[55]. With comparable equipment to the 787, the system should produce around 1 megawatt of electrical power.

10.5 Pressurization

Most current aircraft such as the 737 and the A320 extract air from the engines to power pressurization. This air is pulled from the compressor stage of the engine where the air temperature is higher. This means current pressurized turbojet aircraft require intercooling to lower the temperature of the air. This results in additional weight for air tubing and a reduction in engine efficiency. To avoid these disadvantages, the BC-175 will use electric pressurization like the Boeing 787. Although there will be additional weight due to a larger APU and electric compressors, a safer, more reliable electrical system can be used.

In electric pressurization, air is extracted from the atmosphere and compressed through electronic compressors which are supplied power from the generators. The main difference in the power scheme to current aircraft is that the system is extracting direct shaft power from the turbine and creating electrical power rather than pneumatic power. This reduces system complexity. By using an electric system, the same goals are achieved as with pneumatic power in a less complex fashion[56].

10.6 Deicing System

Current aircraft such as the Boeing 737 and Airbus A320 utilize heated exhaust from the turbofan engines to melt ice. However, this can adversely affect the flow over the surface as well as reduce the engine's performance.

New deicing technologies such as electric heating mats can be used without bleed air. A company named GKN Aerospace has developed a heating mat to be used on various new aircraft[53]. The mat is a composite laminate made of layers of carbon and glass fibers with a metal conductive layer in the middle. The heat comes from passing an electric current through the metal layer. A picture of the system is shown below.

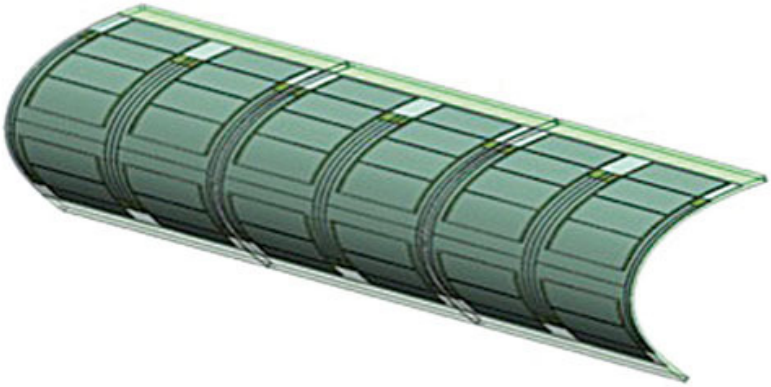


Figure 10.9: GKN Deicing Heat Mat[57]

Temperatures can reach anywhere from 45-70 degrees Fahrenheit and consumes about 45-75 kilowatts. The BC-175 will use the mats for deicing and for anti-icing to prevent any ice formation during flight.

10.7 Fuel Systems

The BC-175 fuel system is optimized to store Algae bio-fuels. To store this fuel larger fuel tanks are needed. Algae fuel requires about 1.08 times the tank volume compared to Jet-A. The fuel tanks are designed to utilize about fifty percent of the wing chord. The figure below is an airfoil with the approximate fuel tank in blue.

Figure 10.10: Wing Tank Location

Using Algae and the fuel weight determined in sizing, the volume needed is about 680 cubic feet. However, the FARs[30] require a two percent increase in volume to account for varying fuel density. Thus, the target volume for max range is about 694 cubic feet. Due to the landing gear, the tank starts at the fuselage and continues 40 feet into the wing. The wing tanks store about 287 cubic feet of fuel. An additional wing-box tank is needed for the remaining 407 cubic feet. The following figure shows the wing and fuselage fuel tank locations.

