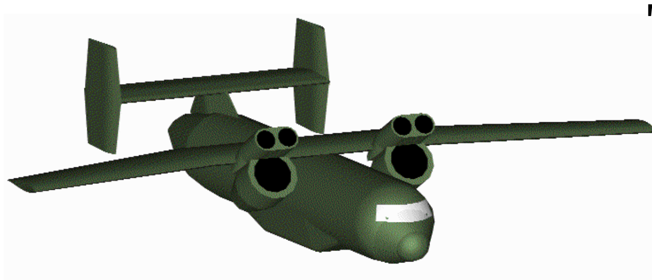
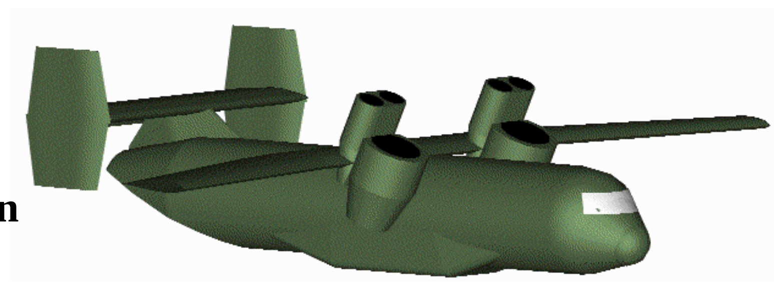
Virginia Tech
Aerospace Engineering

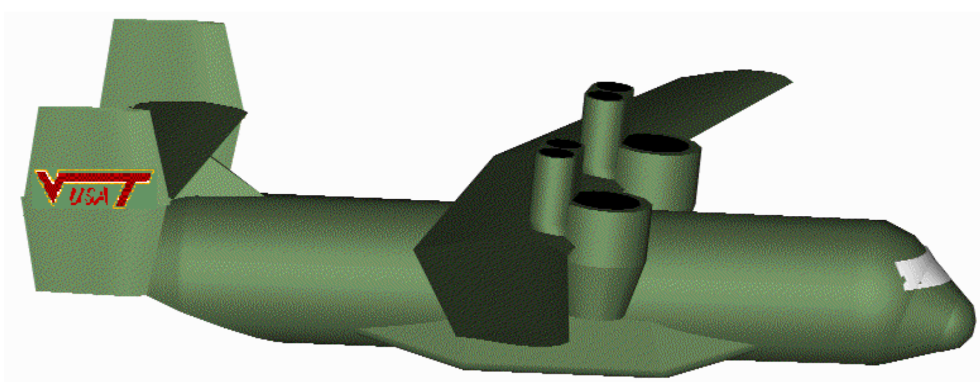
The Skyhopper





1998/1999 AIAA Undergraduate Team Aircraft Design Competition

SSTOL Carrier On-Board Delivery (COD) Aircraft



Acknowledgements

The members of VTUSA would like to thank our friends, families, and roommates for their continuous support and patience through the long nights and stressful days in which the Skyhopper was created. We would also like to extend our appreciation to our faculty advisors, Dr. W.H. Mason and Mr. N. Kirschbaum. Without their guidance, assistance, and Mr. Kirschbaum's endless supply of handouts, the Skyhopper would have never reached the level of excellence that it has attained.

1998/1999 AIAA Team Aircraft Design Competition

Virginia Polytechnic Institute and State University

May 15, 1999

Designer's Name	Signature	AIAA Membership Number
Matt Coffin (Team Leader)	________________________	148337
Jerry Ammann	________________________	181932
Paul Burnette	________________________	183483
Alex Edwards	________________________	167786
Mike Henry	________________________	183617
Randy Hutchison	________________________	146436
Mark Nelson	________________________	183748
John Smyth	________________________	183612
Kevin Waclawicz	________________________	183492

Faculty Advisors

W.H. Mason ________________________ N. Kirschbaum ________________________

Executive Summary

VTUSA is proud to present the Skyhopper for the 1998/1999 AIAA Undergraduate Team Aircraft Design Competition for a SSTOL Carrier On-Board Delivery (COD) Aircraft. The aircraft was designed as a dual use transport aircraft for commercial regional commuter purposes, and as a Navy COD replacement for the aging Grumman C-2A Greyhound.

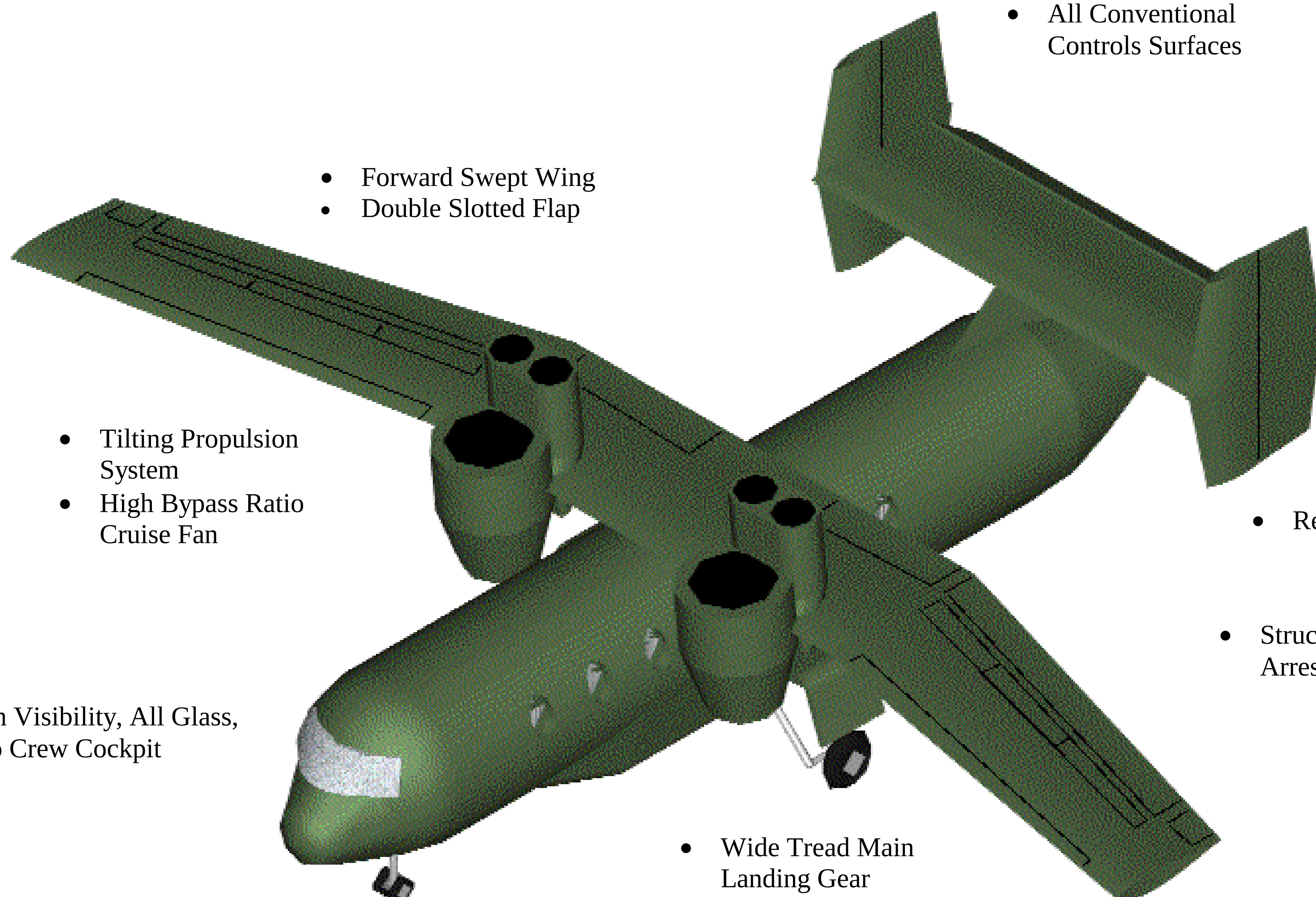
The Skyhopper is designed for takeoff and landing ground runs of 300 and 400 feet respectively, making the aircraft a true SSTOL design. With a minimum range of 1500 nautical miles, and cargo capacity for 2 GE F110-400 engines (for the F-14D) or 30 commercial passengers, the aircraft is an ideal medium range transport for commercial and Naval aviation.

There were three main design hurdles encountered during the Skyhopper's design process. The first was the capability for short distance takeoff and landing. Second, the attainment of efficient propulsive and aerodynamic cruise performance, with a configuration based on SA plus 27° F day SSTOL conditions. The third obstacle to overcome was the overall aircraft size restrictions for carrier suitability. In addition, the design of a dual use military and commercial aircraft proved to create many challenges.

The main difference between versions is a rear loading cargo door for the military version, and a conventional tail cone shape for the commercial version. The high lift system is a combination of powered lift from tilting engines, and a full span double slotted flap system on the wing. The wing was placed above the fuselage, and swept slightly forward to increase low speed control. The propulsion system features two advanced tip turbine cruise fans, powered by four Rolls Royce Adour Mk. 781 gas generator engines. High takeoff thrust, cool exhaust temperatures, and efficient cruise performance were deciding factors in its selection. This system was derived from a 1965 General Electric propulsion system based upon the lift fan system for the experimental Ryan XV-5A VTOL aircraft. Wing folding was added to the military version to meet carrier storage requirements. Also, an H-shaped tail arrangement was necessary to avoid tail folding due to height restrictions.

The Skyhopper is an innovative design, blending the features of a conventional transport with an unconventional VTOL aircraft. Overall, the Skyhopper is a capable combination of two radically different aircraft, and thus is the best solution for a SSTOL commuter and Navy COD aircraft.

The Skyhopper



- Fly-By-Wire Controls
- Small CG Range
- All Conventional Controls Surfaces
- H Tail Section with Double Elevator, Common to MIL/CIV Versions
- Forward Swept Wing
- Double Slotted Flap
- Tilting Propulsion System
- High Bypass Ratio Cruise Fan
- Rear Cargo Door – Military
- Structural Provisions for Arresting Hook – Military
- High Visibility, All Glass, Two Crew Cockpit
- Wide Tread Main Landing Gear
- Meets Navy Turnover Requirements
- High Component Commonality Between Mil/Civ Version
- High Content Aluminum Structure to Facilitate Repairs At Small Fields and Carriers

Type: SSTOL COD, Medium Range Transport

Wings: High, Forward Swept

Fuselage: Conventional semi-monocoque construction primarily of aluminum.

Tail Unit: H-Tail, Modular build, Military- Cargo door; Civilian – Slimmer Tail Cone.

Landing Gear: Retractable tricycle type. 2 main wheels 40"x14". 2 nose wheels 22"x6.6-10". Steerable nose wheel.

Powerplant: 4 Rolls Royce Adour Mk. 781 turbofans powering two 76" diameter Cruise fans. System derived from 1965 GE design for the Ryan XV-5A.

Accommodations: Two crew member flight deck. Military – 30 passengers aft facing; two GE F110-400 engines; three 468L Pallets; 16 Medevac stretchers, 2 crew.
Civilian – 30 passengers forward facing, 1 flight attendant, galley, lavatory.

Dimensions, External:

Wing Span:	63.7 ft
Length overall:	60 ft
Height overall, mil/civ:	22/21.5 ft
Wheel track:	40.4 ft
Wheelbase:	16.7 ft

Areas:

Wing:	582 ft^2
Horizontal Tail:	263 ft^2
Vertical Tail:	208 ft^2
Lift Dumpers/Spoilers:	31.7 ft^2
Elevators:	93.9 ft^2
Ailerons:	12.0 ft^2
Rudder:	98.8 ft^2

Weights:

Civ. Empty:	25,619 lbs
Civ. TOGW:	45,959 lbs
Mil Empty:	27,764 lbs
Mil TOGW:	52,214 lbs

Cost:

Flyaway Civilian:	$22.8 Million
Flyaway Military:	$23.6 Million

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Nomenclature

Symbols

a	Acceleration
AEW	Airborne Early Warning
AR	Aspect Ratio
ASW	Anti Submarine Warfare
C	Thrust Specific Fuel Consumption
C_{DO}	Parasite Drag
C_D	Drag Coefficient
C_l	2-D Lift Coefficient
C_L	3-D Lift Coefficient
C_{La}	Lift Curve Slope
C.G.	Center of Gravity
COD	Carrier On-Board Delivery
D	Drag
d	Distance
FAR	Federal Aviation Regulations
g	Acceleration due to gravity
Kg	Gust alleviation Factor
L	Lift
L/D	Lift to Drag Ratio
M	Mach Number
n	Load Factor
P	Pressure
RFP	Request for Proposal
S	Wing Reference Area
SA	Standard Atmosphere
SR	Specific Range
SSTOL	Super Short Takeoff and Landing
T	Thrust
T	Temperature
t	Time
t/c	Thickness to Chord Ratio
TOGW	Takeoff Gross Weight
TSFC	Thrust Specific Fuel Consumption
Ude	Equivalent Gust Velocity
V	Velocity
Ve	Equivalent Velocity
W	Weight

Greek Symbols

α	Angle of Attack
$\alpha*$	End of Linear Lift Curve Slope
δ	Deflection
δ_ε	Elevator Deflection
Δ_{CL}	Change in Lift Coefficient
Λ_{LE}	Leading Edge Sweep
θ	Engine Vector Angle
μ	Mass Parameter
ρ	density

Subscripts

app	Approach
b	braking
B	Rough Air
C	Cruise
cr	Cruise
D	Dive
LOF	Liftoff
MAX	Maximum
p	Powered
SL	Sea Level
sn	Maneuver Stall
TD	Touchdown
TO	Takeoff
eff	Effective

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1. Overview

1.1. Introduction

For nearly fifty years, the desire to develop a means of air transportation from city center to city center has been sought by the commercial transportation industry. Traditionally this type of transportation, with a few exceptions, was restricted to vehicles capable of vertical takeoff and landing. Hence, the helicopter was the only vehicle capable of meeting this criteria. The development of tilt rotor aircraft such as the Bell-Boeing V-22 and the Bell 609 has increased expectations for this type of travel. Despite the high expectations held for these "convertiplanes," problems associated with costs and liabilities continue to restrict further development in this area.

The main constraint on center city service is the limited space for an aircraft to land or takeoff. When compared to a conventional aircraft, a super short takeoff and landing (SSTOL) aircraft has a reduced noise footprint and thus would affect a smaller area as seen in Figure 1.1. Coupled with the decreased noise footprint, the shorter takeoff and landing distances allow for conveniently located airports. The fact that many large cities are located near a river or some large body of water has raised the idea for developing "barges" to provide an operating site. The use of a short landing barge would avoid a costly construction project in a downtown area. A planned SSTOL aircraft would operate from the barge site. It has been envisioned that this aircraft would provide an efficient means of city center to city center transportation. A SSTOL aircraft will avoid foreign object damage (FOD), hot exhaust gas ingestion and other problems associated with vertical takeoff and landing (VTOL) aircraft.

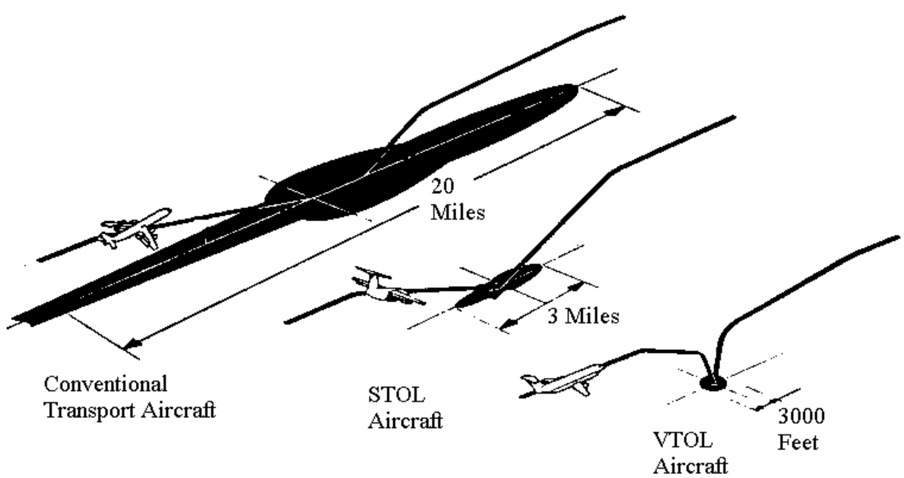


Figure 1.1 - General Noise Footprint Areas (Kohlman[1.1])

In addition to the demand for a SSTOL aircraft for civil use, there is also a demand for a military aircraft with similar requirements. The only existing transport used for carrier on-board delivery (COD) is the C-2A Greyhound which has been in service for over thirty years. The Navy is in search of a replacement aircraft capable of operating on carriers without the use of arresting hooks, heavy-duty landing gear, or catapults. This proposed Navy mission calls for an aircraft with a similar payload and range to the civilian commuter aircraft. Hence, an aircraft design that can perform both tasks would be preferred.

The purpose of this proposal is to describe a dual use SSTOL transport aircraft design, capable of performing either military or civilian missions. The nature of a “two aircraft in one” design would likely benefit in reduced design and life cycle costs.

1.2. AIAA RFP

The AIAA RFP states, “The objective of this project is to design a dual-use SSTOL transport aircraft capable of carrying cargo, and/or passengers for commercial city center to city center service and for carrier on-board delivery for the Navy.” The design concept must obtain this primary objective while fulfilling a variety of requirements and constraints stated by the RFP. It permits the assumption of a technology availability date of 2005, but emerging technologies should be shown to be practical and technologically mature. The design must meet all requirements at standard sea level atmospheric conditions (T_{sl} = 58.69°F, P_{sl} = 2,116 lb/ft^2) unless otherwise noted.

DESIGN MISSION PROFILE

- Warm up and taxi for 10 minutes, at sea level standard atmosphere + 27°F day.
- Takeoff within a ground roll of 300 feet, at sea level standard atmosphere + 27°F day, with full passenger and baggage load.
- Climb at best rate of climb to best cruising altitude.
- Cruise at best speed (at least 350 knots) for 1500 nmi.
- Descend to sea level (no credit for range).
- Land with domestic fuel reserves within ground roll of 400 feet.
- Taxi to gate for 5 minutes.

Figure 1.2 is a graphical representation of the design mission profile.

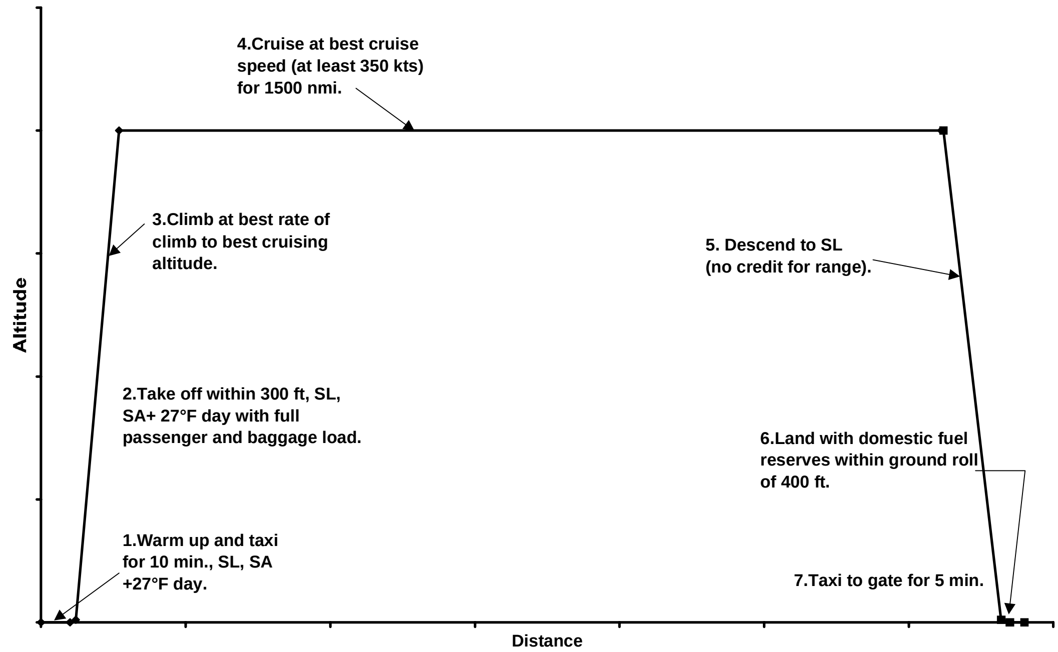


Figure 1.2 - RFP / Design Mission Profile

In addition to meeting the design mission profile shown in Figure 1.2, both the commercial and military designs are subjected to special design requirements.

COMMERCIAL REQUIREMENTS

- Passenger capacity – 24 passengers (commercial) and baggage at a minimum 32 inch seat pitch.
- Overhead stowage space shall be provided
- Weight of passenger and baggage – 200 lbs.

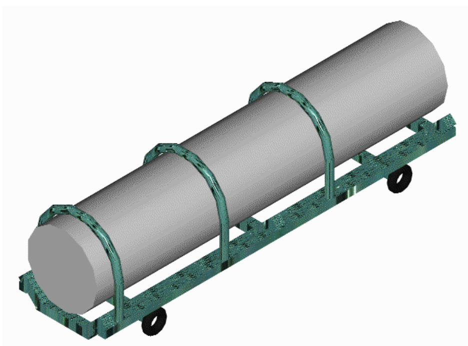
The commercial design must also conform to applicable FAR requirements for this type of aircraft.

MILITARY REQUIREMENTS

- Can accommodate priority cargo, passengers or both.
- Must be capable of carrying two GE F110 engines (for F-14D) (Figure 1.3).
- Wing folding allowed to meet spot factor requirements of 60 feet by 29 feet.
- Maximum payload is 10,000 lbs.
- Arresting hooks for landing or catapult devices for launch not allowed.

The Navy military design must also conform to applicable MIL requirements for this type of aircraft.

The RFP requires the aircraft to be able to stow two GE F110 engines for the F-14D. There are three versions of the GE F110 engine; the -100, -129, and -400. The -100 and -129 are used in F-16 variants. The difference between the three engines is that the -400 engine has a much longer augmentor duct for installation in the F-14D. The longer augmentor duct increases the overall length of the engine to just under 20 feet (as opposed to 15.1 feet for the -100 and -129). When coupled with the spot factor requirements (60 feet by 29 feet) the extreme length of this engine plays an important role in determining cargo area dimensions. Figure 1.3 is a rendered idealization of the GE F110-400 engine for the F-14D with its support carriage.