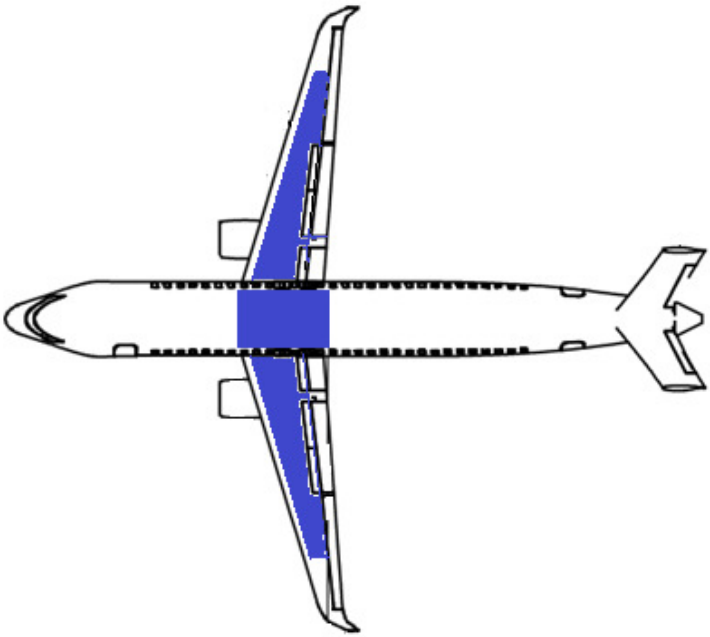


Figure 10.11: Fuel Tank Locations

10.8 Landing Gear

The landing gear for the BC-175 is designed to allow the aircraft to pitch during takeoff and landing and to support the aircraft. The tricycle configuration will be used which consists of two main gear and a nose gear. The main landing gear usually appear beneath the wing but are located a certain distance behind the total aircraft center of gravity. This distance is found using Raymer[8]. Raymer states that the angle between the vertical at the landing gear and the CG location must be around 15 degrees to allow the aircraft to pitch during takeoff. This angle allows for sufficient rotation. Using this method the angle to the main gear was set at 14.3 degrees. This means the landing gear is 56.6 feet aft of fuselage station zero, 2.7 feet aft of the CG.

The tailscrape angle is the angle between the ground and the aircraft bottom from the main gear. This must be larger than the required angle of attack for takeoff and landing. This is shown on the figure below.

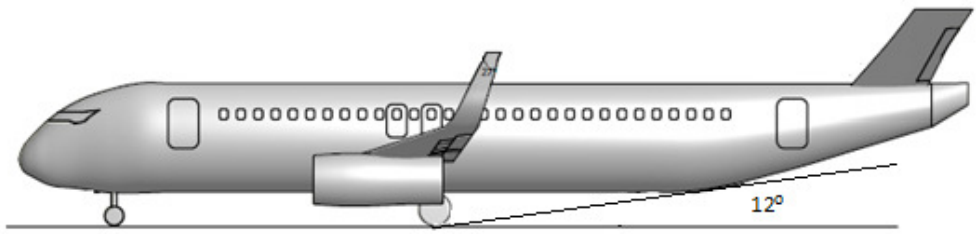


Figure 10.12: BC-175 Right Side View

Another consideration is the rollover or overturn angle. This is the angle between the CG and the ground at the main landing gear. Raymer states that the angle must be less than 63 degrees for tricycle landing gear. The rollover angle is about 50 degrees for the BC-175 as pictured below.

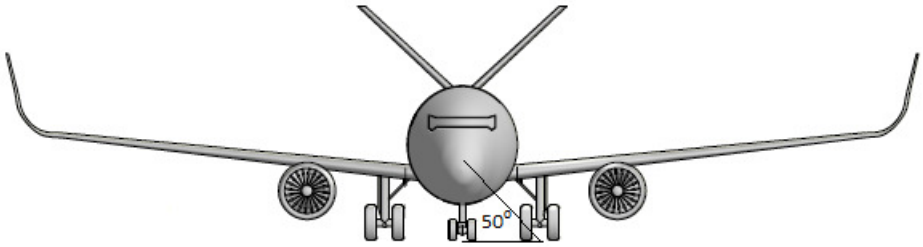


Figure 10.13: BC-175 Front View

Further analysis was done to determine the approximate tire sizes. Using Raymer's statistical tire sizing in Chapter 11, the load on the gear and the coefficients for transport aircraft were determined. When satisfying the angle requirements, it was found that the nose gear should hold about 7.5 percent of the TOGW and the main gear split the rest. This results in about 9,375

pounds-force on the nose gear and about 57,812 pounds-force on each main gear. Each gear has two wheels. The approximate size of the main gear tires for the BC-175 is a 42 X 15, where the first term is the diameter in inches and the second is the width in inches. The nearest manufactured size is the 46X16. The approximate size of the nose gear tires is 25 X 8.8. The nearest manufactured size is 30 X 8.8. All tires are rated for 225 miles per hours, well above the max takeoff or landing velocities.

10.9 Noise Reduction

The RFP requests a reduction in noise emissions along with an overall increase in efficiency and performance. When considering noise, the common transport aircraft produce the most noise during takeoff and landing. The largest contributors to noise are the engine, high-lift devices, landing gear and the airframe. There are numerous technologies to reduce noise.

The turbofan engines used on most jet transports are the leading noise producers. Thus, there is significant research being done to reduce engine noise through more efficient engines and nacelles. Goodrich Aerospace has designed a new more aerodynamic nacelle to be used on the Boeing 787.

Figure 10.14: Boeing 787 with Goodrich Nacelle[58]

Figure 10.14 shows a constant paint scheme over the nacelle keeping the surface as smooth as possible to insure laminar flow is maintained. The most noticeable features are the trailing edge chevrons. The chevrons, constructed of a shape memory alloy, deform during flight with temperature change. The spiked design generates trailing edge vortices to help mix the flow over the nacelle with the high temperature engine exhaust helping to reduce noise[59].

Landing gear noise production comes mainly from the awkward non-streamlined structure. Air simply collides with the gear, strut, and wheel sections causing flow detachment, resulting in noise. Thus, the best way to reduce noise is reduce separation or production of turbulence through the use of fairings. Fairings are effectively caps that cover intricate high noise sections of the landing gear system helping reduce noise. An experiment was performed on an A340 landing gear with fairings finding that up to a 3 decibel reduction can be achieved[60]. Pictures of the test configuration are shown below. The top photo is the standard main landing gear and the bottom photo is the main gear with fairings over the wheel connection and the leg-door connection.

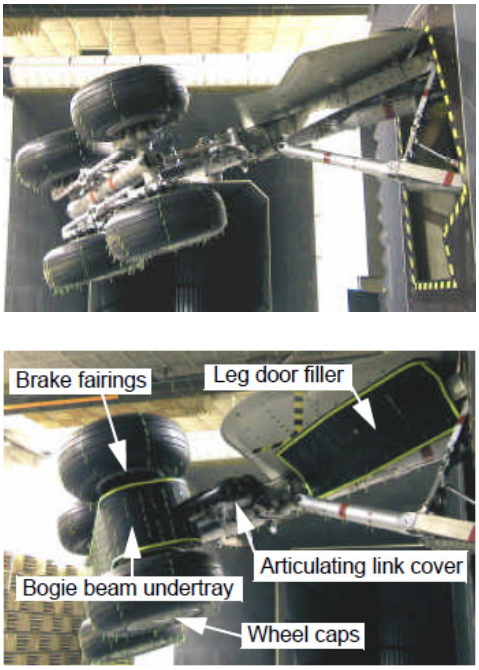


Figure 10.15: A340 Main Landing Gear Noise Test Configuration[60]

10.10 Airport Systems

The BC-175 will use an Algae-based Biodiesel. Because the fuel is not widely used, a new system will have to be considered. However, since the Algae-based Biodiesel is similar to Jet-A in density and energy content there will not be significant changes. The fuel system will remain relatively unchanged except for methods of fuel distinction. Since a new type of fuel is being introduced, it will have to be distinguished from other fuels so minor changes such as new fuel nozzles and labeling will be used. Fuel nozzles for Algae tanker trucks and aircraft will be shaped differently as to not fit into other aircraft. This will reduce refueling error and help make the change to Algae simpler. The actual fuel transport process will remain the same; below is a schematic of current fueling schemes.