<u>GE F110-400 Engine Characteristics:</u>
Length – 232.3 in (19.4 feet)
Maximum Diameter – 46.5 in (3.9 feet)
Weight – 4,400 lbs.

Source: Aviation Week Aerospace Source Book 1999

Figure 1.3 - GE F110-400 Engine with Carriage

1.3. Additional Constraints

In addition to the RFP spot factor requirements for carrier use, the aircraft will also be limited to typical on-board restrictions of 82 feet span, and 80,000 lbs. maximum gross weight. For Navy carrier suitability the maximum folded height is not to exceed 18.5 feet. However, most of the three-deck hanger bay has a height of 25 feet. This is for the main deck, 01 level, and 02 level obtained from Air and Space[1.6], and hull inboard profiles for post CVA/N 60 carriers (Naval Air Report[1.4]). The only locations in the hanger deck that are not 25 feet in height are at small areas away from the lifts where auxiliary fuel tanks and other equipment are hung from overhead areas (Kirschbaum[1.3]). To account for maneuvers over hanger bay bumps and push-pulling rough stops, the maximum folded height will be limited to 23 feet. These constraints are only applicable to the Navy design.

An additional in-house design team constraint for the commercial design will be a maximum longitudinal acceleration limit of 0.4 g. This upper acceleration limit was chosen primarily for the comfort of most passengers during takeoff and landing. This limit was selected by constructing a study of the acceleration a passenger might be subjected to in common types of transportation seen in Figure 1.4.

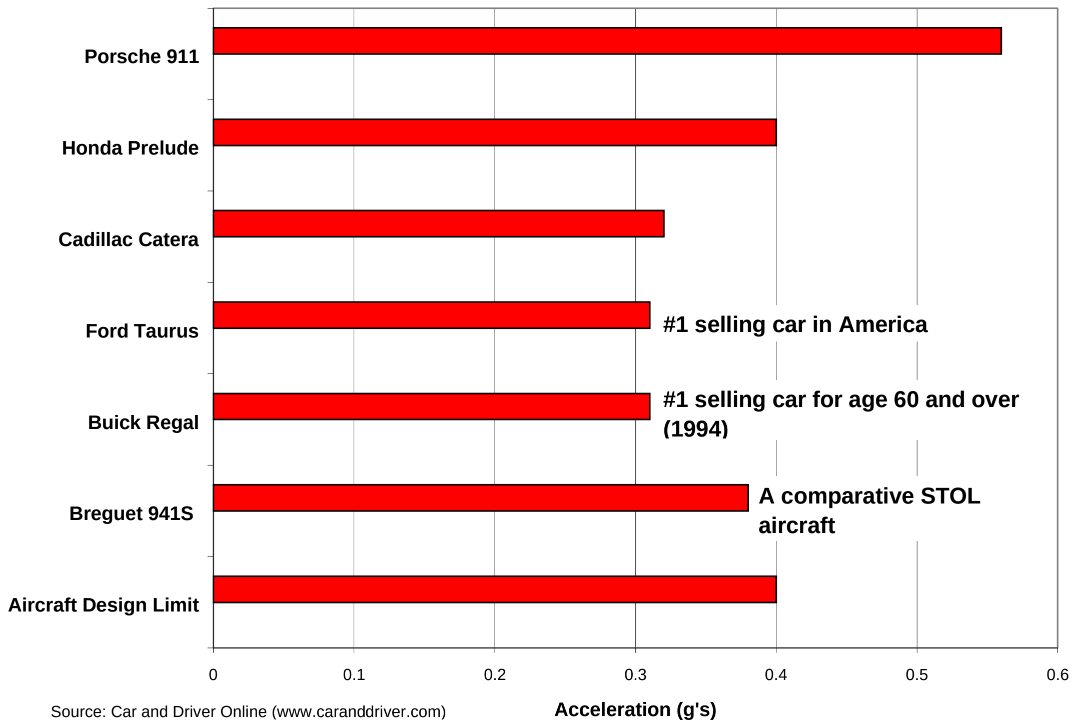


Figure 1.4 - Acceleration Comparison

The number one selling American car, the Ford Taurus, and the number one selling car for people over the age of 60 were set as the base level of the study. The limit was raised above the 0.31 g maximum acceleration of these vehicles because it is believed that a passenger would be expecting a higher acceleration given the special nature of the aircraft. It is believed that the average and/or elderly person would not worry about riding in a Honda Prelude (maximum acceleration of 0.4 g). Although the maximum acceleration of a passenger car is rarely utilized, the potential is there. A comparative STOL aircraft, the Breguet 941S had a maximum acceleration of about 0.38 g on its takeoff run (Quigley[1.3]). In addition, the "tolerance of commercial passengers to deceleration, is generally agreed to be something less than 0.5 g" (Kohlman[1.1]). A 0.4 g acceleration is equivalent to a 0 to 60 mph acceleration in 6.8 seconds. This is not believed to be excessive. Both the acceleration on takeoff and the deceleration upon landing will be limited to a maximum of 0.4 g for the commercial aircraft only.

1.4. Comparative STOL Aircraft Study

Currently there are two transport aircraft that the military uses for short takeoff and landing purposes. These consist of the Grumman C-2A Greyhound, which has been in operation since 1966, and the Bell-Boeing V-22 Osprey, which is currently in flight test. The Breguet 941S was designed as a STOL transport for civilian use when it was introduced in 1967. While these three aircraft proved to be great STOL aircraft for their time, none of them meet all of the requirements of the RFP for this particular design.

The twin turboprop Grumman C-2A Greyhound was first introduced in fleet service in 1966 and has served the Navy as a Carrier Onboard Delivery (COD) aircraft faithfully since. Although the Greyhound was an effective STOL aircraft it was never modified for commercial use. The C-2 has a wingspan of 80.5 feet, an overall length of 56.5 feet and is powered by two 4910 SHP T56-A-425 turboprop engines. This aircraft can takeoff in a distance of 2,180 feet and land in a distance of 1,428 feet, while carrying a maximum payload of 10,000 lbs. When taking off from a carrier deck the C-2A requires a catapult to accelerate to takeoff speed, and an arresting hook to stop when landing. The turboprop engines limit the C-2A to a maximum cruising speed of 260 knots and a range of over 1,040 nautical miles. The Greyhound can carry a maximum of 32 military personnel, or various combinations of passengers and cargo. This aircraft also meets the RFP stowage requirements because it is used as a carrier transport. The C-2A does not meet the RFP for takeoff and landing because it uses the catapult and arresting hook systems; and as noted, it does not meet the minimum cruise speed and range requirements.

The newest COD aircraft is the Bell-Boeing V-22 Osprey. This recently introduced aircraft can perform a wide range of missions. Initially designed for the military, Bell-Boeing has plans to produce a commercial transport as well. This aircraft has two large 6000 SHP T406-AD-400 turboprop engines that can rotate between 0° and 95° to provide vertical takeoff and landing. The Osprey has a wingspan of 51 feet and a length of 57 feet. When in STOL mode, the V-22 can takeoff in a distance less than 500 feet, with maximum payload. When taking off and landing vertically, the V-22 has a maximum payload of 12,000 lbs. Again the turboprop engines limit the V-22 to a maximum speed of 314 knots and a range of 1800 nautical miles. The Osprey meets the RFP for number of passengers at 24. Therefore, the only RFP requirement that this aircraft fails to meet is the minimum cruise speed of 350 knots.

One of the first STOL aircraft was the Breguet 941S. This aircraft was originally designed to benefit commercial transportation by making short-range city to city travel possible. This design used four turboprop engines to provide blowing over triple slotted flaps and ailerons. This aircraft had a wingspan of 77 feet and an overall length of 78 feet. With a maximum payload of 22,000 lbs., the 941S was able to takeoff in approximately 600 feet and land in a distance of 345 feet. Due to the turboprop engines this aircraft's maximum cruise speed was only 251 knots, with a range of 539 nautical miles. Since the Breguet 941S was proposed as a commercial aircraft, it could accommodate 57 passengers. This early design could only meet three of the RFP requirements; the landing distance, maximum payload, and passenger capacity**.** Figure 1.5 contains graphical comparisons of performance characteristics of historically similar aircraft

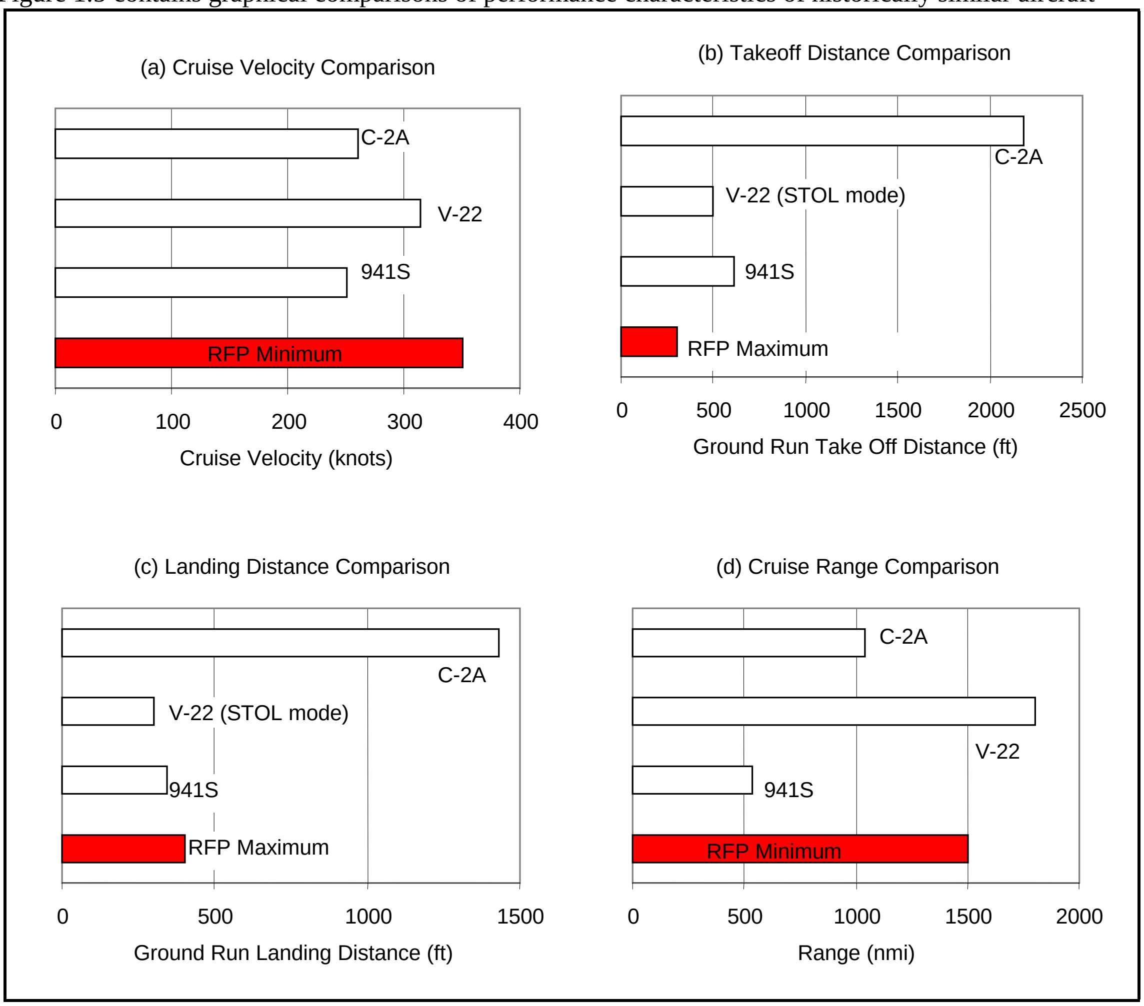


Figure 1.5 - Comparative studies on (a) Cruise Velocity, (b) Takeoff Distance, (c) Landing Distance, and (d) Range

to the RFP requirements of this design proposal. All the characteristics of the comparative aircraft were obtained from various issues of *Jane's All the World's Aircraft*.

1.5. Design Drivers

Analysis of the RFP requirements and additional factors regarding military and commercial transport aircraft led to six elements that influenced initial design concepts. The following six drivers are:

1) Maximum takeoff distance of 300 feet: This requirement forced the designs to consider three main issues. First, a large thrust to weight ratio, *T/W*, would be needed to achieve high accelerations for reasonable takeoff speeds. Second, the thrust would most likely have to be vectored. The wings alone could not provide sufficient lift for takeoff and thrust vectoring would have to be used to augment the aerodynamic lift. Third, the importance of a relatively high lift coefficient. Higher lift coefficients could reduce the needed *T/W* ratios and vector angles. Mechanical devices such as double or triple slotted flaps, or aerodynamic techniques like circulation control or over-the-wing blowing, could be used to increase the lift coefficient.
2) Range of 1,500 nmi and minimum cruise speed of 350 knots: To achieve these requirements, three important priorities were established. The first is the desire for a clean fuselage to reduce the parasite drag levels. Secondly, a high wing loading is desired for long range flight. Third, efficient engines are needed to reduce the amount of fuel needed, and thus the overall weight. High bypass turbofan engines are probably preferred because of decreasing propeller propulsive efficiency above 350 knots and their good lapse rate with altitude (the minimum cruise speed).
3) Cargo area dimensions and characteristics: To stow two GE F110-400 engines and their support equipment in a tandem position, the minimum fuselage cabin dimensions must be about 40 feet in length; 7 feet in height; and 5 feet in width. The cargo area for the military version also has to be quickly interchangeable to accommodate cargo, passengers, or both.
4) Human Comfort: The main importance of this driver is the 0.4g acceleration limit on the passengers for the commercial version aircraft. This limits the takeoff speed of the aircraft to a maximum of 52 knots (88 ft/s). A secondary effect of this limit is to promote the use of thrust vectoring. This design driver has no effect on the military version. Additional comfort

factors include the passenger seating arrangements, aisle widths, and the incorporation of flight attendants, galley and lavatory.

5) Safety: The main safety factors for this aircraft are engine out capabilities, and low speed control. The engine out capability is important because of the low takeoff speeds, and the operation of the aircraft over water. Low speed control of the aircraft is needed due to the low takeoff and landing speeds. Some possibilities for safe operation at low speeds include vectored engine thrust roll, yaw, and pitch control, and large control surfaces.
6) Affordability: To produce a transport aircraft without undue economic compromises two aspects are important. The first is that a successful commercial aircraft will differ from its military version. To minimize this effect on cost, a modular design must be developed. With a modular design, fabrication of both aircraft versions will be similar and affect cost for the smaller Naval buy slightly. A second motive to attain affordability is to use off-the-shelf components. Incorporating existing engines or propulsive components, avionics systems, and other items into the design can reduce research and development costs. Existing systems already proven in the field should also reduce maintainability costs.

These drivers summarize what the RFP demands, a medium range transport aircraft for commercial and military use, capable of taking off and landing in extremely short distances.

1.6. Alternate Missions

The demands for a commercial commuter and a Navy COD aircraft alone provide a sufficient market for a STOL aircraft. However, with its versatility, such an aircraft could be used for many other purposes.

ADDITIONAL APPLICATIONS

1) A capability of the aircraft could be to combat forest fires. Modifications could be made to store water or other fire suppression materials. The inherent slow flight speeds of the aircraft would then be utilized to unload the suppression materials with superb accuracy. The low landing and takeoff footprint would allow operations closer to the scene and thus more load drops per hour.

2) An emergency supply and evacuation aircraft with SSTOL capabilities would be a considerable asset for both the military and humanitarian organizations. A SSTOL aircraft could operate in devastated areas of the world where fully equipped airports are not accessible. Cleared off roadways or fields could provide sufficient takeoff and landing distances for operation. The aircraft could also operate from crippled aircraft carriers, where its greater range and speed with respect to helicopters would provide faster evacuation of wounded personnel.

ADDITIONAL NAVY APPLICATIONS

1) The Navy COD version could be modified to carry sonar buoys and torpedoes in an Anti-Submarine Warfare (ASW) mode. The low flight speeds and carrier operability of the aircraft could provide protection for a carrier battle group. This version of the aircraft would supplement the current ASW carrier operating aircraft, the S-3A Viking, along with numerous helicopters performing the same mission.
2) Again, the high cruise speeds combined with minimal take off and landing distances make the aircraft an excellent platform for the insertion and extraction of Special Forces. This version of the aircraft could be used as a substitute for the UH-60 Blackhawk or the V-22 Osprey.
3) Modifications to include a radar dome and other electronic devices could allow the aircraft to serve Airborne Early Warning (AEW) purposes. The aircraft supplies sufficient cabin space for multiple operators and their equipment. The current Navy carrier aircraft that performs this mission is the turboprop E-3C Hawkeye, a close relation of the C-2A Greyhound.
4) The large cargo area could be modified to stow fuel. With additional tankage, refueling mechanisms, and trailing refueling lines the aircraft could be converted into an in-flight refueling tanker. Currently there is no aircraft specifically designed as a tanker operating from aircraft carriers.

The many possible variations of this aircraft not only make it a commercially viable option, but also an attractive multi-use aircraft for the Navy. Having one aircraft that can perform different missions would greatly decrease maintenance and operating costs. Basically, the aircraft provides "more for less."

2. Concept Evolution

2.1. Preliminary Takeoff Distance Study

An approximate analysis of the takeoff distance was made to identify the key design characteristics necessary to meet the RFP requirements. The following free body diagram (Figure 2.1) simulates flight when the total lift developed by the wings and engines is equal to the weight of the aircraft. A thrust vector angle, θ, is incorporated into the diagram. Neglecting drag forces, a rough derivation of the takeoff distance is as follows.

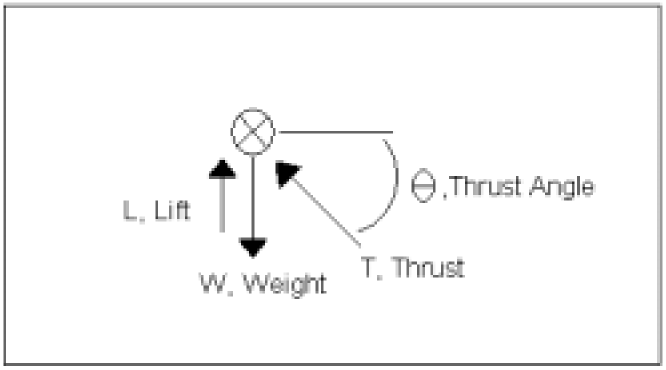


Figure 2.1 - Takeoff Analysis Force Diagram

First, the lift and thrust components are set equal to the weight of the aircraft.

$$L + TSin\theta = W$$

Introducing, $L = C_L qS$, and rearranging terms

we get: $$\frac{qC_L}{(W/S)} + \left(\frac{T}{W}\right)Sin\theta = 1 .$$

This can be used to obtain an expression for the takeoff velocity, V_{TO},

$$\tfrac{1}{2}\rho V_{TO}^2 = \frac{(W/S)}{C_L} - \left(\frac{W}{S}\right)\frac{1}{C_L}\left(\frac{T}{W}\right)Sin\theta .$$

Assuming a constant acceleration, *a*, we can relate the takeoff distance, D_{TO}, to the takeoff velocity,

$D_{TO} = \frac{1}{2}\frac{V_{TO}^2}{a}$. We can write out the acceleration in terms of the thrust, weight, and vector angle,

$a = g\frac{T}{W}Cos\theta$. Finally, we can combine all terms for an expression relating the design parameters to the takeoff distance.

$$D_{TO} \cong \frac{(W/S)}{\rho g C_L (T/W) Cos\theta}\left[1-\frac{T}{W}Sin\theta\right] \qquad \textbf{(2.1)}$$

Equation 2.1 is an approximate estimate of the vectored thrust takeoff distance. This equation also agrees well with Krenkel's[1.2] more precise analysis. Initial takeoff distance analysis investigated wing loading, thrust vectoring, takeoff lift coefficients, and the *T/W* ratios necessary to complete the takeoff RFP requirement. A carpet plot was created for a conventional aircraft with a takeoff lift coefficient of 2.5. Figure 2.2 is a plot of the dependency of the *T/W* ratio according to the wing loading and the takeoff distance. The wing loading and takeoff distances were varied to be within a reasonable range for a STOL transport aircraft. Results from the carpet plot indicate that a conventional design would be impractical, because an unreasonable *T/W* ratio is needed to achieve the 300-foot takeoff. *T/W* ratios greater than 1.1 indicate that an aircraft should have VTOL capability. This leads the designer to consider either increasing the lift coefficient or vectoring the thrust of the aircraft.

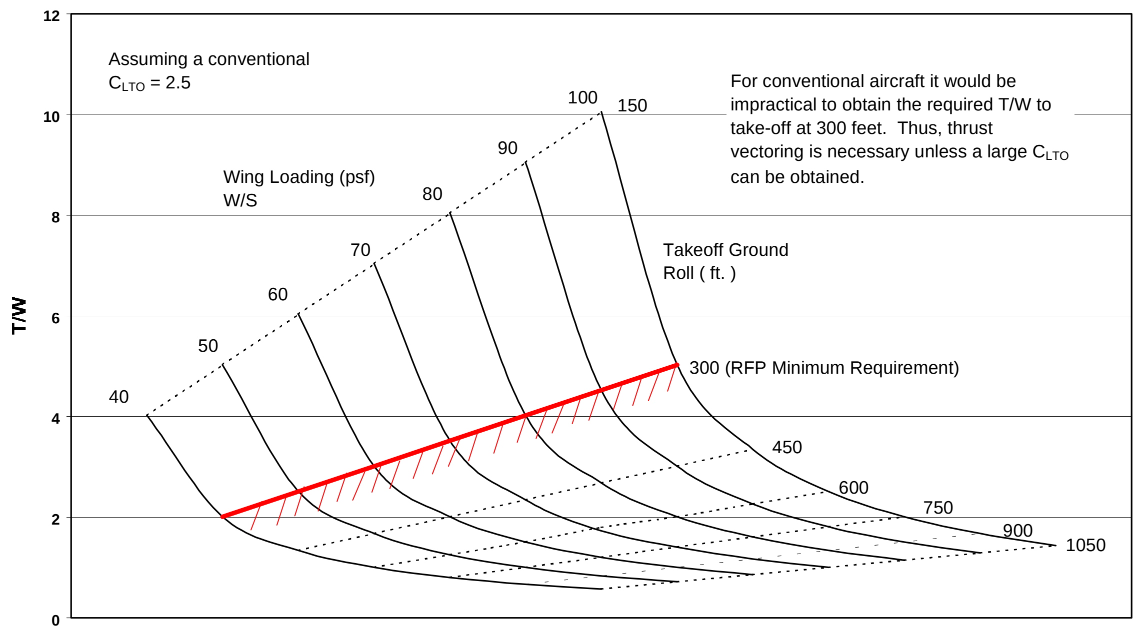


Figure 2.2 - Dependency of *T/W* and *W/S* for Varying Takeoff Distances

Figure 2.3 is a carpet plot of the *T/W* dependency to *W/S* and the thrust vector angle θ. The takeoff distance was held to the RFP requirement of 300 feet, and the takeoff lift coefficient was held at 2.5 for the study. This investigation varied the vector angle from 20° to 80°, and the wing loading from 40 to 100 psf. The result was the required *T/W* ratio to achieve the takeoff distance with a specific wing loading and vector angle. Figure 2.3 indicates that thrust vectoring significantly lowers the necessary *T/W* ratio compared to those required for a conventional aircraft. The carpet plot also indicates that for a specific wing loading, there is an optimum thrust angle to minimize required thrust. This is shown by how the curves overlap around each other at lower *T/W* ratios. At a specific wing loading, vector angles above 60° require greater *T/W* ratios than the smaller vector angles. This plot indicates that *T/W* ratios less than 1 can be achieved.

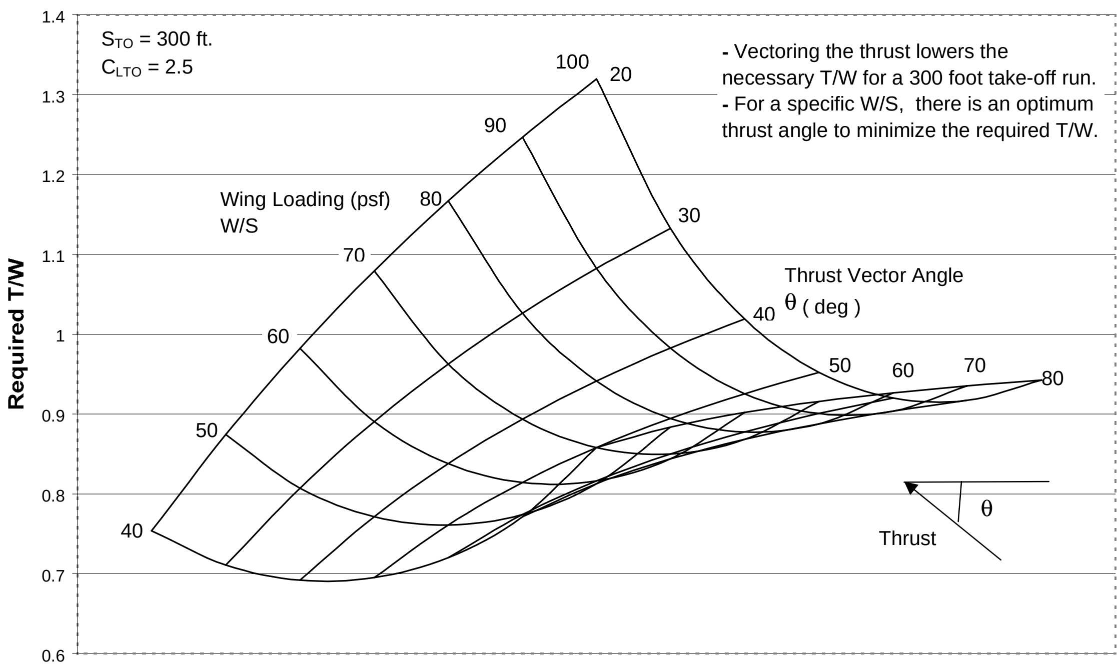


Figure 2.3 - Required *T/W* for Specified *W/S* and Vector Angles

Figure 2.3 indicates that a SSTOL aircraft without an exceptionally high lift coefficient would need a much higher *T/W* ratio than a conventional transport aircraft. Traditional transports comparable to the Boeing 727, 737, and the DC-10 have *T/W* ratios around 0.28. The penalty for the SSTOL capability is an overpowered aircraft. An understanding of the problem derived from the two carpet plots helped influenced the initial design concepts.

2.2. Initial Design Concepts

Six preliminary designs were based mainly on the carrier spot factor requirements, stowage area size for two GE F110-400 engines, and incorporation of high lift systems. The following designs were the initial concepts analyzed.

2.2.1. Tilt Wing/Engine

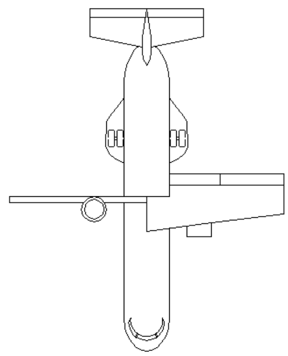


Figure 2.4 - Tilt Wing/Engine, Concept 1

Concept 1 is a tilt wing and engine aircraft similar to the Canadair CL-84. The maximum rotation for the wing and engine would be 90 degrees with two high bypass turbofan engines used to produce external flap blowing underneath the wing. This blowing will help in stabilizing the aircraft in roll at low speed flight. The two high-lift devices, tilt wing and blown flaps, each help to achieve the landing and takeoff distances as required. The turbofan engines in this design are cross-shafted in order to account for single engine failure. This would result in an installation thrust loss for the engines. Fuel for the engines are stored in a bladder system under the floor and in the wings.

In normal flight, the elevator, rudder, and aileron are employed for control inputs about the three axes. For low speed flight, devices such as spoilers, engine vanes, and blown flaps are used.

An 8x3 seating arrangement was chosen for commuter flights. A lavatory and galley are included for convenience, as well as a large storage area for items that do not fit in the overhead bins such as oversized carry-on luggage. The cockpit section accounts for the first 8 feet of the aircraft. The seats and other passenger related aspects of the aircraft are removable for transition to a military cargo plane. Two cabin versions of this aircraft would be designed so that the military cabin would have strengthened floors and seat pallets, where as the civilian design would have a normal floor with standard passenger seating installation. The engine payload is loaded into the aircraft in tandem via a rear cargo door, leaving room for a front entrance door. An inherent problem with this design is the stall characteristic of the wing while in transition mode. The addition of large leading edge slats would delay stall at high angles of attack.

2.2.2. CSTOL (USB)

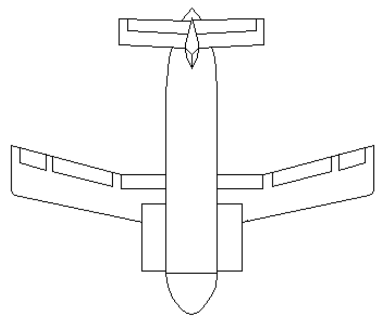


Figure 2.5 - CSTOL (USB), Concept 2

This SSTOL concept aircraft combines aspects of historical aircraft with new technology. The first similarity comes from the Boeing YC-14 which incorporated an over wing installation of the power plant. The exhaust produces wing upper-surface blowing (USB). Full span leading and trailing edge flaps are employed with Coanda-type trailing edge flaps located behind the engines, which are positioned close to the fuselage. The Coanda flaps induce the high-speed airflow produced by the engines to cling to the surface of the wing/flap system and direct it downwards, thereby generating the powered lift necessary. Additional control and lift would be obtained by blowing over the ailerons of the aircraft.

The design requirement for over-wing engine placement pushes the center of gravity of the airplane forward. Therefore, nose loading is used with the cabin of the aircraft pivoting open sidewise. To meet carrier spot factor requirements, wing folding is used as in the Lockheed S-3A Viking. This allows one wing to be folded slightly forward while the opposite wing is folded to the rear at a small angle. The same cabin accommodations exist as for concept 1.

2.2.3. CSTOL (USB with Lift Fans)

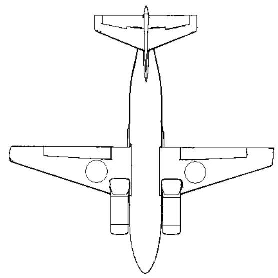


Figure 2.6 - CSTOL (USB with Lift Fans), Concept 3

This conventional style aircraft utilizes upper surface blowing and Coanda flaps to attain the lift necessary for a short takeoff. To decrease necessary takeoff acceleration and increase lift, two lift fans were installed near the fuselage and under the wings. Folding the wings for the stowage requirement would also be a formidable problem.

Stowing two GE F110-400 engines in tandem required the length of the new concept to be set at the maximum spot factor requirement of 60 feet. Loading of the two engines is completed through the use of a rear cargo door. Again the cabin accommodation as for concept 1 are included.

2.2.4. Joined wing tail

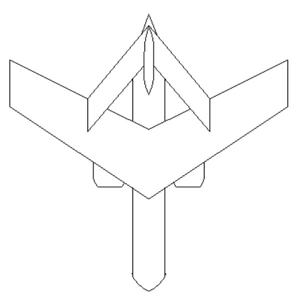


Figure 2.7 - Joined Wing/Tail, Concept 4

This concept consists of a high mounted, highly swept wing system, which was joined in a box configuration with a forward swept, anhedral tail leading from the top of the vertical tail. The tail joined the wing at a point midway between the fuselage and the wing tip. This enabled the wing to fold upwards to meet the spot requirement for carrier use.

A cargo door located below the tail-section was designed to swing open and provide a ramp for rear cargo loading. The cargo engines are loaded and stored in tandem. The cabin again has similar accommodations as described in Concept 1.

Other unconventional devices included in this design concept were externally blown flaps on the trailing edge of the wing and tail. The propulsion system included two high bypass turbofan engines close to the fuselage. To produce the desired effects of the externally blown trailing edge flaps at low speed flight, the engines are mounted away from the fuselage. The high wing configuration used in this design concept is effective for short takeoff/landing designs primarily because it reduces "floating" effects during landing

2.2.5. Blended wing body

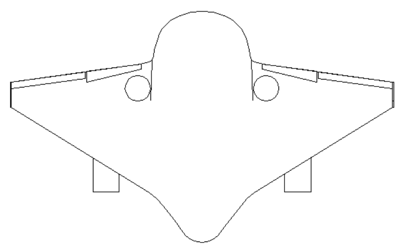


Figure 2.8 - Blended Wing Body, Concept 5

This concept is a small blended wing-body aircraft with a platypus aft fuselage section. The cargo engines are stored side by side in the "fuselage" of the aircraft. The blended wing-body concept has a wingspan of 60 feet, and a length of 36 feet. The platypus aft end acts as a rear loading door and hinges upward and over to fit into the required 29 foot carrier width. This aircraft requires no wing folding or any other space saving measure other than opening the cargo door to fit in the carrier spot requirement. However, the landing gear wheels would be required to rotate 90° to maneuver the aircraft for stowage while on the carrier.

To achieve the required takeoff run, the aircraft employed two rear lift fans, and two forward mounted thrust vectoring turbofan engines. Power was supplied to the lift fans by two turboshaft engines buried in the fuselage. During cruise, flaps, ailerons, and rudders mounted on winglets at the wing tips would be used for control. Slow speed flight control would be a combination of the control surfaces and power sources. Differential thrust combinations between the lift fans and vectored turbofans could control both pitch and roll, while yaw would be controlled with variable vanes in the lift fan exits.

2.2.6. Tilt Engine

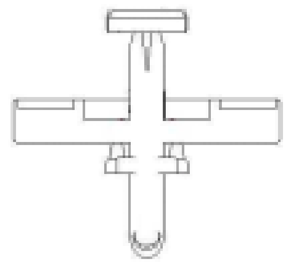


Figure 2.9 - Tilt Engine, Concept 6

This design was initially conceived from a design patent (# 4,296,896) from Grumman Aerospace. Engine pods near the center of gravity location would rotate upward for short takeoff. Vanes placed in the exhaust path of the engines would help control pitch, yaw, and roll.

This concept has a rear cargo door and a layout for tandem engine stowage. A 3x8 seat layout with baggage section, galley, lavatory, and attendant seat was also arranged. The propulsion system could allow for vertical takeoff with high *T/W* ratios. A thrust vector angle around 60 degrees would place the thrust slightly in front of the C.G. to provide rotation during takeoff. Control during cruise for this aircraft consists of ailerons, an H-tail with a full span elevator, and two rudders that act as endplates on the horizontal tail.

2.3. Selection Process

It became evident that the six preliminary designs for a SSTOL could be combined to three well-defined concepts. The best concepts out of the initial design base were chosen for further analysis. Concept 6 employed two engines which could be tilted to provide takeoff lift vectoring and forward cruise propulsion. This was chosen as the first of our three designs for further study.

Concepts 2 and 3 were designs with the engines positioned in front and above the wing to utilize over-the-wing blowing for high lift. Concept 3 required the use of lift fans located in the wing. A problem with this design was that the lift fans were positioned at the rear of the USB engines. Therefore, they would be ingesting the hot exhaust of the turbofan engines. The lift engine installation would also have increased wing weight with the loss of torsion box area and make fuel installation difficult. Wing folding would be an additional complication due to the wing mounted lift fans. Concept 2 only used turbofan engines for high lift and forward propulsion and had already been proven by such planes as the Boeing YC-14, Antonov AN-72, and NASA QSRA. This became our second design choice for further investigation.

The selection between concepts was, in part, based upon the consumer's acceptability of concept 4. It is known that people fear what they do not understand or appears strange. Thus, concept 4, the joint tail and wing design was eliminated.

Another unconventional design eliminated was concept 5, the blended wing/body aircraft. The major problem with this design arose when trying to meet the RFP stowage requirement. This design called for the cargo engines to be placed side by side in a 29 foot long fuselage. The tail cone platypus design needed for the carrier spot factor requirements was very bluff and would cause an increase in drag that would prove unacceptable for the mission. Also, the commercial version would not have passenger visibility from the cabin.

The final design choice was concept 1, the tilt wing design with blown flaps. Tilting the wings vectored the thrust while also increasing the wing angle of attack for a higher lift coefficient. The three final concepts are displayed in Figure 2.10.

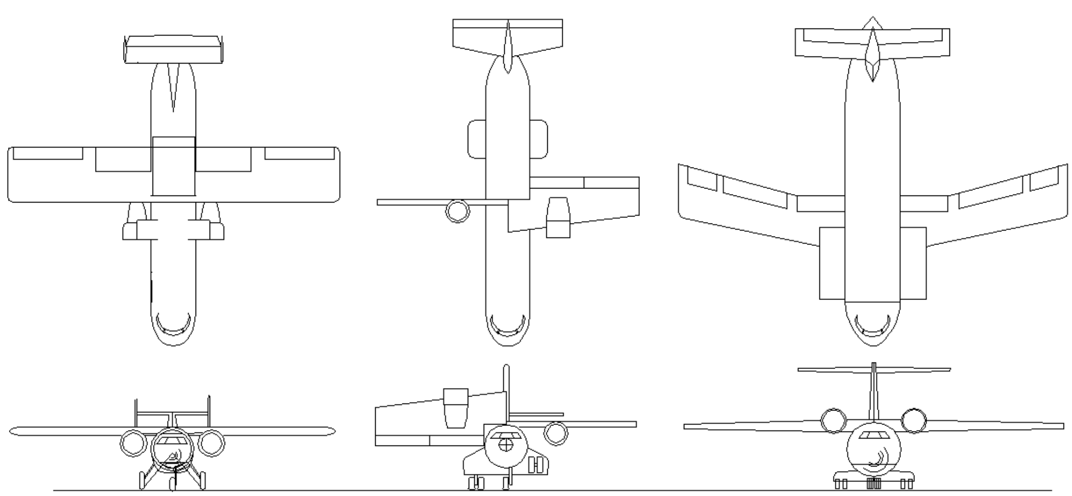


Figure 2.10 - Final Three Concepts

2.4. Concept Analysis

2.4.1. Weight Estimates

Following the statistical equations given in Raymer[2.1], initial weight estimates were made to determine the various component weights of the aircraft. The weights of the three concept aircraft were found to be similar. They ranged from 50,000 lbs to 52,000 lbs This was because the aircraft were of comparable sizes and configurations. A breakdown of the main groups used in determining the total takeoff weight can be seen below in Table 2.1.

Table 2.1 - Preliminary Weights; Military Design

Group Weights (lbs)	Tilt Engine	CSTOL with USB	Tilt Wing
Structures	13396	13774	13140
Propulsion	5088	5068	5077
Equipment	6254	6652	6307
Total Empty Weight	**24738**	**25494**	**24524**
Crew	600	600	600
Payload	10000	10000	10000
Fuel	15600	16000	15600
Takeoff Weight	**50938**	**52094**	**50184**

2.4.2. Fuel Requirements

The method used in the mission segment analysis to find the fuel required was a combination of analytical, statistical, and historical estimates as described in Raymer[2.1].

Table 2.2 illustrates the mission fuel analysis for the Tilt Engine (concept 6) and Tilt Wing (concept 1) aircraft.

Table 2.2 - Mission Fuel Analysis –Tilt Engine and Tilt Wing

Mission Segment	Weight Fraction Equation	$\frac{W_N}{W_{N-1}}$	Aircraft Weight (lbs.)	Consumed Fuel (lbs.)
TOGW	-	-	51000	-
Start/Taxi/Takeoff	-	0.98	49980	1020
Climb/Accelerate	W_2/W_1=1.0065-0.0325M	0.987	49330	650
Cruise	$W_3/W_2 = e^{\frac{RC}{V(L/D)}}$	0.769	37934	11396
Loiter	$W_3/W_2 = e^{\frac{EC}{L/D}}$	0.947	35924	2010
Descent	-	0.993	35672	252
Land/ Taxi	-	0.994	35458	214
			Total	**15542**

The TOGW was rounded up to 51,000 lbs for the fuel consumption and takeoff analysis. The fuel analysis method for CTOL with USB concept was the same, but resulted in a slightly higher fuel weight total.

2.4.3. Takeoff and Landing Distances

For the tilt engine and tilt wing aircraft the design mission takeoff and landing weights were found to be about the same. Both of these landing weights were rounded up to 38,000 lbs for further landing analysis. Table 2.3 describes the TOGW and landing weights used for the initial performance analysis.

Table 2.3 - Weights used for Performance Analysis

Aircraft	Takeoff Gross Weight (lbs)	Landing Weight (lbs)
Tilt Engine	51000	38000
Tilt Wing	51000	38000
CSTOL w/ USB	52500	39000

The landing approach speed was required to determine the ground roll. The inclusion of thrust vectoring in the landing approach required the derivation of an approach speed equation. An evaluation of the aircraft in level approach flight with thrust vectoring yields the following free body diagram:

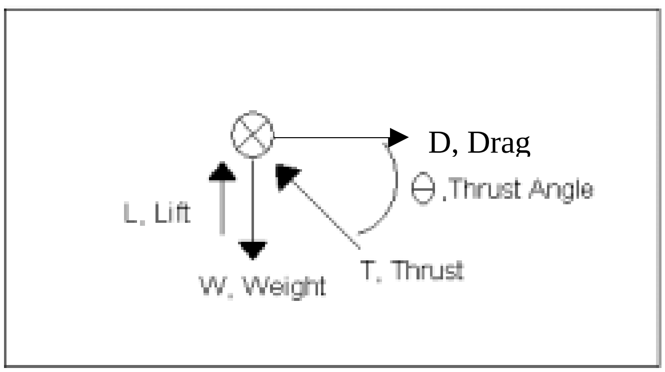


Figure 2.11 - Landing Approach Force Diagram

Equating the forces in the vertical direction yields the following derivation solving for the approach velocity, and an effective wing loading term. First, the lift and vertical thrust components are equated to the aircraft weight, $L + TSin\theta = W$. Next, the lift and dynamic pressure are reduced into their constituent, and introduced into the derivation.

$$L = C_L qS$$

$$q = \frac{1}{2}\rho V^2$$

$$C_L qS + TSin\theta = W$$

$$\frac{1}{2}\rho V^2 C_L S = W - TSin\theta$$

An effective wing loading term is then introduced to account for reduced wing loading due to thrust vectoring and an expression for the approach velocity is determined.

$$\frac{1}{2}\rho V^2 C_L = \frac{W - TSin\theta}{S} = \left(\frac{W}{S}\right)_{eff}$$
$$V_{app} = \sqrt{\frac{2(W/S)_{eff}}{\rho C_L}} \qquad \textbf{(2.2)}$$

The effective wing loading term (Equation 2.2) is very important, because it takes the thrust vectoring into account. The vectoring unloads the wing and allows for slower flight speeds. Equations from Raymer[2.1] were modified to include the approach speed with effective wing loading, enabling the calculation of the ground roll with thrust vectoring.

Table **2.4** is a list of the takeoff and landing performance characteristics of the three initial concepts.

Table 2.4 - Takeoff and Landing Performance Characteristics

	TILT ENGINE	TILT WING (SMALL TILT ANGLE)	TILT WING (HIGH TILT ANGLE)	CSTOL WITH USB
TOGW (lbs)	51000	51000	51000	52500
T/W @ Takeoff	0.84	1.19	0.86	1.01
Vector angle (deg)	61.5	15	62	0
C_L at Takeoff	3	3.5	3.5	5
Takeoff Acceleration (g's)	0.4	1.14	0.4	1.01
D_{TO} (ft)	297	300	300	300
Landing Weight (lbs)	38000	38000	38000	39000
V_{app} (ft/s)	89.6	114.7	92.4	114.0
D_{land} (ft)	395	635	400	735

Assumptions made during the calculations for the ground roll landing distance include sea level static conditions, no applied thrust reversing, a dry asphalt landing surface, the mission landing weight, and minimum thrust levels calculated to achieve the 400 foot landing distance. Although reverse thrust on the CSTOL with USB could have reduced the landing roll, the total time of the landing ground roll was deemed to be too short to activate thrust reversing flaps for effective use. The tilt wing concept was evaluated with both a small and large wing tilt angle.

2.5. Preferred Concept Selection

To further analyze the three design concepts, a criteria was developed for direct comparison of the aircraft. Eight topics related to the aircraft's characteristics were selected and each aircraft was rated based on collected data and projected results (Table 2.5). The rating scale used in this comparison was from 1 to 5, 1 being the lowest rating and 5 the highest.

Table 2.5 - Concept Criteria Comparison

Criteria Comparison	Tilt Wing (Concept 1)	CSTOL w/ USB (Concept 2)	Tilt Engine (Concept 6)
C_{Lmax}	2	1	4
TOGW	4	4	4
TO Acceleration	2	1	4
Landing Attainability	4	1	5
Propulsion Compatibility	4	4	4
Cost	4	4	4
Simplicity	2	1	3
Comfort & Aesthetics	2	3	3
Overall	**24**	**22**	**31**
Average Rating	**3**	**2.8**	**3.9**

The first comparison was the maximum lift coefficient for the aircraft. For the CSTOL (USB) design, the ability of the aircraft to meet the short takeoff distance requirement was entirely dependent on the aircraft's ability to obtain a very high C_L at relatively low speeds. The fact that this design required such a high lift coefficient (C_L= 4-5), resulted in a low rating for this category. The tilt wing design did not require as high a lift coefficient, but as the wings rotated during transition, the threat of losing lift due to stall became a problem, and more of a problem when considering a gusty environment. The tilt engine concept also avoided the requirement for a significantly high C_L, but by maintaining a low wing angle of attack, it did not encounter the stall dilemma found with the tilt wing design.