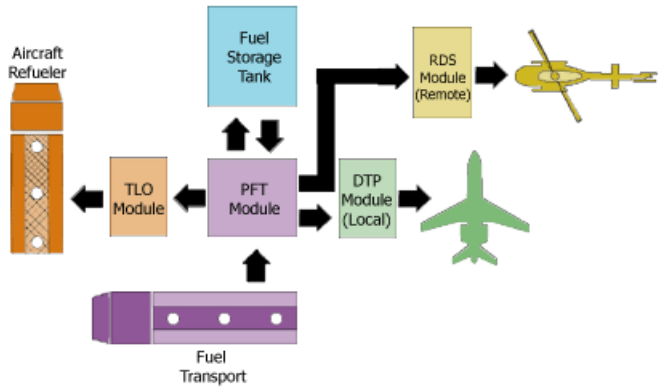


Figure 10.16: Airport Fueling System[61]

The figure shows a system including an onsite fuel storage tank, direct-to-plane fueling (DTP), pump and filtration (PFT), remote dispensing (RDS), and refueling truck loading (TLO).

The BC-175 fuel system is based on current fuel systems with slight modifications like larger aircraft tank sizes for the storage of Algae-based biodiesel. From the fuel tank sizing, the BC-175 will carry 4,550 US gallons. Current Jet-A airport tankers store up to 5000 gallons and have pump rates up to 600 gallons per minute. This will result in common refueling times of about 7.5 minutes.

Figure 10.17: 5,000 Gallon Jet-A Refueler with 300 GPM Pump System[62]

10.11 Cargo

The RFP requires at least 1240 ft^3 of cargo space for passenger luggage. This includes carry-on and luggage storage below the deck. For carry-on storage compartments, the maximum standard size is 9 by 14 by 22 inches or about 1.605 ft^3. Thus for 175 passengers plus an additional free space, the carry-on compartments will store about 300 ft^3. The below the deck storage will be about 1000 ft^3. The below the deck storage compartments are located below the front entrance to the wing root and below the rear exit to the wing trailing edge. Loading will start at the entrance storage area. The aircraft will be able to use cargo containers or manual bulk loading. Cargo containers allow quicker loading times decreasing cost. The cargo containers to be used are the LD-3-45 pictured below.

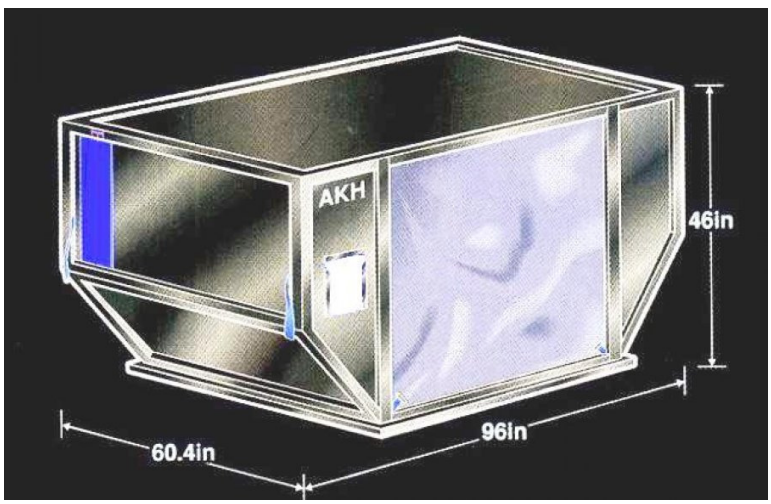


Figure 10.18: LD3-45 Cargo Container[63]

Each container stores about 124 ft^3 of luggage. Therefore, a maximum of ten containers are needed if no onboard storage is used. This will take up about 50 ft of the fuselage length for cargo leaving additional space for other systems. Specifically, cargo will be loaded starting 15

feet aft of the nose to about 40 ft aft of the nose. The remaining half of the containers will be loaded from behind the wing at about 65 ft to 90 ft.