The second category under which the aircraft were rated was the takeoff gross weight. All three of these aircraft rated fairly high in this category as a result of the low calculated TOGW's.

Takeoff acceleration was the third category under which the aircraft were compared. The CTOL USB design concept was determined to be incapable of taking off within the required takeoff distance without exceeding the maximum acceleration of 0.4g. The tilt wing design received a low rating in this category as well because the required wing rotation could result in a stalled wing. The tilt engine design was determined to be entirely capable of taking off within the required distance at a reasonable acceleration and therefore received a high rating.

The fourth topic considered in the comparison was the ability of the aircraft to land in the required distance. For the USB design concept, the approach speed was estimated to be too high to allow a 400-ft landing distance. Both the tilt wing and the tilt engine designs should be capable of landing within the maximum landing distance, but again complications with wing stalling posed a problem for the tilt wing design.

Another area considered in comparing the concepts was the propulsive system options. At this period in the design process cross ducting or shafting was considered mandatory to handle an engine out condition. There were three propulsion options; cross-ducting/tip turbine fans, cross shafting engines, and cross ducting engines (Figure 4.1). Each design concept was rated based on its compatibility with these propulsion systems. The USB design concept was compatible with only two of the three propulsion options. For the tilt wing design concept, the complicated wing setup for the tilting mechanism and volume requirements for cross ducting resulted in compatibility with only one of the three concepts. For this reason the tilt wing rated the lowest in this category. Because of the flexibility of the tilt engine design concept, this aircraft was reasonably compatible with all three options.

The estimated costs for each concept were fairly similar. As can be seen in this comparison, the estimated cost was not an influential factor in selecting a final design concept.

Another factor considered in the criteria comparison was the simplicity of the design concept. The simplest overall design was the USB concept. This rating was based on the fact that the USB design had the fewest unconventional features. The tilt wing concept was rated as the most complex design due to the structural, aerodynamic, and systematic complications involved in the rotation of the wings. The tilt engine design was not as complex structurally or aerodynamically as the tilt wing design, but presented more complications than the USB concept.

The final comparison dealt with the comfort and aesthetics of the aircraft. Because the aircraft were designed to serve both commuter and transport purposes, none of the concepts rated especially high in this category. The tilt wing aircraft was rated lower than the other designs based on the assumption that an aircraft with such unconventional features would increase anxiety among passengers.

The average and overall rating with respect to all the criteria topics was determined for each aircraft concept. The results were then compiled into a bar chart from Table 2.5 for comparison as shown in Figure 2.12. This figure shows that the tilt engine design had a higher overall rating than the USB and tilt wing concepts. As a result, the tilt engine design was selected as the preferred concept for further development.

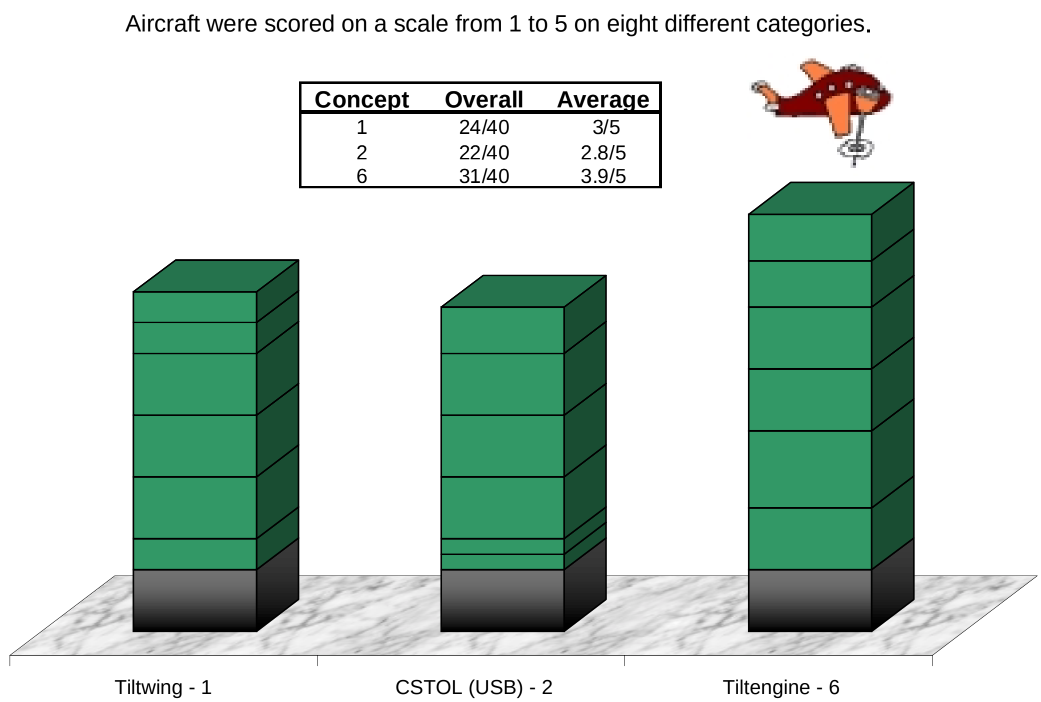


Figure 2.12 - Relative Concept Ranking

3. Configuration

3.1. Skyhopper Layout

The Skyhopper configuration can be seen in Figure 3.1. All of the major features and dimensions are shown on this drawing as well. The overall length of the aircraft is 60 feet and the wing span is 63.7 feet. The maximum fuselage width is 9.6 feet (115.2 inches); It is composed of two circular arcs, a 9.6 foot cabin diameter and a 17.4 foot under floor diameter. These sections are pressurized with the exception of the underfloor wheel wells. Maximum height with wings spread is 21.4 feet (Civilian version), with wings folded 22.0 feet (Military Version), providing sufficient overhead clearance on post CVA/N 60 carriers. The 21.4-foot (tail) height should pose no problems with commercial airfield hangers.

The wing has a rectangular inboard section on which the propulsion system is mounted, and tapered outboard forward swept wing sections. The slightly forward swept wing was developed to provide desired stability margins with the inclusion of the propulsion system. In the naval version these panels fold at the start of the taper which yields a folded width of 28.6 feet. The fold system is an “overfold” system, reminiscent of some pre-war Japanese carrier based aircraft, with panel fold synchronized to avoid interference in the fold process. The inboard wing panels have extending double slotted flaps that extend from the wing fillet to the wingfold location. The outer panels have similar flaps that extend to 28.3 foot span. Three segment spoilers/lift dumpers are located immediately ahead of the flaps. The rear section of the double slotted flaps also deflect differently about the nominal flap deflection angle to provide roll control. Normal plain flap ailerons are located outboard of the flaps to the wing tip. They supply roll control in cruise flight when the flaps are retracted and for additional roll control power in low speed flight conditions. They can also supply lateral trim in cruise. An electronic flight control system is employed to control the Skyhopper throughout the low speed transition in takeoff and landing and supplies stability augmentation throughout the flight envelope.

The propulsion system and its integration in the Skyhopper is the unique feature of the configuration. Two 76 inch diameter cruise fans each powered by two Rolls Royce 5990 lb Adour turbofan engines are mounted on the wing leading edge and rotate between 0 and 85 degrees. They supply the additional thrust required to meet the specified takeoff and landing distances.

The Skyhopper’s empennage is of the H configuration with two vertical tails mounted at the tips of the horizontal tail. The vertical tails are thus located outboard of the cruise fan efflux. This empennage is mounted off the fuselage on a pylon, which locates the horizontal tail above the wing chord and the cruise fan exhaust in cruise. The pylon and tail surfaces are common to both the commercial and naval COD versions of the Skyhopper. The upper fuselage contours of both versions are the same with common bulkhead locations to allow fitting of the empennage to both versions to reduce development and manufacturing costs.

The control surfaces are all aerodynamically sized for sufficient control power at takeoff, climbout, approach and flare. This avoids the inclusion of controls in the cruise fan exhaust usually needed in VSTOL transition flight conditions and without their drag, allows higher propulsive efficiency in cruise. The control surfaces consist of double acting outer flap segments and ailerons located on the wing outer panels (as noted above) for roll control. A large elevator mounted on the fixed horizontal stabilizer with two-element elevator surfaces provide large, but gentle camber for pitch control. Also a rudder is mounted on each of the vertical fins.

The landing gears are located for positive ground stability, meeting Navy turnover angle requirements, but yet provides easy rotation for takeoff with vectored thrust. A twin nose wheel landing gear retracts forward and stows beneath the cockpit. The nose wheel can be extended and locked to lower the aft ramp for easier loading. Single wheel main gears retract inward and stow beneath the cabin floor within faired wheel housings. These fairings are located primarily beneath the fuselage.

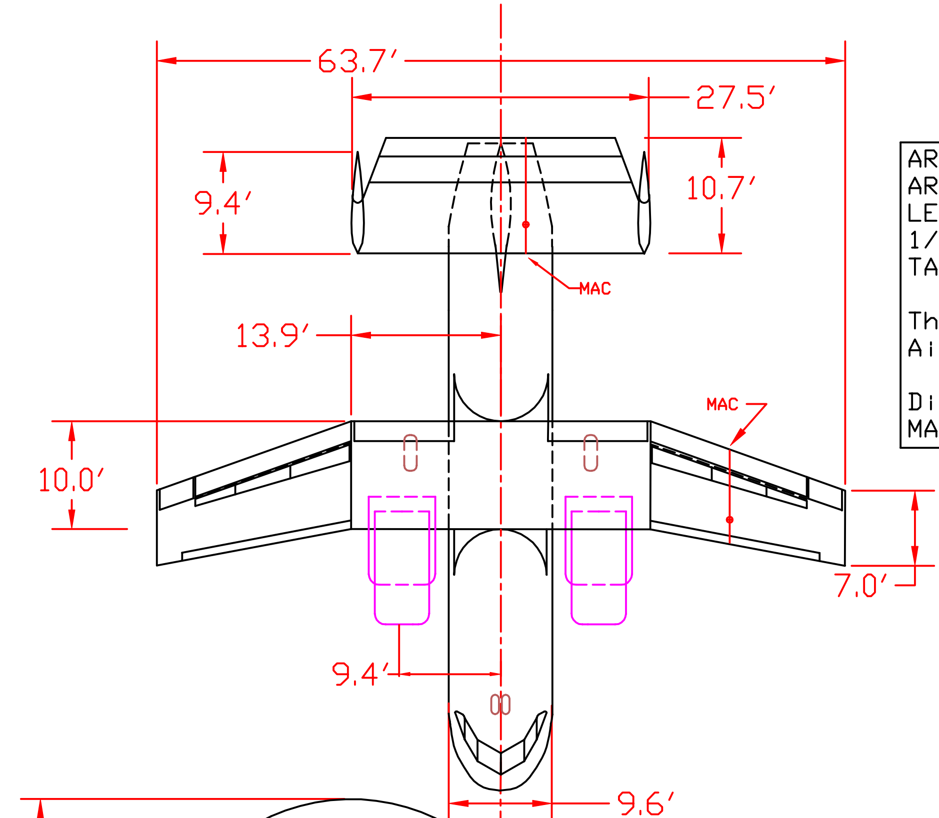
The fuel is housed in five integral wing tanks; one in the center section, two outboard of the engine mounting position, and two outboard of the wing fold location. The reserve fuel tank is located forward of the main gear storage in the faired wheel housing. The naval Skyhopper version has provisions for an extendible in-flight refueling probe above the forward cabin and cockpit.

During the design of this aircraft, it was evident that there may be a need for two slightly different aircraft for the commercial and military missions. The military mission requires a cargo door in the tail for loading and unloading cargo. This can be a big weight penalty for the commercial aircraft, which has no use for this door. A trade-off study was performed to find an optimum tail cone for the commercial aircraft. The two options that were considered were: a two dimensional tail cone with the cargo door replaced by a smaller passenger entrance into the aircraft, and a more slender, three dimensional tail cone with no door. The drag and weight savings from the second option was a benefit that was optimal. Figure 3.2 shows both the military and civilian tail cones.

This aircraft was designed to perform a number of missions, and therefore the interior of the aircraft is configurable in several ways. Several of these configurations are shown on the inboard profiles in Figure 3.3. For the military, the main layout was for the two GE F110-400 aircraft engines. Since these engines are one of the largest engines used by Navy aircraft, this COD has the ability to carry a wide variety of aircraft engines. Both the GE F414, for the F/A-18E/F, and future versions of the engines for the JSF could be stowed in the Skyhopper. The engines are loaded and extracted through the aft cargo door with the use of an internal winch and are stored end to end. The aft cargo door is a double fold-over ramp so that the ramp may extend farther and reduce the angle between the ramp and the ground. The military seating is loaded on pallets, which contain a total of 30 aft facing seats, per military requirements. The military version can also be configured for a medavac evacuation with 16 litters. It can also carry general pallet sized cargo, for which a cross-section is shown, or configured with a cargo and passenger mix depending on pallet type and arrangement. In all of these military configurations, there is only a lavatory, no galley.

The interior configurations for the commercial aircraft are similar to the military ones. The civilian aircraft can carry 30 passengers at 32 inch seat pitch in a 2+1 abreast seating arrangement, one flight attendant, and 2 pilots. The passenger carriage is more than the RFP requirement of 24 passengers. This configuration also includes a galley, a lavatory, overhead storage, and cargo area in the tail. The attendant seat is located in the rear of the aircraft for convenient access to the galley, as well as for a easy forward view of the passenger cabin. The commercial aircraft can also be configured for carriage of 16 medical litters.

The cockpit layout is designed to meet the requirements of FAR 25 for certified transports. As shown in Figure 3.3, the pilots have a 15° over the nose line of sight and an upward line of sight of 20°. The cockpit is configured for two pilots, as well as a radio cabinet, and other electrical equipment that is needed.

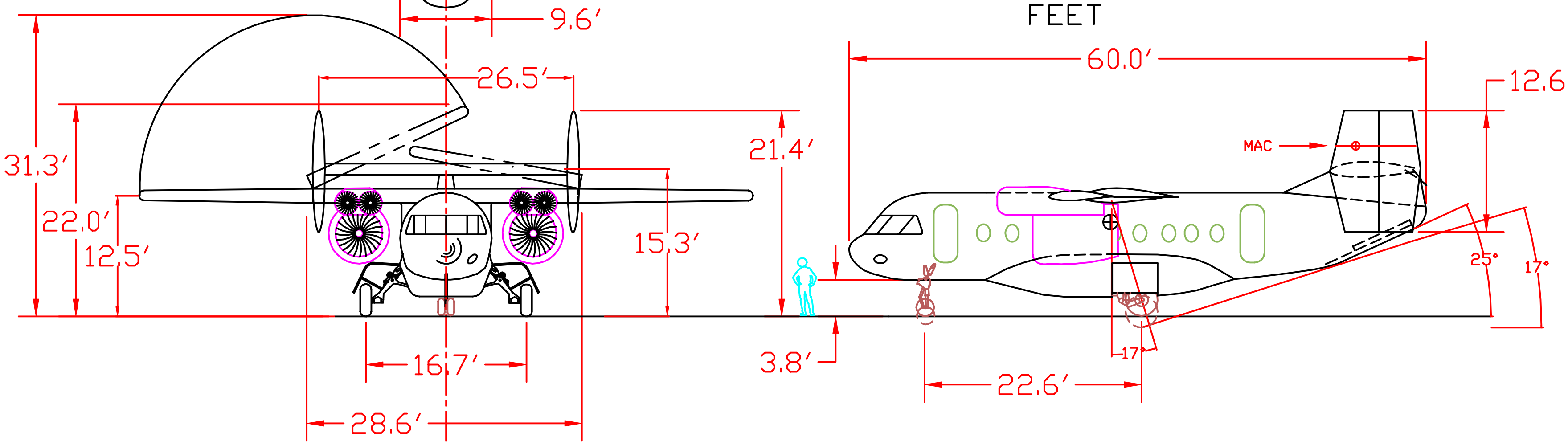


DATA SUMMARY

	WING	HORIZ TAIL	VERT TAIL
AREA SQFT	582	263	208
AR	6.96	2.55	1.52 ea
LE Swp(O'B/I'B)	10°/0°	0°	13°
1/4c Sweep(O'B/I'B)	11°/0°	0°	8°
TAPER RATIO outb'd	0.7	1	0.75
inb'd	1.00		
Thickness Ratio	15%	15%	12%
Airfoil Sect	NACA 63A-415	NACA 63A-415	NACA 0012
Dihedral (up surf)	0°	0°	NA
MAC, ft	8.59	10.7	8.3

ENGINE TYPE:
(4) ROLLS ROYCE ADOUR TURBOFANS OF 5990 lbs THRUST
(2) 76 inch DIA CRUISE FANS

0 5 10 15 20
FEET



VUSAT

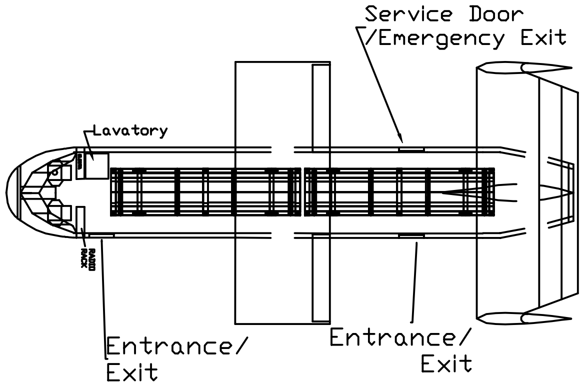
GENERAL ARRANGEMENT
MILITARY CONFIGURATION

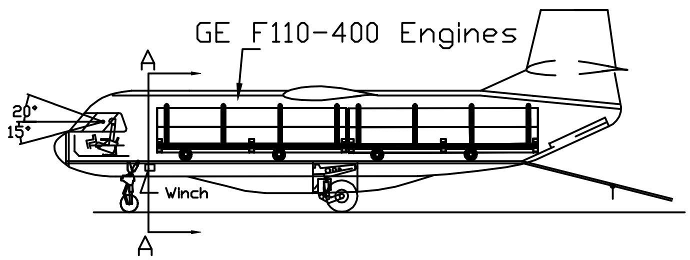
Scale: 1:160
Date: 5/15/99

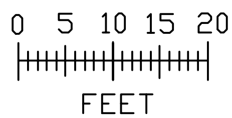
SHEET NO: 1

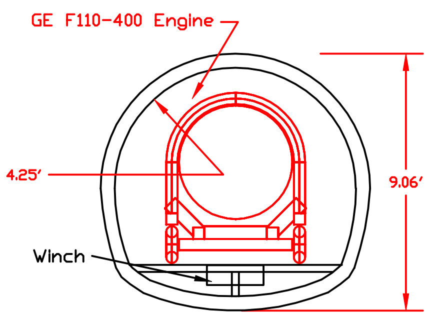
Fig.: 3.1

Military Cargo Engine







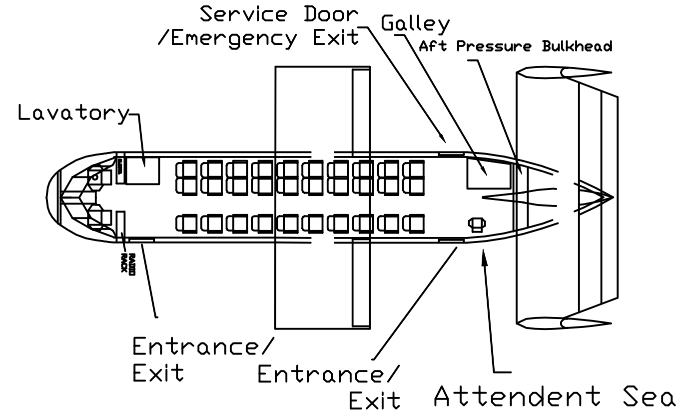


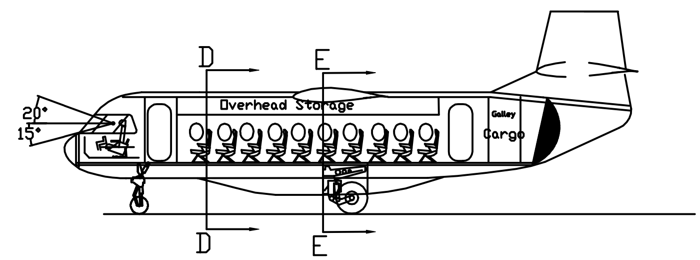
GE F110-400 Engine Carriage

View AA

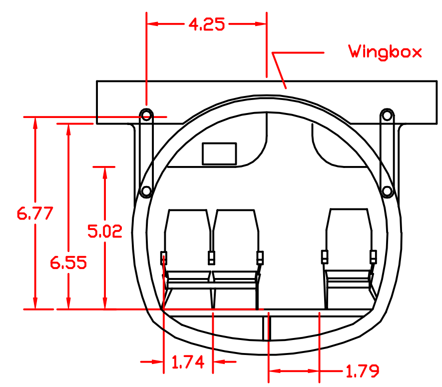
3x

Civilian Seating





View EE on Fig 3.3

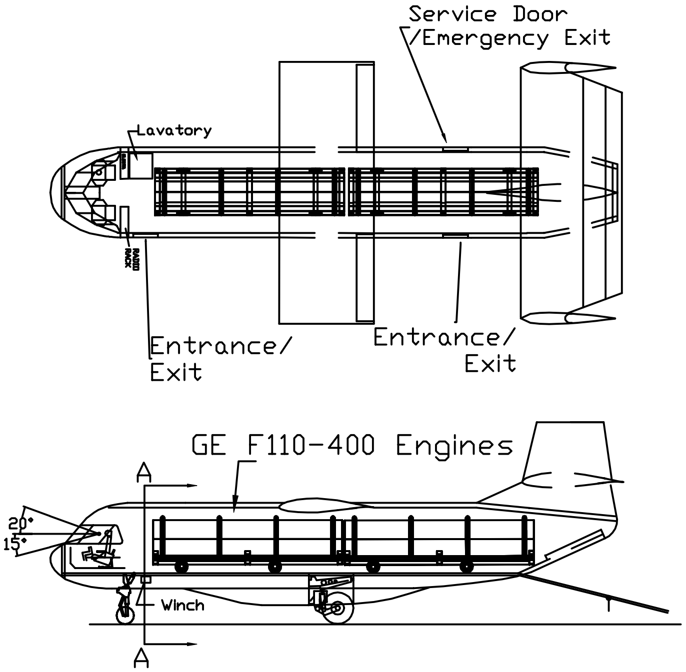


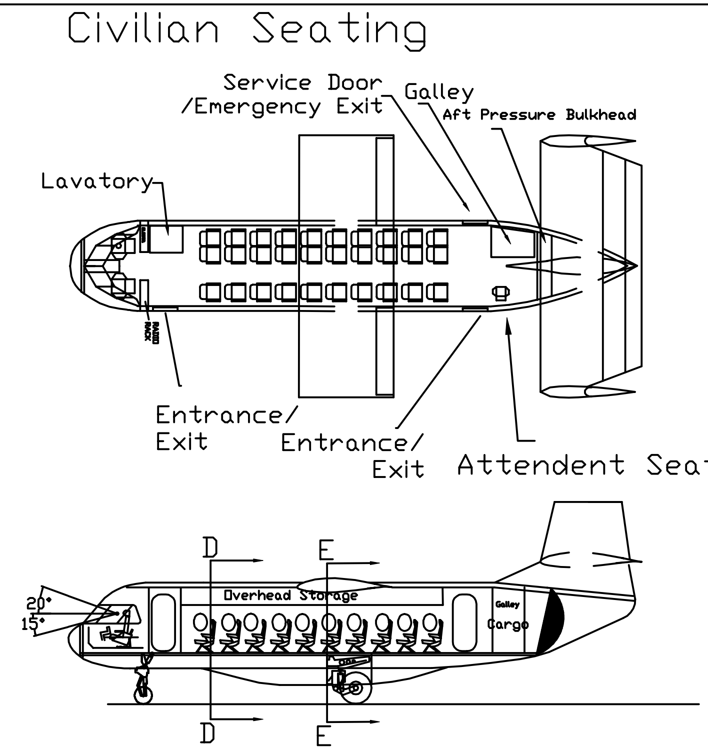
Passenger Cabin

View DD

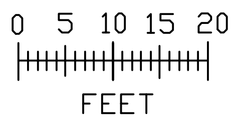
3x

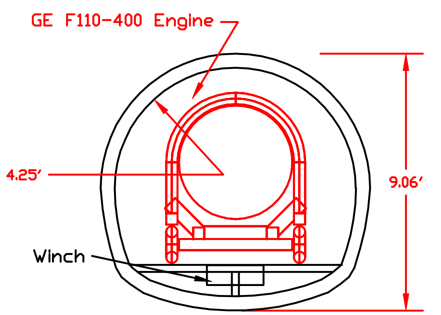
VUSAT	SKYHOPPER MAIN INBOARD PROFILE AND CROSS SECTIONS	Scale: 1:250 Date: 5/15/99	SHEET NO: 2	FIG.: 3.2





View EE on Fig 3.3

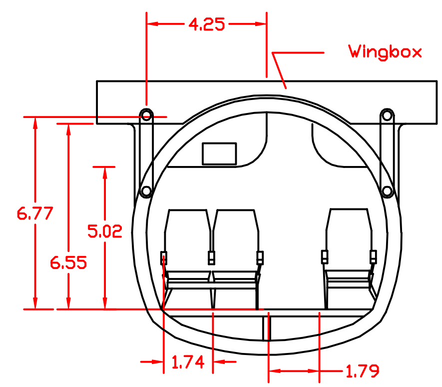




GE F110-400 Engine Carriage

View AA

3x



Passenger Cabin

View DD

3x

VUSAT

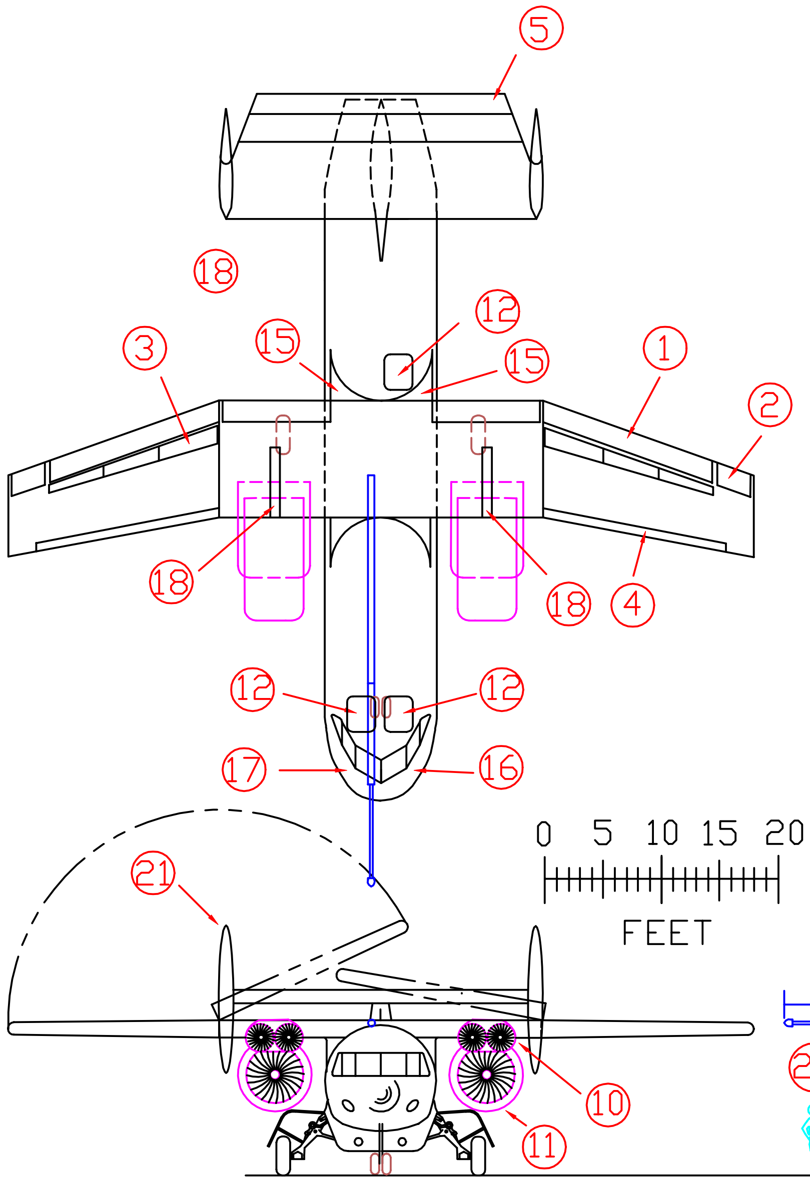
SKYHOPPER MAIN INBOARD PROFILE AND CROSS SECTIONS

Scale: 1:250

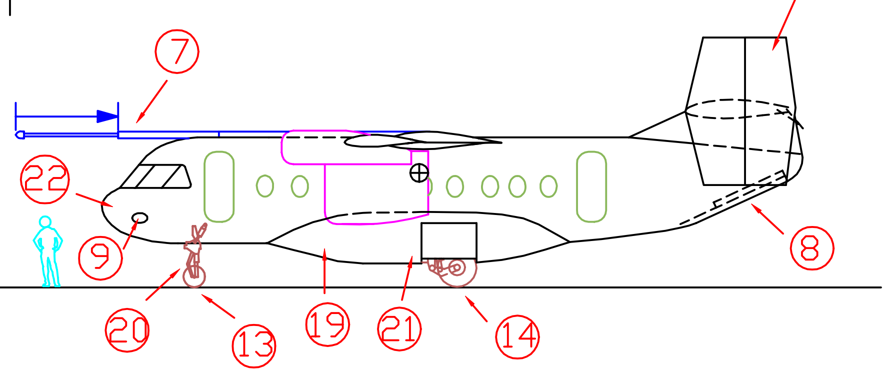
Date: 5/15/99

SHEET NO: 2

FIG.: 3.2



1. Double Slotted Flaps
2. Aileron
3. 3 Segment Spoilers/Lift Dumpers
4. Nose Droop
5. Double Elevator
6. Single Piece Rudder
7. Refueling Probe
8. Cargo Door
9. APU Inlet, ECS Inlet Side Opposite
10. Rolls Royce Adour Turbofan Engine
11. 76inch DIA Cruise Fan
12. Escape Hatchs
13. Nose Gear Wheel 22″ X 6.6-10″
14. Main Gear Wheel 40″ X 14″
15. Life Raft Storage Location
16. APU Installation
17. Environmental Control System (ECS) Installation
18. Cruise Fan Rotation Activator
19. Retractable Landing Lights (2)
20. Taxi Lights (2)
21. Anti Collision Lights
22. Radar



VUSAT	GENERAL ARRANGEMENT MILITARY CONFIGURATION	Scale: 1:150 Date: 5/15/99	SHEET NO: 4	Fig.: 3.4

4. Propulsion System

4.1. Propulsion Selection

Preliminary studies showed that takeoff and landing requirements were the main drivers in determining overall thrust to weight of the aircraft and the need to incorporate thrust vectoring. A required range of 1,500 nautical miles at a cruising speed of at least 350 knots also made cruise TSFC an important consideration. From preliminary performance studies, the following conclusions were made:

- With a takeoff lift coefficient of 3.0, thrust vectoring is necessary
- Thrust vector angle $\cong 60°$
- Required *T/W* at takeoff $\cong 0.8$
- Efficient *T/W* for cruise is approximately half of *T/W* for takeoff

The following design criteria were combined with these conclusions for the initial concepts of the propulsion system.

- Thrust to meet RFP takeoff requirement of 300 feet on SA + 27° day
- *T/W* to approach efficient cruise line at 350 knot cruise speed
- Best TSFC for partial power at cruise

4.2. Initial concepts

Initial concepts included multiple engines to allow some to be shutdown during cruise to approach an efficient cruise line with less TSFC penalty for partial power. With this in mind, a method was needed to reduce any moments produced from engine shutdown during cruise and engine loss considerations during takeoff. Propellers were eliminated as an option because of possible transonic tip speeds, lower efficiency at high speed and large propeller diameters required for low disk loading during takeoff and landing. Initial concepts based on these ideas are; Cross-shafted turboshaft driven cruise fans (option 1), Cross-ducted single exhaust turbofan engines (option 2), and Cross-ducted, generator powered, tip turbine cruise fans (option 3), as seen in Figure 4.1.

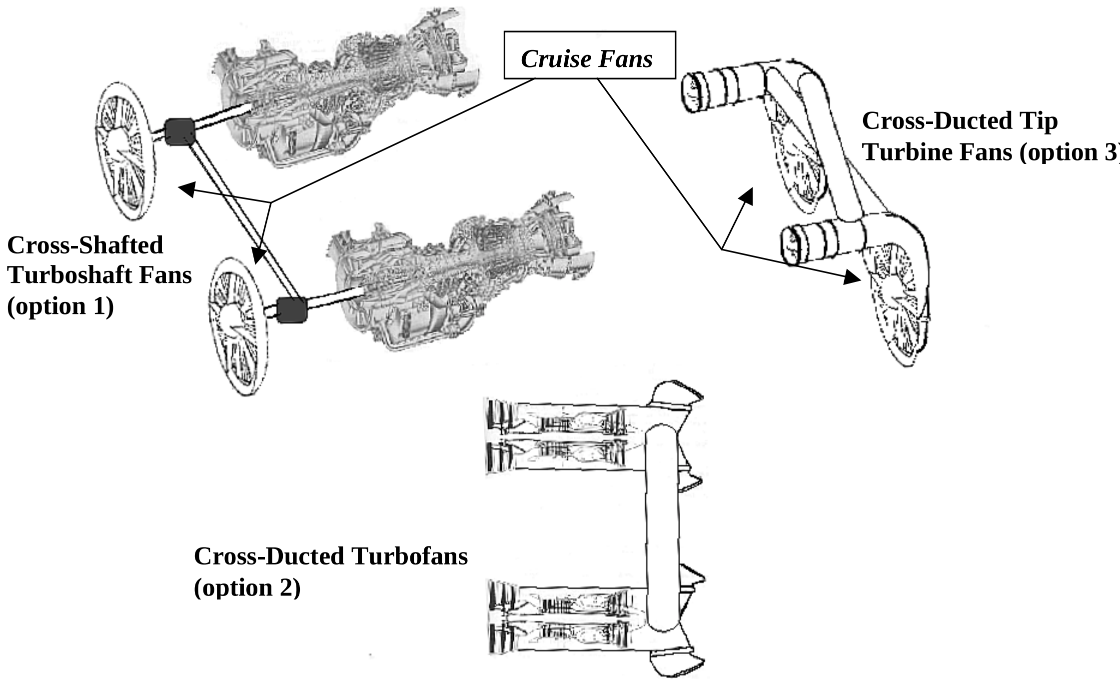
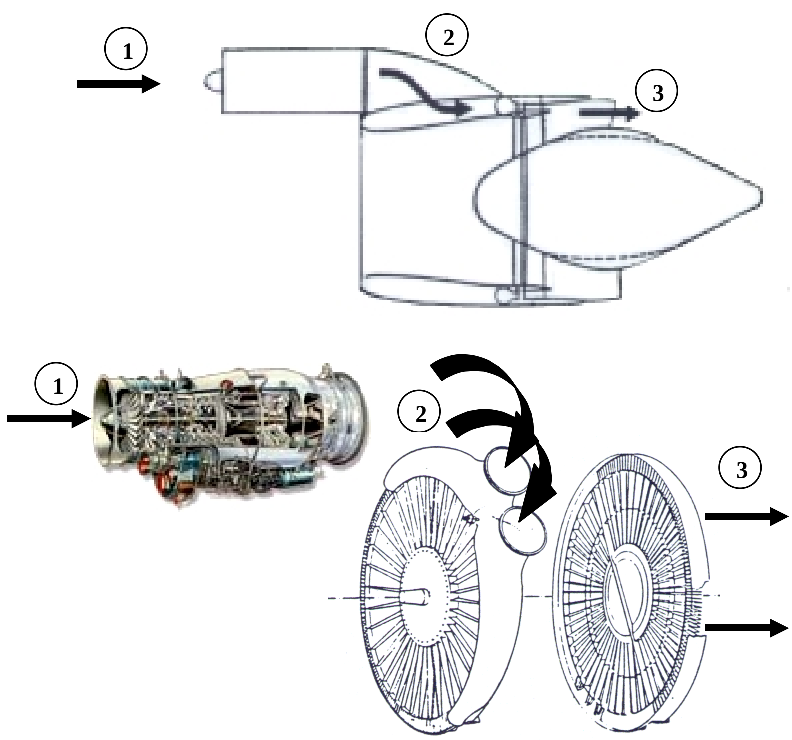


Figure 4.1 - Initial Engine Concepts

Cross-shafted turboshaft engines have been used extensively in helicopter and propeller driven propulsion systems. V/STOL aircraft such as the Bell-Boeing V-22, Breguet 941, and the Chance-Vought XC-142 have both used cross shafting of turboshaft engines. Cross-shafting eliminates lateral directional problems during engine out conditions. Cross-shafting would need to be incorporated through the wing connecting the engines to drive the cruise fans for option 1. In addition to the cross-shafting, a rotation mechanism would need to be incorporated to rotate the cruise fans and/or the engines for vectored thrust. Problems associated with this design were the ability to find turboshaft engines with sufficient power to accommodate thrust required on takeoff.

Cross-ducted turbofans were another option considered. Thrust vectoring rotating nozzles, used on the Rolls Royce Pegasus engine is a proven way to vector thrust. Cross-ducting consists of ducting exhaust from the operating engine to the nozzles of the inoperable engine to balance or negate moments from thrust. The engines would be required to be single exhaust/low bypass to provide pressure through the cross-ducting for engine out purposes. Cross-ducting would be incorporated through the wing. For an engine out condition, the only yawing moment produced would be from ram drag from the inoperable engine since the thrust axis would not change. One major disadvantage using low bypass engines is the high TSFC compared to high bypass engines.

Tip turbine cruise fans are a GE propulsion concept derived from lift fans in the Ryan XV-5A VTOL prototype. A generator, usually a small turbojet engine, powers a high bypass fan with turbine blades at the tips of the fan blades as seen in Figure 4.2 (Goldsmith[5.3]). GE built and tested prototypes of tip turbine cruise fans, which were found to increase bypass ratio. Increases in TSFC at partial power were avoided for multiple generators per cruise fan through engine shutdown during cruise (Ashock[5.1]). The cruise fan augments thrust by increasing bypass ratio. The fan augmentation factor, FF, decreases at cruise due to altitude and Mach number effects, which drops thrust to match cruise performance. The Ryan XV-5A also incorporated cross-ducting between two generator turbojet engines for engine out consideration. Cross-ducting allowed equal generator exhaust to the lift fans for an engine loss consideration. Features for all three options were compared to narrow down the propulsion system to a single concept (Table 4.1).



Flow Path
1. Free stream air
2. Generator exhaust drives tip turbine fans
3. Generator exhaust mixes with cruise fan exhaust

Figure 4.2 - Cruise Fan Assembly

Table 4.1 - Propulsion Comparison

Cross-Shafted Turboshaft Cruise Fans (option 1)	**Cross-Ducted turbofan** (option 2)	**Cross-Ducted Tip Turbine Cruise Fans** (option 3)
Complex linkages and clutches for engine shutdown on cruise	Low bypass required for thrust vectoring, no augmentation from large bypass ratio	Thrust Augmentation from fan
High bypass, lower TSFC	Low bypass, higher TSFC	High bypass, lower TSFC
Generator shutdown possible for closer thrust matching at cruise	Drag increase and moment at cruise if one engine shut down	Generator shutdown possible for closer thrust matching at cruise
Hot Generator exhaust on landing/takeoff surface	Hot Generator exhaust on landing/takeoff surface	Generator exhaust mixes with bypass air, cooler exhaust
Mechanical linkages through wing/near fuselage for cross-shafting	Piping near fuselage for cross ducting.	Piping near fuselage for cross ducting.
Multiple generators per fan		Multiple generators per fan

It was desired to remove the mechanical cross shafting with its multiple gear boxes, clutches and bearings. This entailed costly maintenance concerns and provided many weak links in a chain for safety. It was also desired to remove the cross ducting which entailed large volume ducts across the wing and produced tadpole airfoils when located ahead of the spar (Kirschbaum[1.3]). An H tail was configured for the Skyhopper to counter lateral directional moments from an engine out for any of the propulsion concepts. This also provided stability and control without possible recourse to vertical tail folding with respect to carrier hanger deck constraints.

With cross-shafting eliminated as an option, this kept options 2 and 3 in consideration. Since thrust was required to be vectored on takeoff and landing, cool exhaust became a factor. Low bypass cross-ducted turbofans were eliminated because of high TSFC and hot exhaust temperatures upon vectoring. Tip turbine cruise fans avoid mechanical linkages as in the option 1. If multiple gas generating engines were used for each cruise fan, the fans would not rely on any cross-ducting to maintain operation with one of two generators operating. Tip turbine cruise fans were chosen as the propulsion system configuration because they offered the most options for multiple engines per cruise fan, cooler exhaust temperatures, and availability of high power generators to drive the cruise fans.

Figure 4.3 shows takeoff thrust to weight vs. wing loading and optimal cruise lines for various cruise speeds and altitudes. By increasing cruise altitude and speed, the thrust to weight required for optimal cruise increases towards takeoff thrust to weight. As shown, 65% of the thrust to weight at takeoff most closely approaches the optimum cruise line, which implies engine shutdown during cruise. For this reason, a trade study was done to evaluate one generator per fan vs. two generators per fan.

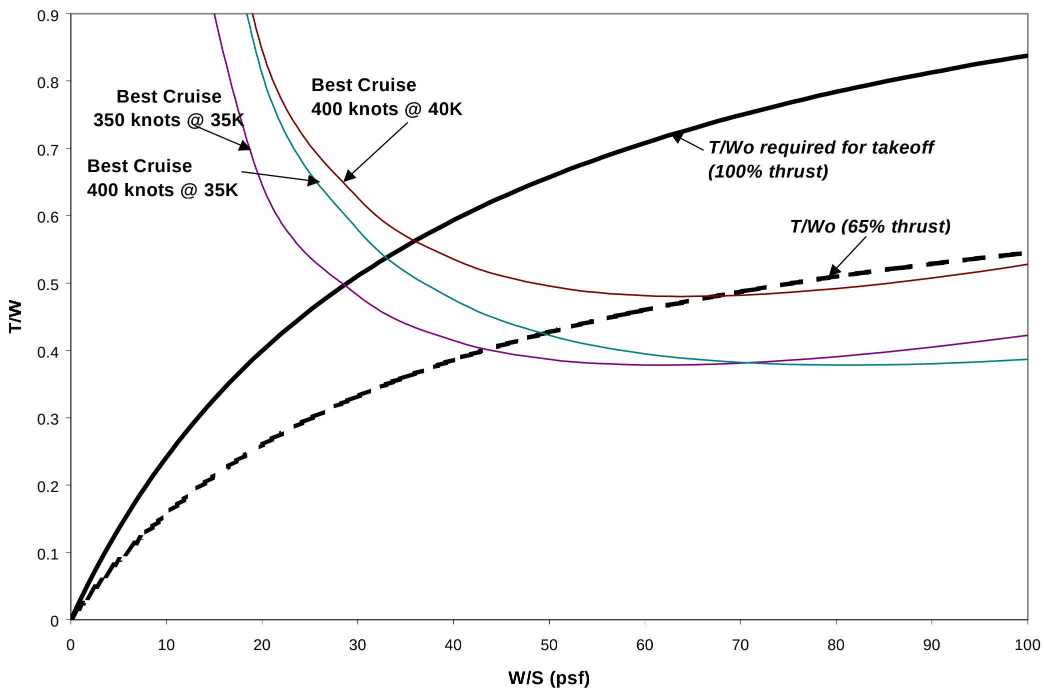


Figure 4.3 - Cruise and Takeoff Thrust Match

From initial takeoff estimates, a total thrust level of 50,000 lbs was required. For a given bypass ratio between the cruise fan and generator, either two 10,000 lb class or four 5,000 lb class generators could be used to generate the thrust. Available engines from the Aviation Week Source Book[5.2] were studied for weight, TSFC and sea level thrust. Because cross-ducting was eliminated, engine shutdown was not a possibility with only two generators. Four generators weighed more for the required takeoff thrust, but offered the option of one engine shutdown per cruise fan during cruise. With this arrangement a more efficient cruise line is approached without changing the thrust axis. Four engines also increased safety for an engine out possibility by decreasing the total thrust loss for a single engine out.