11. Cost

The cost of this aircraft must be competitive with current aircraft to be profitable. These costs consist of the flyaway and life cycle costs that a potential buyer would consider before deciding to purchase an aircraft.

11.1 Life Cycle Cost

The life cycle cost of a program consists of the costs of research, development, testing and evaluation (RDTE), acquisition, operation and support, and the disposal of the airplane. Aircraft disposal consists of 10% of this total cost. The cost was estimated using Roskam's cost estimating method from *Airplane Design Part VIII*[64].

11.2 Research, Development, Testing, and Evaluation

RDTE covers the planning, design, development and testing of the aircraft. The dollar rates used in the RDTE phase are shown in table 11.1. In this period, 104 million man hours were required. Four aircraft were assumed to be used for this phase, two static test aircraft and two flight test aircraft. Overall, the total cost of the RDTE phase was 1.23 billion dollars.

Table 11.1: Research, Development, Testing and Evaluation Rates

RDTE	Rate USD/hr
Engineering Dollar	104.81
Manufacuring Dollar	58.42
Tooling Labor Dollar	75.60

11.3 Acquisition

The acquisition cost of the aircraft is based on the number of aircraft to be produced, the manufacturing cost of these aircraft, and the profit that the company expects to make. For this study a 500 unit production run was assumed with a ten percent profit and another ten percent going to financing. The total acquisition cost was found to be 20 billion for this production run. This cost combined with the RDTE cost results in a cost of 42.53 million dollars per aircraft.

11.4 Program Operating Cost

The operating costs of an aircraft are divided into direct and indirect costs. Direct operation costs (DOC) are those that are incurred as a direct result of aircraft use. Indirect operating costs (IOC) are a result of commercial airline operations. As such this cost indicates to the airline the cost of each flight that an aircraft makes. For these calculations the range is assumed to be 3500 nm with the aircraft performance as predicted in Section 6. This results in an operating cost of $81,081 per trip with the biofuel assumed to be $4.00 a gallon.

Table 11.2: Passenger Airline Systems (Cents per Available Seat Mile)[65]

Airline Group	3rd Quarter 2007	4th Quarter 2007	1th Quarter 2008
Network	13.6	14.5	15.3
Low-Cost	9.6	9.5	10
Regional	14.7	14.9	16.3
21-Carrier Total	**12.8**	**13.6**	**14.4**

Table 11.2 shows airline financial data from the Bureau of Transportation Statistics. When this data was collected jet fuel was $2.50 a gallon. The cost per seat mile at that time was on average $0.136. For the BC-175 the cost per seat mile is $0.132 with a higher fuel cost. This

indicates that our aircraft can successfully compete with the current aircraft market in the cost to the airline.

12. Conclusion

Biojet began its design of the BC-175 by comparing similar 175 seat commercial airliners that are currently in service, resulting in the two initial designs. After a comparison of the two designs the tube and wing concept was chosen. The design was then sized based on the RFP specifications.

The BC-175 utilizes a combination of new engines, and advanced aerodynamic and material technology to satisfy the RFP requirements. The aircraft carries 175 passengers in a one class configuration and can carry 1300 cubic feet of cargo between the overhead compartments and the LD3 containers in the cargo hold. The aircraft has a maximum range of 3,500 nm, meeting the 3500 nm required in the RFP. The wing was designed such that a maximum *L/D* of 27 can be achieved, exceeding the 25% increase required by the RFP. This wing allows for a cruise Mach of 0.8 and for a landing speed of 124 knots. The takeoff field length is 5390 feet, well below the 8000 foot requirement. The BC-175 will be certifiable to appropriate FARs for entry into service in 2020. The BC-175 is able to meet and in many cases surpass the requirements provided in the AIAA RFP.

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