With the 300-ft takeoff distance and an acceleration limit of 0.4 g for the commercial design, the maximum time for the entire takeoff run would be around 6.8 seconds. This time was judged to be too short for a pilot to make an emergency stop decision in case of an engine loss. For safety reasons it was decided to have thrust levels sufficient to provide takeoff speeds with only three of the four generator engines in operation. Two generators per fan for a total of four became a necessary choice over one generator per fan. Penalties included an increased weight of 400 lbs and a minimal increase in C_{DO}. These penalties were considered acceptable due to safety and more efficient cruise.

From Ashock[5.1], fan augmentation factor of the cruise fan, *FF*, increases with bypass ratio. For a bypass ratio of 7, a fan augmentation factor of 2.5 is attainable for a sea level standard day. This data has been proven in the Ryan XV-5A, which achieved a *FF* of 2.85 by increasing bypass ratio from the lift fans. *FF* also augments thrust which in turn decreases TSFC (Ashock[5.1]).

Engine TSFC normally increases with a decrease in thrust. With one engine shutdown in cruise, the operating engines can operate at optimal thrust paying no TSFC penalty for the propulsion system to operate at partial power. Normally with two out of four engines operating, 50% of thrust is lost. Because of lower fan disk loading only 35% of fan thrust is lost during cruise. According to data obtained by GE cruise fan tests (Ashock[5.1]), *FF* still decreases TSFC of the system up to M = 0.8.

Due to the inaccessibility of engine data for particular engines, ONX/OFFX[5.4] was used to model the generator used to drive the cruise fans. The model was based on low bypass turbofan and turbojet engines and was calibrated to match data from the Aviation Week Source Book. The fan factor was then incorporated from Ashock[5.1] and Wilkinson[5.6] to match the integration of the cruise fan and generators. Thrust required was finalized through performance analysis. Engine selection was based on engine thrust available and the lowest TSFC. The Rolls Royce Adour Mk. 871 from the Aviation Week Source Book[5.2] was chosen as the best match for our requirements.

4.3. Engine Removal

The engine is removed from the aircraft through a structural access door in the bottom of the nacelle around the generators. Figure 4.4 shows the engine removal path and the maintenance access doors for the cruise fan. The access doors allow for maitenence on the cruise fans without removal from the nacelles. No components of the cruise fans need to be removed to acces the generator engines. The generator engine is first decoupled from the scroll. Then the engine is lowered by winch to the elevated cart platform. The cart platform is then lowered and rolled toward the front of the aircraft.

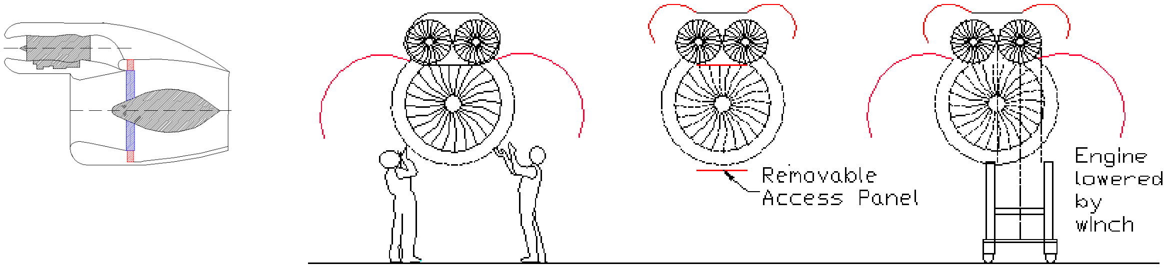


Figure 4.4 - Engine Removal

4.4. Fuel Capacity

Integral wing fuel was selected to house the fuel necessary for flight in the wing box, and in bladder tanks under the fuselage. Vent tanks were placed at the ends of each wing tank (Figure 5.5). The fuel tank under the fuselage is the reserve tank and is located in the main landing gear fairing ahead of the retracted landing gear. The two fuel tanks installed on the fuselage were to keep the fuel tankage in the outer wings to a minimum to reduce wing folding loads.

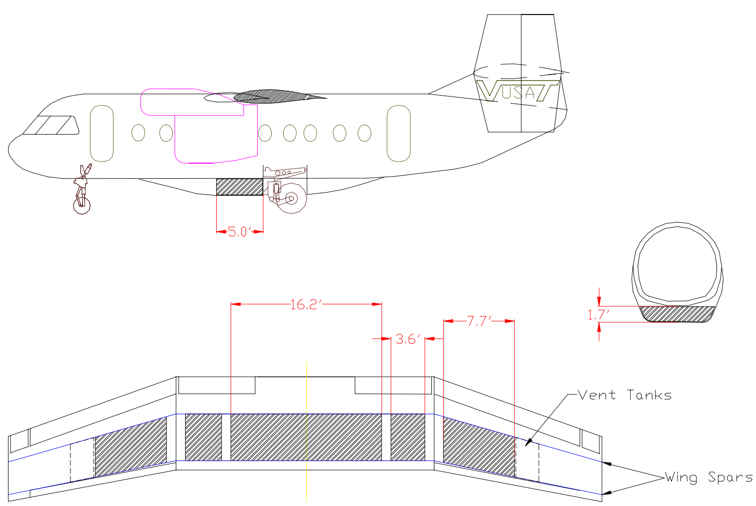


Figure 4.5 - Fuel Tank Configuration

The pounds of fuel along the span of the wing box was calculated using a strip method assuming 92% usable fuel volume between the outer airfoil ordinates and front and aft spar webs, and terminated when the desired fuel load of 11,000 pounds was accommodated. This tankage was checked against Raymer's[2.1] method of integrating the airfoil between the tank end and taking 85% of that volume to be usable (accounting for the additional wing structure fore and aft to the spar box) and found to be reasonably close. The volumes of this area were found using AutoCAD's area and dimensional tools.

Figure 5.6 shows the pounds of fuel per inch across the span of the aircraft. In addition to the 7-15% used to account for wing structure, an addition foot of span was left out about the wing fold Axis and the cruise fan tilt actuator. (Figures 5.5,5.6)

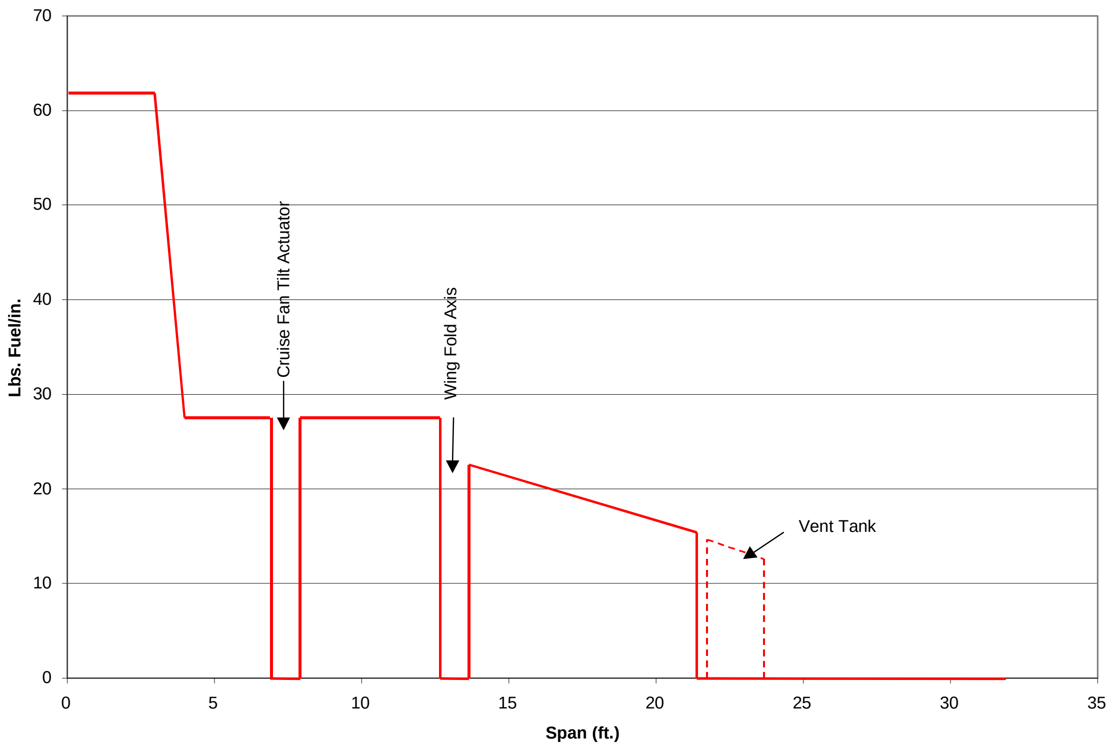


Figure 4.6 - Pounds of Fuel per Inch Across the Span

5. Weights and Balances

5.1. Weight Component Breakdown

Weight estimates made for each major component of the Skyhopper were found using statistical equations based on Roskam's[6.1] Class II Method. Two versions of weights were calculated to account for the commercial and military configurations of our airplane. Table 5.1 was developed to show the breakdown of the component weights and the changes necessary to convert the military design to a commercial aircraft. One of the main differences between versions was the development of a new tail cone section for commercial use that helped decrease the weight of the fuselage by nearly 1800 lbs. It should be noted that the entire tail assembly, the H-tail and mounting pylon is retained in the conversion to the civilian version. Reasons for other significant changes in weight include wing fold penalties, fuel weight, payloads and required military systems such as chaff and flare deployment and in-flight refueling.

Table 5.1 - Summary Group Weight Statement

Operational Aircraft - Tiltengine Summary Group Weight Statement					
Group / Configuration	Military Weight	Additions for Civilian	Subtractions for Civilian	Reasons	Civilian Weight
Wing (Includes high lift devices, ailerons, spoilers and wing fold penalty)	2962.1		-445.0	No wing fold penalty	2517.1
Horizontal Tail	415.1				415.1
Vertical Tail	890.2				890.2
Fuselage (Cargo floor w/aft roll-down ramp tail section)	6878.6		-1782.3	Commercial floor, tail section	5096.4
Nacelle (includes air induction system)	781.4				781.4
Landing Gear	1697.8				1697.8
Cruise Fan Tilt Mechanism	500.0				500.0
Structure Subtotal - Lbs	**14125.2**		**-2227.2**		**11898.0**
Engines (Oil system and cooler)	4036.0				4036.0
Cruise Fans	1160.0				1160.0
Fuel System	904.1				904.1
Inflight Refueling System (Retractable probe)	241.3		-241.3	Not required	0.0
Fuel Dumping System	26.9				26.9
Proplusion System (Wp = Wec+Wess)	157.3				157.3
Engine Controls	52.7				52.7
Engine Starting System	104.6				104.6
Powerplant Subtotal - Lbs	**6525.6**		**-241.3**		**6284.3**
Flight Control Sys.(w/hydraulics and pneumatics)	397.2				397.2
Electrical System	1617.9		-47.6	No military systems inc.	1570.3
Instrumentation, Avionics and Electronics (Inc. IFF system, RWR, IRWR, chaff and flares)	1016.0		-110.0	No military systems inc.	906.0
A.C., Pressurization, Anti- and De-Icing Sys.	2103.3				2103.3
Oxygen System (Passenger cabin and cockpit)	89.7				89.7
APU	350.0				350.0
All Furnishings (Includes lavatory)	418.2	1341.1		Seating and Galley	1759.3
Baggage and Cargo Handling System	960.0		-860.0	Handling Sys.	100.0
Paint	160.8				160.8
Fixed Equipment Subtotal - Lbs	**7113.1**	**1341.1**	**-1017.6**		**7436.6**
Empty Weight Total - Lbs	**27763.9**	**1341.1**	**-3486.1**		**25618.9**
Mission Fuel-Wing Tanks	11052.3		-1095.1	Less fuel cruise	9957.2
Mission Fuel-Lower Fuse. Tanks (Trapped fuel included)	2647.5	785.8		More reserves	3433.3
Design Cargo Weight	10000.0		-10000.0	No cargo	0.0
Trapped Oil	350.0				350.0
Crew	400.0	200.0		1 Attendent	600.0
Passengers	0.0	6000.0		Commercial usage	6000.0
Takeoff Weight Total - Lbs	**52213.7**	**8326.9**	**-14581.2**		**45959.4**

5.2. Center of Gravity Position and Travel

Center of gravity (C.G.) positions were located for each major component and placed on a side view drawing of the "commercial version" Skyhopper in Figure 5.1. During flight, the position of the C.G. moves as fuel is burned. To keep the C.G. range within acceptable stability limits, about 25% of the fuel was placed in the reserve bottom tank. This tank is located closer to the nose than the fuel tanks in the wing, thereby reducing the moment created by the vectored thrust. Figure 5.2 shows the longitudinal C.G. location and weight of the aircraft at each stage of flight for both military and commercial versions.

Table 5.2 - Commercial C.G. Location

Component #	Commercial Version	X-position from nose	Z-position from ground
1	Wing (includes normal high lift devices and ailerons) (Includes Spoilers! No Wing Fold Penalty!)	27.3	12.3
2	Horizontal Tail	54.1	15.3
3	Vertical Tail	53.9	14.4
4	Fuselage w/Commercial Tail Section	29.7	6.5
5	Nacelle (Includes Air Induction System)	19.6	12.0
6	Landing Gear	24.0	3.1
7	Cruise Fan Tilt Mechanism	23.5	12.0
8	Engines (Oil System and Cooler)	17.5	12.0
9	Cruise Fans	20.2	9.0
10	Fuel System	25.5	3.2
11	In-Flight Refueling Sys. (Not Req'd for Commercial)	-	-
12	Fuel Dumping System	26.8	2.5
13	Engine Controls	3.5	7.6
14	Engine Starting System	17.0	12.0
15	Flight Control System (w/hydraulics and pneumatics)	25.7	12.6
16	Electrical System and Batteries	16.0	10.5
17	Instrumentation, Avionics and Electronics	3.2	7.0
18	A.C., Pressurization, Anti- and De-Icing Systems	6.0	4.3
19	Oxygen System	18.7	10.9
20	APU	6.0	4.3
21	All Furnishings (Includes lavatory)	23.8	6.5
22	Baggage and Cargo Handling System	48.4	7.4
23	Paint	30.3	8.6
24	Mission Fuel-Wing Tanks	26.5	12.0
25	Mission Fuel-Lower Fuselage Tanks (Trapped Fuel Included)	25.0	3.0
26	Design Cargo Weight	30.6	8.1
27	Trapped Oil	17.5	12.0
28	Crew	5.4	7.2
29	Passengers	26.5	6.8

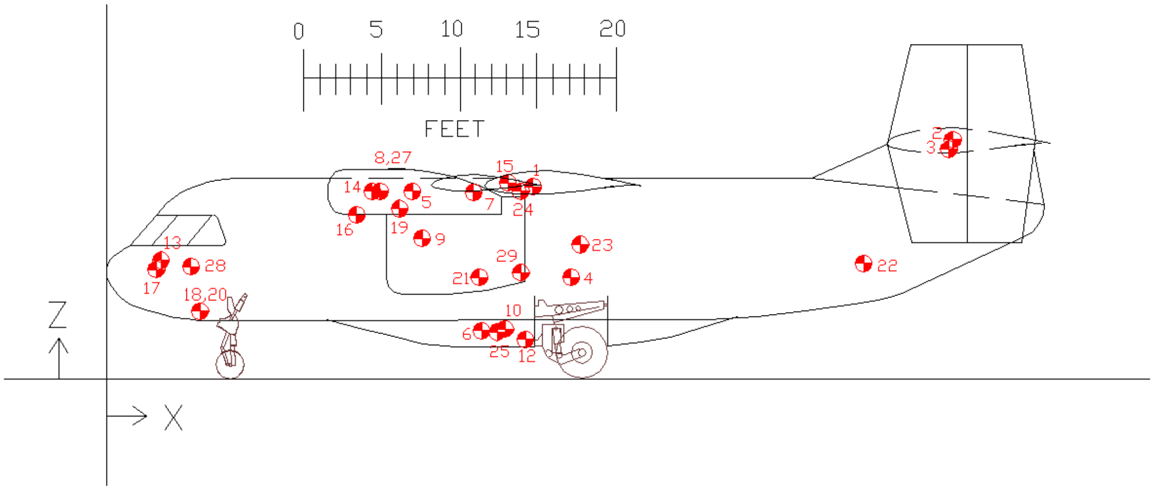


Figure 5.1 - C.G. Breakdown

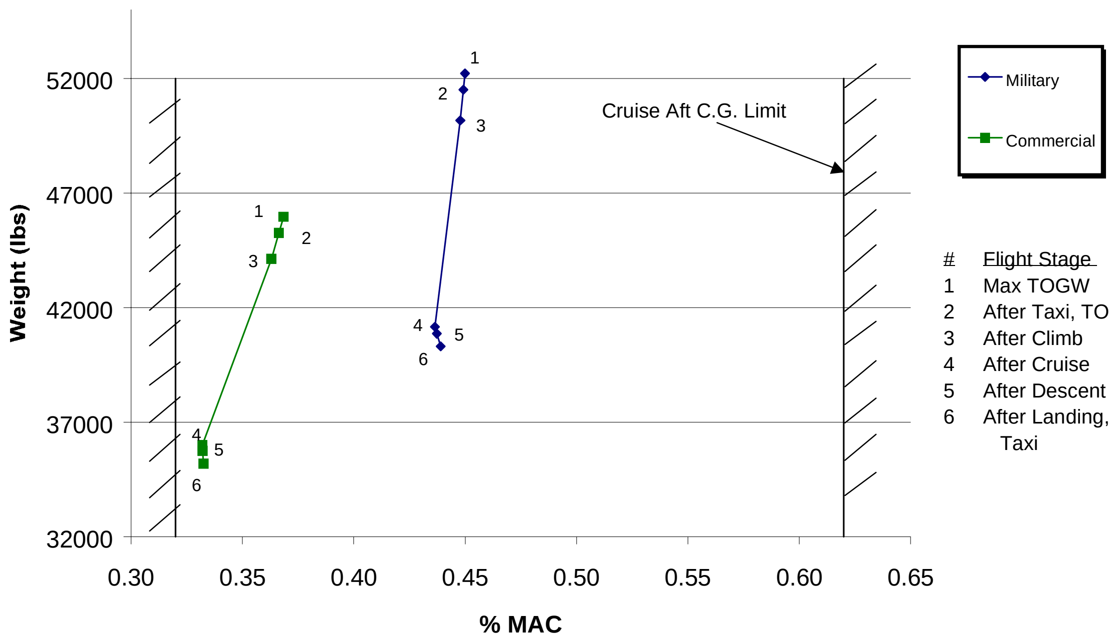


Figure 5.2 - C.G. Envelope Performance

6. Performance

6.1. Takeoff Analysis

The AIAA RFP requirement was for a takeoff ground roll less than 300 feet on a standard atmosphere plus 27° F (85.69° F) day. This temperature decreases the air density from 0.002379 slug/ft^3 to 0.002262 slug/ft^3. It was recognized that equation 2.1 derived in chapter 2 was insufficient for calculating the takeoff distance because it neglected the FAR and MIL stall speed requirements of the aircraft. Table 6.1 lists the appropriate liftoff and landing approach speed requirements for each aircraft.

Table 6.1 - Stall Velocity Requirements

AIRCRAFT TYPE	TAKEOFF	LANDING	REFERENCE
Military	$V_{LOF} \geq 1.1V_{Stall}$	$V_{app} \geq 1.2V_{Stall}$	MIL-C-005011B*
Commercial	$V_{LOF} \geq 1.2V_{Stall}$	$V_{app} \geq 1.3V_{Stall}$	FAR 25*

*Roskam

The stall speed is calculated from Equation 4.1, where W/S_{eff} is the effective wing loading as described in Chapter 2. The liftoff speed is dependent on the acceleration due to the horizontal component of the engine thrust, and the distance traveled.

$$V_{Stall} = \sqrt{\frac{2(W/S)_{eff}}{\rho C_{L\max}}} \qquad \textbf{(4.1)}$$

With the 300 ft takeoff distance and an acceleration limit of 0.4 g for the commercial design, the maximum time for the entire takeoff run would be around 6.8 seconds. This time was judged to be too short for a pilot to make an emergency stop decision in case of an engine loss. For safety reasons it was decided to have thrust levels sufficient to provide takeoff speeds with only three of the four generator engines in operation. From the propulsion analysis, the maximum available thrust from the cruise fan system on a SA plus 27° F day was 53,900 lbs. With one generator not in operation a total thrust loss of only 17.5% results due to lower disk loading on the cruise fan, leaving an available thrust of 44,467 lbs. The absolute minimum thrust necessary for the military takeoff run was determined to be 42,400 lbs.

The takeoff thrusts and vector angles were determined to create liftoff velocities in accordance with the appropriate stall speed requirements described in Table 6.1. Table 6.2 is a list of the takeoff parameters for both the normal takeoff run with all generators operating, and the emergency run with one engine out. Note that the acceleration for the military aircraft is not restricted by the 0.4 g acceleration limit. This is also the case for the commercial version during emergency situations. It is assumed that in case of an engine failure, the flight control system would increase the thrust of the operating gas generators and make needed changes in vector angles during the spool down time of the inoperable engine.

Table 6.2 - Takeoff Parameters

Aircraft	TOGW (lbs)	Thrust (lbs)	Vector Angle (deg)	V_{LOF} (knots)	V_{Stall} (knots)	Acceleration (g's)	**Takeoff Distance (ft)**
Military (4 engines)	52213	53900	37	74.6	54.1	0.82	**300**
Military (3 engines)	52213	44467	37	67.8	61.4	0.68	**300**
Commercial (4 engines)	45959	49000	68	52.0	8.84	**0.4**	**300**
Commercial (3 engines)	45959	44467	66.5	52.0	27.7	**0.4**	**300**

6.2. Climb and Cruise Analysis

Both the climb and cruise portions of the mission are executed with two of the four gas generators turned off. The climb portion of the RFP required that the aircraft climb at best rate of climb to the best cruising altitude, and cruise for 1500 nmi. The best climb rate to cruise altitude varied, but on average was 2570 fpm for the commercial design, and 2235 fpm for the military design. The climb rates were higher for the civilian version due to the decreased TOGW of the aircraft.

Cruise requirements stated a minimum cruise speed of 350 knots, and minimum range of 1500 nmi. To avoid transonic drag issues, a maximum cruise Mach number of 0.65 was used. A cruise analysis following the method described in Roskam[4.3] was used to create a specific range diagram (Figure 6.1). Specific range was determined from equation 4.2 and used to find the optimal cruise conditions for both aircraft, where C is the TSFC, and W_{av} is the average cruise weight.

$$SR = \frac{\frac{V_{cr}}{C}\left(\frac{L}{D}\right)_{cr}}{W_{av}} \qquad \textbf{(4.2)}$$

Considering the high thrust to weight ratio necessary for takeoff, the cruise fan propulsion system, with one gas generator per cruise fan, was able to obtain a nominal cruise TSFC of 0.62 lb/hr/lb. This resulted in minimal cruise performance penalties when compared to other high bypass engines. Results from the specific range analysis are listed in Table 6.3.

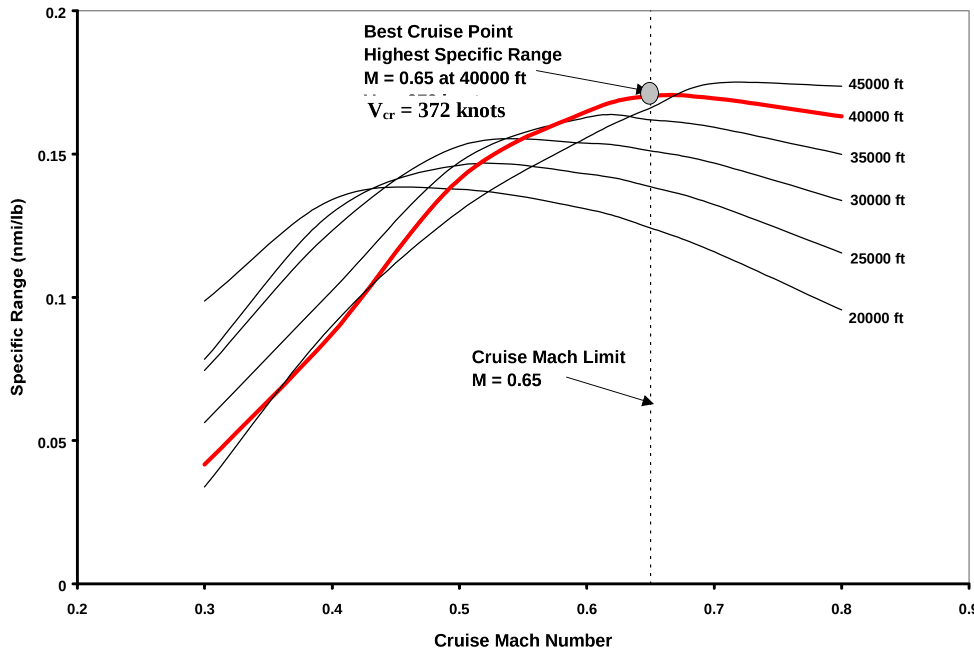


Figure 6.1 - Specific Range Analysis (Commercial Design)

Table 6.3 - Best Cruise Parameters

Aircraft Version	M_{cr}	V_{cr} (knots)	Cruise Altitude (ft)	TSFC (lb/hr/lb)
Military	0.65	372	40000	0.62
Commercial	0.65	372	40000	0.62

6.3. Landing Analysis

The RFP requirement called for landing with domestic fuel reserves within a ground roll of 400 feet. The appropriate landing approach speed requirements were listed previously in Table 6.1. Figure 6.2 is a diagram of the approach and ground roll for the SSTOL aircraft. A concern during landing was the creation of more drag than thrust without the complication of speed brakes. A solution was found by vectoring the engines to high angles. This reduced the horizontal component of the thrust levels necessary for the approach. Wing spoilers could not be used during approach because they effectively terminate any lift generated by the wings. However, they could be used during the ground roll as “lift dumpers” to increase the weight on the main wheels for improved braking. The ground run distance was calculated from the method in Roskam[4.3], where the braking distance is $D_b = \frac{V_{TD}^2}{2a}$. The average deceleration was determined for an aircraft with spoilers acting as lift dumpers, speed brakes at touchdown, and anti-skid devices during the attendant rollout. The military version had an average deceleration of 0.5 g, while the commercial aircraft was limited to a deceleration of 0.4 g. The pilot was allotted the first 1.5 seconds of the ground roll to make a decision to abort the landing. The rest of the ground roll was scheduled for braking and deceleration to achieve a total 400 foot ground roll. It is assumed again that in the case of an engine loss, the flight control system would increase the thrust of the operating generators and make needed changes in vector angles to continue with the approach or abort the landing. Table 6.4 is a breakdown of the important landing factors.

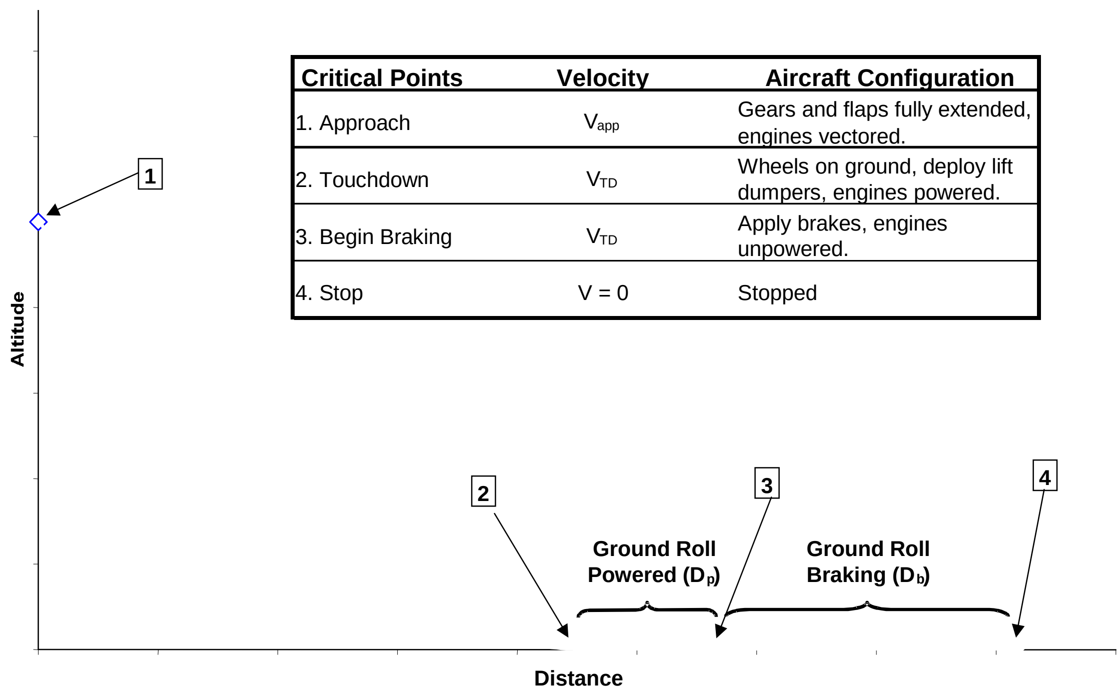


Figure 6.2 - Approach and Ground Roll Diagram

Table 6.4 - Landing Parameters

Aircraft	Landing Weight (lbs)	Thrust (lbs)	Vector Angle (deg)	V_{app} (knots)	V_{Stall} (knots)	V_{TD} (knots)	D_p (ft)	D_b (ft)	**Total Ground Roll (ft)**
Military	40463	25800	84	54.8	45.7	54.3	137.6	261.5	**399**
Commercial	35350	25000	85	49.9	38.4	49.7	125.4	271.2	**397**

6.4. Fuel Requirements

The fuel use of the aircraft was broken up into 7 mission segments. The first was 10 minutes of engine warm up and taxi. The RFP requirement was for 10 minutes of warm up time. Fuel rates at idle thrust levels based on an ONX/OFFX engine model were used to determine the fuel use. The same method was used to determine the second segment fuel consumption for the takeoff run, but with full throttle fuel rates. The climb fuel use was iterated every 5000 feet in altitude. The fuel weight change was calculated from equation 4.3**,** where T is the thrust, and Δt is the time to climb for each climb phase**.**

$$\Delta W_{fuel} = (-CT)\Delta t \qquad \textbf{(4.3)}$$

The fourth mission segment was the cruise phase. The RFP required a 1500 nmi range; for fuel analysis the 1500 nmi was decreased for the range achieved during climb, approximately 68 nmi for the commercial aircraft and 87 nmi for the military version. The Breguet range equation was then used to determine the required fuel amounts. The reserve fuel segments differed greatly between the military and commercial versions. According to the AS-5263 Naval requirement (Roskam[4.3]), a military transport is required to carry 30 minutes of loiter fuel and 5% of the initial usable fuel. The domestic fuel reserves for a commercial transport is essentially equivalent to an additional cruise range of 500 nmi (Loftin[4.1]). This requirement is in excess of the FAR requirement for this type of aircraft. The final two fuel weights were analyzed from the ONX/OFFX model. An addition allowance of 1% for trapped fuel is also allotted (Raymer[4.2]). Table 6.5 is a breakdown of the fuel consumption for each segment of the mission.

Table 6.5 - Fuel Consumption Analysis

	Fuel Consumed (lbs)	
Mission Segment	**Military**	**Commercial**
1. Warm Up and Taxi for 10 min.	307.2	307.2
2. Takeoff	399.6	399.6
3. Climb to Cruise Altitude	1342.7	1127.2
4. Cruise for 1500 nmi	9002.8	8123.2
5. Fuel Reserves	1657.4	2492.2
6. Descent and Landing	700.7	654.9
7. Taxi for 5 min.	153.6	153.6
Addition for 1% Trapped Fuel	135.7	132.6
Total	**13699.8**	**13390.5**

7. Aerodynamics

7.1. Design Drivers

The design drivers for the wing of the Skyhopper were identified by investigating other SSTOL aircraft and comparing their aerodynamic properties to those that performance calculations demanded to meet the RFP requirements. Initial performance calculations indicated that a $C_{L\text{-}TO}$ and C_{LMAX} of 3 and 3.6, respectively, were needed in order to achieve the required takeoff and landing distances. These two aerodynamic properties determined the design drivers for the wing. An investigation of SSTOL aircraft tabulated in Table 7.1 indicates that no other similar aircraft could accomplish this feat, which made these goals difficult tasks to accomplish. The data tabulated in Table 7.1 was obtained from Torenbeck[7.5].

Table 7.1 - STOL Comparative Aerodynamic Study*

	Airfoil	t/c	AR	Λ_{LE}	C_{LMAX}
Brequet 941	64_A-218	18%	7	0	2.7
DHC-5 Buffalo	63_A-615	15%	10	0	2.55
DHC-6 Twin Otter	63_A-418	18%	10	0	2.55
DHC-7 Dash 7	63_A-418	18%	10	3	2.21

*All data obtained from Torenbeck[7.5]

7.2. Airfoil Selection

A high lift airfoil, which would be able to generate the necessary lift for takeoff, was the next step in the aerodynamic design of the wing. Various airfoils were investigated and it was determined that a NACA 63_A series airfoil would be the appropriate choice because of their high lift, low drag characteristics, as well as its known success in other STOL aircraft.

After investigating the aerodynamic properties of various NACA 63_A airfoils, the 63_A-415 was chosen and can be seen in Figure 7.1. This high lift, low drag airfoil generates a clean C_{lmax} of 1.7 at an α of 16^o, a C_{L0} of 0.4, and has its maximum thickness at 30% of the chord. A *t/c* of 15% creates a large leading edge, providing a gradual loss of lift with small pitching moment changes.

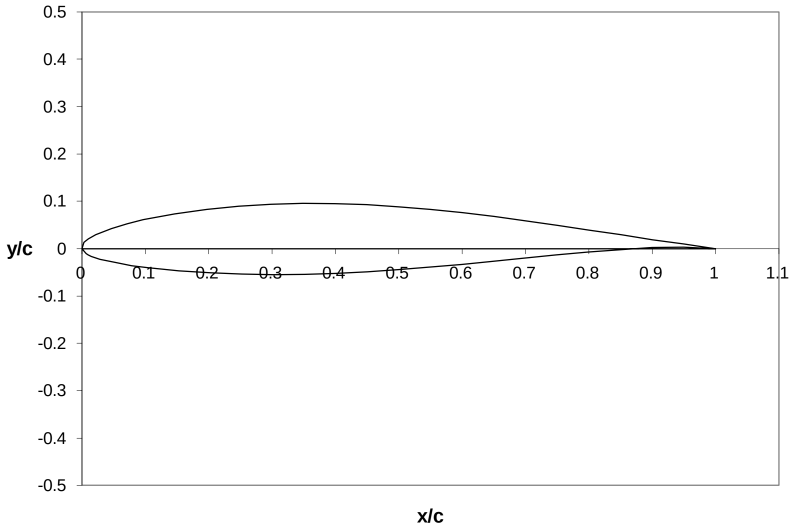


Figure 7.1 - NACA 63_A-415 airfoil

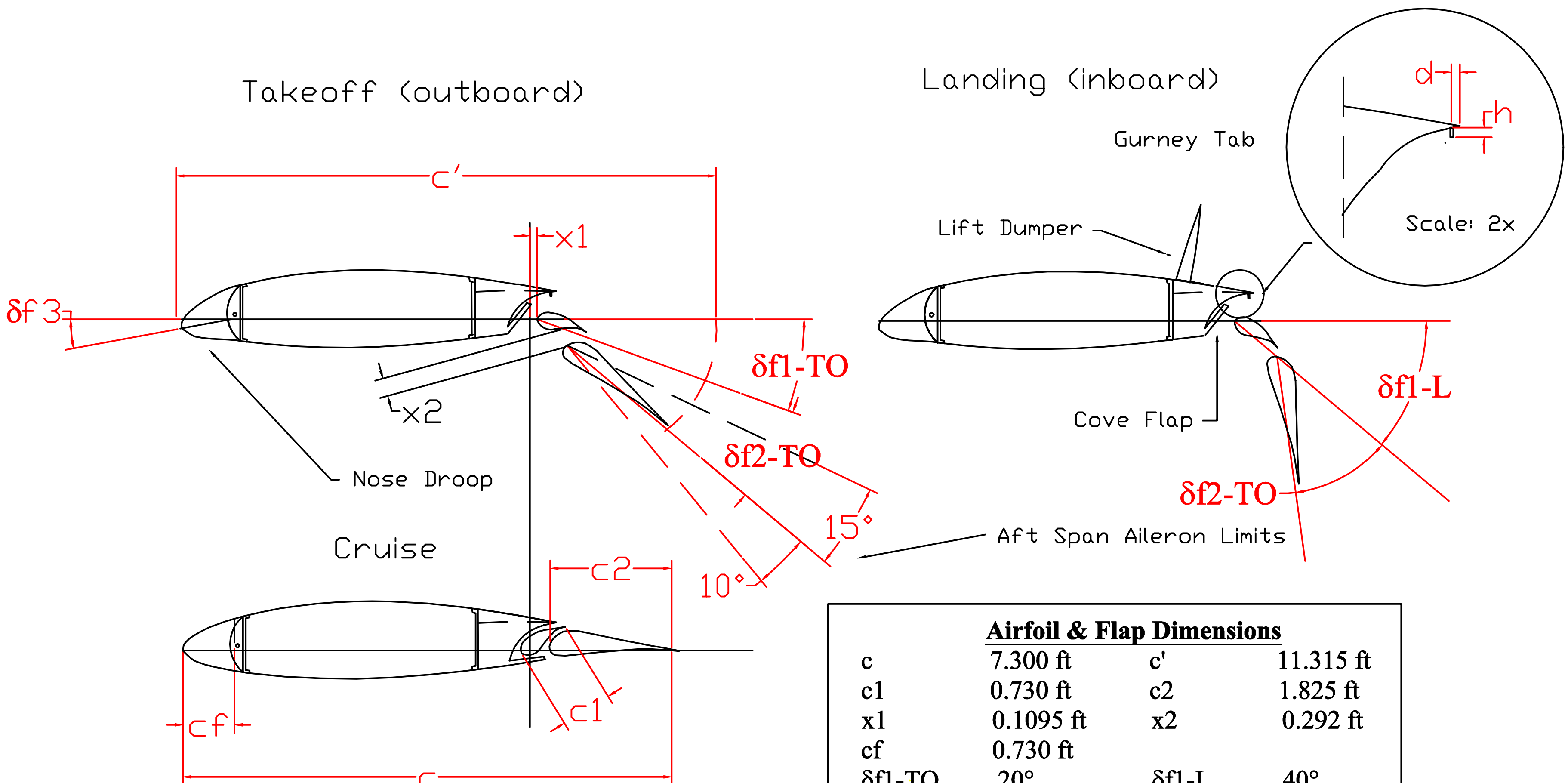
7.3. Wing Geometry and High Lift Devices

The comparative study, as well as stability and control issues, influenced the geometry of the wing planform. Ranges for basic wing geometry came from historical trendlines and from basic calculations outlined in Raymer[7.3]. With ranges for the geometric properties, the final geometry of the wing was determined by considering performance, stability, control and aesthetics. After making these considerations, the wing planform dimensions of S, AR, and λ were chosen to be 580 ft^2, 6.9,and .71, respectively. The sweep of the wing was chosen such that the Skyhopper's stability margin was acceptable for cruise, which is why an unconventional forward sweep of 11 degrees quarter chord was chosen. The forward sweep of the outer panel should provide excellent aileron control.

Finalizing the wing design enabled the aerodynamic properties of the Skyhopper to be determined, as outlined in Roskam[7.4]. Taking into account a loss of C_L of approximately 0.2 due to blockage effects of the engines, these calculations indicated that without high lift devices, the wing would obtain a C_{LMAX} of 1.5, at α=10, with a lift curve slope of 5.20/rad (0.09/deg), and a C_{L0} of 0.4. It is evident from these calculations that high lift devices would be necessary. High lift options were required for the Skyhopper to produce the needed ΔC_{LMAX} of 2. No conventional flap system investigated could perform this feat, and circulation control was left as a last resort due to their complexity, unreliability, and weight. The only system that would give the required ΔC_{LMAX} was the full span double-slotted flap with a nose droop, as seen on the DHC-Buffalo. These high lift devices increase the camber of the airfoil, thus increasing the C_{LMAX} and α_{STALL}. Lift-enhancing tabs shown together with the entire flap system, in Figure 7.2, were also integrated into the flap system ensuring that the necessary C_{LMAX} can be obtained. These tabs are located just in front of the trailing edge of the first element of the flap and extend down approximately 0.05c. The purpose of these tabs is to delay the flow separation on the flap, which significantly increases the C_{LMAX}. Experimental data obtained from Carrannanto[7.1] indicates that an increase of C_{LMAX} of 5% is obtainable assuming the placement of the tab is optimum, as specified. The lift-enhancers, as seen in Figure 7.2, were also implemented to assist the flow through the gap to regenerate the main airflow.

Thus, it was decided that a full span double-slotted flap system similar to that of the Breguet 941S, lift-enhancing tabs and a nose droop, as seen in Figure 7.2, must be integrated into the wing to accomplish the necessary goals. This flap system would increase C_{L0} to 2.11, and C_{LMAX} to 3.6.

Figure 7.3 shows C_L plotted versus α for takeoff and cruise. The curve was plotted to an α of 10^{o}. The dotted curve was approximated using empirical data and historical trends to find the max C_L. Obtaining the C_{LMAX} of 3.6, necessary for performance requirements, is expected from the results of the empirical data.



	Airfoil & Flap Dimensions		
c	7.300 ft	c'	11.315 ft
c1	0.730 ft	c2	1.825 ft
x1	0.1095 ft	x2	0.292 ft
cf	0.730 ft		
δf1-TO	20°	δf1-L	40°
δf2-TO	20°	δf2-L	40°
δf3-TO	10°	δf3-L	10°
d	0.073 ft	h	0.0365 ft

VUSAT

NACA 63A–415 CROSS SECTION

Date: 5/15/99

SHEET NO: 5

Fig.: 7.2

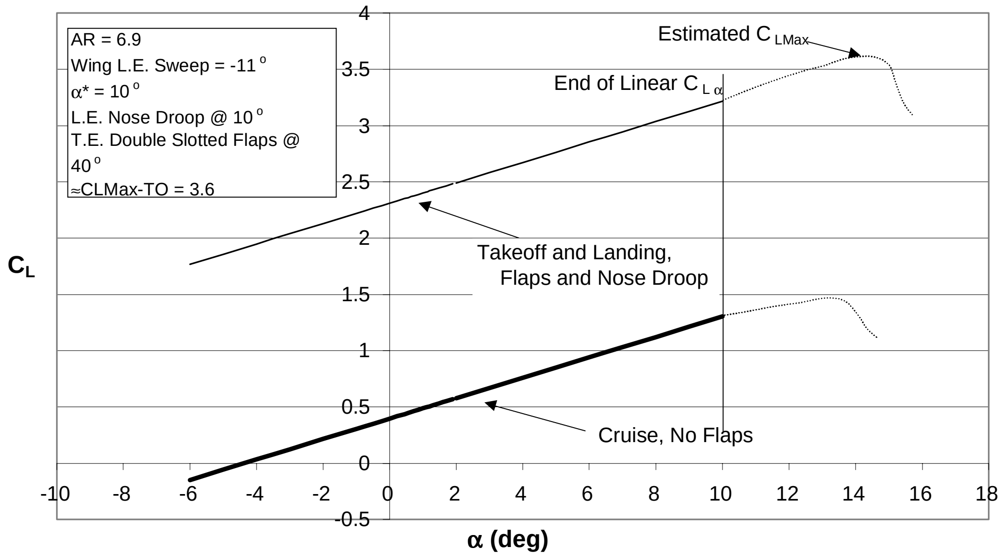


Figure 7.3 - Skyhopper Lift Curve Slope (C_L vs. α)

7.4. Drag Predictions

The drag of the Skyhopper was predicted following the methods outlined in Roskam[7.4]. Empirical data along with theoretical data are combined in these methods to estimate the drag of the complete configuration. The method consists of calculating the component parasite drag from the fuselage, wing, powerplant, empennage, landing gear, high-lift devices, and trim surfaces. Components of the parasite drag were calculated using the characteristic length of their surfaces and Reynolds number to obtain their friction coefficient from the Prandl Glavert curve, then transformed with respect to the wing reference area and summed. The breakdown of the parasite drag for the Skyhopper is displayed in Table 7.2. The parasite drag is summed for the configuration and added to the drag due to lift to predict a drag polar for the aircraft. Figure 7.4 and Figure 7.5 display the drag polar for takeoff, landing and cruise conditions.

Table 7.2 - Parasite Drag Build Up

Conditions	*Takeoff*	*Cruise*	*Landing*
Altitude	Sea-level	40,000 ft	Sea-level
Flaps	40^o	0^o	80^o
Gear	Extended	Retracted	Extended
C_L	1.9	0.55	2.55
Component C_{DO}			
Fuselage	0.00330	0.00341	0.00330
Wing	0.00640	0.00702	0.00640
Empennage	0.00534	0.00586	0.00534
Powerplant	0.04326	0.00369	0.04326
Trim	0.06632	0.00686	0.06632
Landing Gear	0.04783	0.00000	0.04783
Flaps	0.10325	0.00000	0.20651
Leakage & Protuberance	0.00130	0.00130	0.00130
Total C_{DO}	**0.27700**	**0.02814**	**0.38026**

Landing calculations indicated that the Skyhopper would be accelerating during landing due to the engine vector angle. It was calculated that a C_D of 1.2 on landing would be necessary to counter this acceleration. Thus the C_{DO} of the Skyhopper would have to increase approximately 0.11 during landing. It was determined that the best solution would be to increase the flap deflection angle to 80^o which would increase the drag. Lift dumpers were also added to the wing for landing; they are deflected up upon touch down in order to "kill" the flow, stalling the flaps such that a maximum load is placed on the Skyhopper's landing gear.

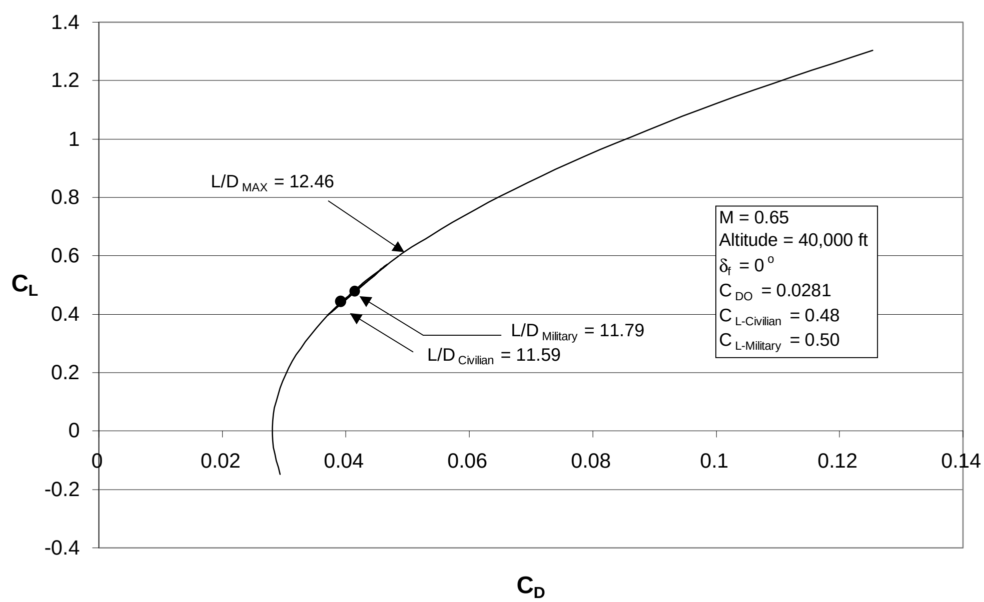


Figure 7.4 - Drag Polar (Cruise)

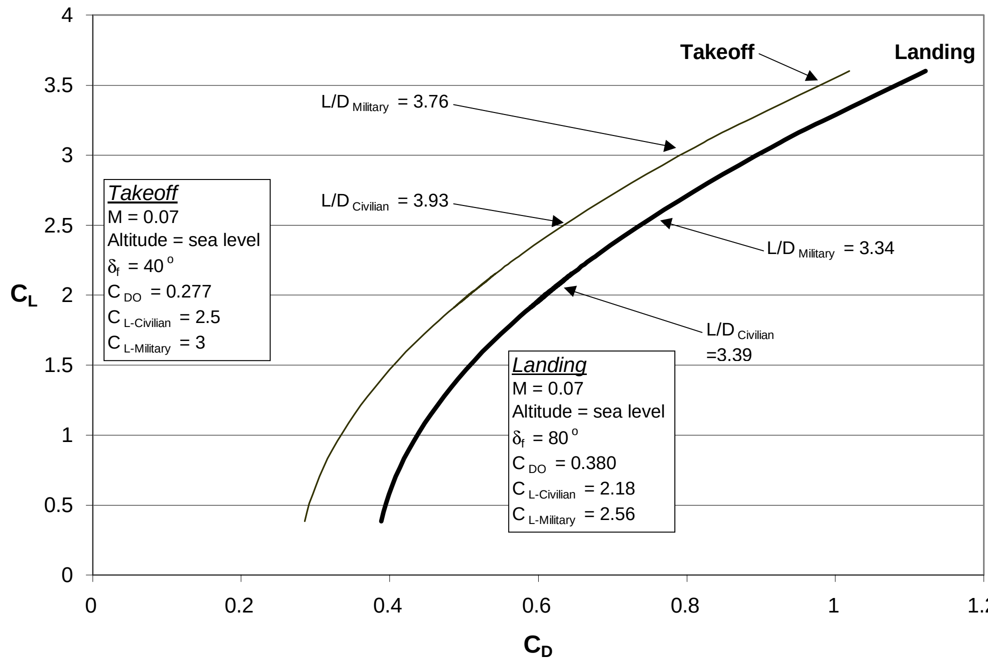


Figure 7.5 - Drag Polar (Takeoff and Landing)

7.5. Special Considerations

Due to the complexity of the Skyhopper configuration, there are unknowns that might arise during wind tunnel and flight tests. Topics that need to be investigated during these tests include ground effects on takeoff and landing, extra lift generated from the horizontal tail on takeoff, upwash on the tail from the recirculating air on takeoff and landing, and an increase in aerodynamic lift due to the conservative geometric properties used in calculations. Powered wind tunnel tests with variable height ground boards as well as full scale propulsive tests in varying cross flow directions will be a necessity before the configuration of the Skyhopper is finalized.

8. Stability and Control

8.1. Overview

The Skyhopper uses eight individual control surfaces to provide the counter moments necessary for takeoff, landing, and transition under full power and with engine out.

The aerodynamic control surface layout can be seen in the general arrangement of the Skyhopper, Figure 3.1. The most noticeable of these surfaces is the large horizontal tail, sized to offset the moments produced by the engines at their specified takeoff and landing angles. The surface area of the horizontal tail is 263 ft^2, a double elevator is used to provide the required control power during takeoff and landing with areas of 56.2 ft^2 for the main elevator and 37.7 ft^2 for the secondary elevator. Two full span double slotted flaperons located on the trailing edge of each wing are deflected to provide necessary lift, as well as providing some roll control with aft section ailerons. Two outboard ailerons are also provided to counter the rest of the rolling moment during emergency engine out situations at takeoff and landing. The flaperons have an area of 26.5 ft^2, and the outboard ailerons an area of 7.6 ft^2. The two vertical control surfaces are the large 49.4 ft^2 rudders on the H-tail. The main purpose of these rudders is to provide enough control power to overcome the yawing moment during engine out.

The Skyhopper's flight control system is a fly-by-wire system that will regulate the engine vector angle and all control surface deflections during takeoff, landing, and transition. The fly-by-wire system is reviewed in Chapter 10.

8.2. Method of Analysis

Stability and control analysis was carried out using different sources and methods. A combination of the abbreviated USAF DATCOM method presented in Etkin and Reid[8.1], and Roskam's[8.4, 8.5] method of calculating control derivatives were the primary source for the control and stability analysis of the Skyhopper. Some of the control derivatives were checked using a FORTRAN code[8.2] that uses a ring vortex method to predict the effects of control surface deflections.

Because of the unconventional takeoff and landing schedules of the Skyhopper, detailed analysis was performed on these two driving flight conditions. Schedules for the engine angle, thrust, and velocity were developed based on performance requirements. The main driver for control was the ability to counter the large nose up pitching moment produced by the engines, making use of the high-lift system and all available control surfaces, while flying at the low takeoff speed.

8.3. Static Stability

Approximate curves for the lift coefficient versus angle of attack for the planform were presented in Chapter 7. This data, along with Roskam's[8.4, 8.5] method to estimate the effects of the engine nacelles on the aerodynamic center, helped to determine the neutral point location of the whole aircraft. The aerodynamic center was calculated to be at 62% of the mean aerodynamic chord. The large horizontal tail is one of the main factors in the neutral point being located so far aft; however, the added engine projection area offset about 20% of the tail effect and helped to keep the neutral point closer to the C.G. location of the Skyhopper. The aft location of the neutral point keeps the Skyhopper stable throughout the flight envelope, becoming most stable at landing. The forward limit is governed by the size of the tail, which is sized by the pitching moment from the engines, giving the Skyhopper a wide limit range for the C.G. travel. The C.G. limits and all C.G. positions for the flight envelope can be seen in Figure 5.2.

8.4. Wing Placement and Tail Geometry

The distance from the thrust line to the center of gravity determined the location of the wing for the Skyhopper. The wing and engine combination was placed as close to the C.G. location as possible to provide the smallest nose up pitching moment for the specific engine vector angle. The tail was then sized to offset this pitching moment produced at takeoff. Figure 8.1 is a plot used to visualize the tail size requirement for the most critical case of civilian takeoff with four engines. A certain pitching moment is provided by the aerodynamics of the plane and engine thrust, the tail and elevators are sized to counter this moment. Using an H-tail design enabled the horizontal tail to increase in lift almost 20%, due to an endplate effect (Perkins[8.3]). This effect was based on the ratio of horizontal tail span to vertical tail span. The first tail design used one elevator, but did not provide enough control power. The second design, with the added elevator being deflected another 25^o, was able to maintain control with a horizontal tail area of 263 ft^2. The tail is set at a zero incidence angle which provides enough counter moment at takeoff, but reduces the amount of nose down moment during cruise.

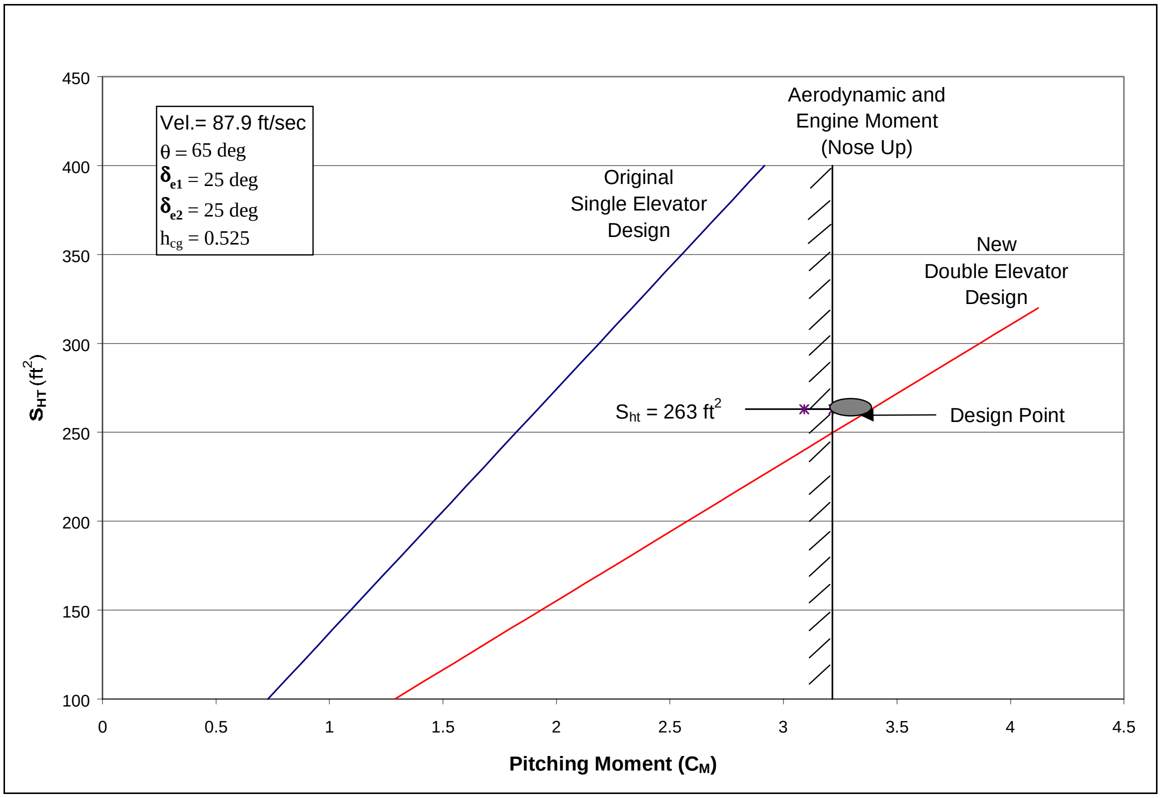


Figure 8.1 - Tail sizing

8.5. Trim

The greatest difficulty in trimming the Skyhopper occurs during takeoff and climb. The tail was sized, as described above, for this reason. Table 8.1 shows the control surface deflection schedule for trim during a four engine civilian takeoff run, which is the worst case scenario for longitudinal control due to the high vector angle of the engines. The vector angle continues to zero during the climb while the thrust stays constant. The military design is less of a problem due to the faster takeoff speed and lower engine vector angle.

Table 8.1 - Trim schedule during a four engine civilian takeoff and transition

Vx (knots)	Theta (deg)	Total Thrust (lbs)	Flaps (deg)	Elev (1) (deg)	Elev (2) (deg)	Aft Flap Ail (deg)	Outboard Ail (deg)	Rudders (deg)	Extra Aileron (deg)	Bank Ang (deg)
52.0	68.0	48511.1	40.0	25.0	27.9	0.0	0.0	0.0	0.0	0.0
62.0	66.0	44679.0	40.0	15.0	15.7	0.0	0.0	0.0	0.0	0.0
70.9	64.0	41454.8	40.0	9.0	10.4	0.0	0.0	0.0	0.0	0.0
78.6	62.0	38708.6	40.0	5.0	9.0	0.0	0.0	0.0	0.0	0.0
85.2	60.0	36345.2	40.0	2.0	9.2	0.0	0.0	0.0	0.0	0.0
90.8	58.0	34293.1	40.0	1.0	7.2	0.0	0.0	0.0	0.0	0.0
95.4	56.0	32497.9	37.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0
99.2	54.0	30917.0	34.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0
102.4	52.0	29517.2	31.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0
104.9	50.0	28271.5	28.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0
107.0	48.0	27158.5	25.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0
108.6	46.0	26160.5	22.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
110.0	44.0	25262.9	19.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0
111.1	42.0	24453.6	16.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0
111.9	40.0	23722.6	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0
112.6	38.0	23061.3	0.0	0.0	-1.5	0.0	0.0	0.0	0.0	0.0
113.2	36.0	22462.6	0.0	0.0	-1.9	0.0	0.0	0.0	0.0	0.0
113.6	34.0	21920.1	0.0	0.0	-2.3	0.0	0.0	0.0	0.0	0.0

Lateral trim was analyzed for the case of engine out. Control of the engine out case was driven by the possibility that engine out would occur on the takeoff run. For this reason the sideslip angle was set to zero in the analysis, to provide ease in takeoff. Table 8.2 shows the control surface deflections during takeoff with a single engine failure on the right side. The control surfaces are able to provide almost all of the countering moments, with only a small bank angle needed. Table 8.2 shows that there is ample power during engine out for longitudinal, lateral, and directional control.

Table 8.2 - Trimming schedule for a right engine out civilian takeoff and transition

Vx (knots)	Theta (deg)	Total Thrust (lbs)	Flaps (deg)	Elev (1) (deg)	Elev (2) (deg)	Aft Flap Ail (deg)	Outboard Ail (deg)	Rudders (deg)	Extra Aileron (deg)	Bank Ang (deg)
52.0	68.0	40021.7	40.0	25.0	10.0	10.0	10.7	-13.2	0.0	0.2
62.0	66.0	36860.2	40.0	15.0	4.3	10.0	3.4	-8.5	0.0	0.2
70.9	64.0	34200.2	40.0	9.0	2.5	7.0	2.5	-6.0	0.0	0.2
78.6	62.0	31934.6	40.0	5.0	3.1	5.0	2.2	-4.6	0.0	0.2
85.2	60.0	29984.8	40.0	2.0	4.6	5.0	0.8	-3.7	0.0	0.2
90.8	58.0	28291.8	40.0	1.0	3.4	5.0	-0.2	-3.1	0.0	0.1
95.4	56.0	26810.8	37.0	0.0	3.3	5.0	-0.9	-2.6	0.0	0.1
99.2	54.0	25506.6	34.0	0.0	1.7	5.0	-1.4	-2.3	0.0	0.1
102.4	52.0	24351.7	31.0	0.0	0.5	5.0	-1.8	-2.1	0.0	0.1
104.9	50.0	23324.0	28.0	0.0	-0.4	5.0	-2.0	-1.9	0.0	0.1
107.0	48.0	22405.8	25.0	0.0	-1.1	5.0	-2.3	-1.7	0.0	0.1
108.6	46.0	21582.4	22.0	0.0	-1.7	5.0	-2.4	-1.6	0.0	0.1
110.0	44.0	20841.9	19.0	0.0	-2.1	5.0	-2.6	-1.5	0.0	0.1
111.1	42.0	20174.2	16.0	0.0	-2.5	5.0	-2.7	-1.5	0.0	0.1
111.9	40.0	19571.2	0.0	0.0	-2.4	5.0	-2.8	-1.4	0.0	0.1
112.6	38.0	19025.6	0.0	0.0	-2.8	5.0	-2.9	-1.3	0.0	0.1
113.2	36.0	18531.6	0.0	0.0	-3.1	5.0	-3.0	-1.3	0.0	0.1
113.6	34.0	18084.1	0.0	0.0	-3.4	5.0	-3.0	-1.2	0.0	0.1

Figure 8.2 shows a graphical representation of the control surface deflections during a right engine out civilian takeoff and transition. The aft-chord ailerons and forward elevator section are scheduled for a

smooth transition to zero deflection, while the outboard ailerons and aft elevator section deflect to keep a smooth transition. This causes the outboard elevator and aft elevator section to fluctuate slightly during the transition seen in Figure 8.2.

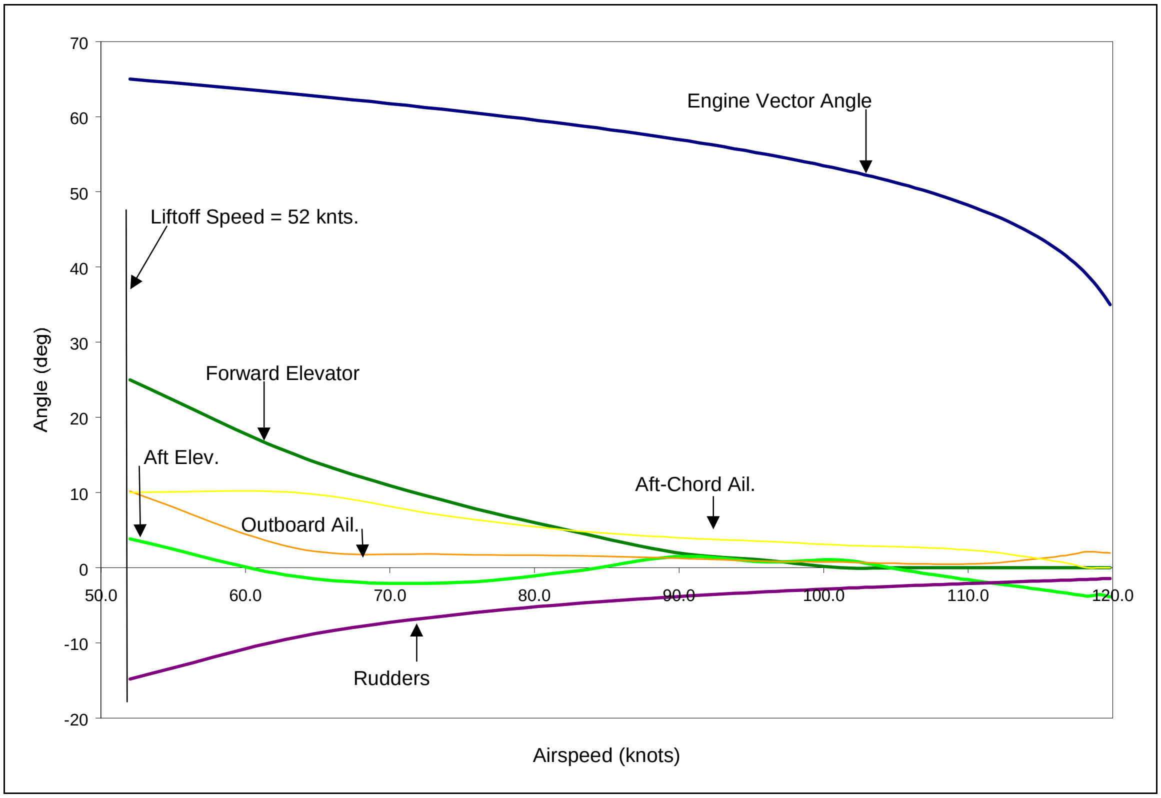


Figure 8.2 - Control surface deflections for a right engine out civilian takeoff

8.6. Control Surface Sizing

The elevators are sized to provide control power for takeoff with maximum deflections of 25 degrees for each elevator segment. The maximum allowed deflections for each elevator is 30 degrees, leaving 5 degrees on each elevator for uncontrollable events. The double elevator was created by lengthening the chord of the original single elevator and splitting it almost in half.

The engine out condition sized lateral and directional control surfaces. Large rolling and yawing moments were produced during takeoff by the engines at the specific vector angle. Aft-chord ailerons on the double-slotted flaps countered about 1/3 of the rolling moment generated, producing a need for ten percent span, plain flap ailerons to enhance low speed roll control. Figure 7.2 shows the deflection limits for the aft-chord ailerons. The swept forward planform increases the effectiveness of these outboard ailerons by preventing stall from occurring on the outboard section of the wing, allowing the ailerons to be immersed in clean airflow. The large rudders provide enough control power to offset the difference in horizontal thrust throughout the takeoff run, and to counter the FAR requirement of a 30-knot crosswind. Table 8.3 is a summary of the control surface characteristics for the Skyhopper.

Table 8.3 - Control surface characteristics

Control Surface	% Span	% Chord	Max. Deflection	Area
Aft-Chord Ailerons (Each)	49 % (Half-Span)	25 %	15° (up) 10° (down)	26.5ft^2
Outboard Ailerons (Each)	10 % (Half-Span)	26 %	25° (up) 20° (down)	6.0 ft^2
Forward Elevator Section	92 % (average)	22.5 %	25° (up) 25° (down)	56.2 ft^2
Aft Elevator Section	85 % (average)	16 %	25° (up) 25° (down)	37.7 ft^2
Rudders (Each)	100 %	46 %	25° (Left/Right Dir.)	49.4 ft^2

With these strict constraints from takeoff and landing on the control surface sizes, the Skyhopper proves to have sufficient control power to exceed any other requirements during flight. Table 8.4 is a list of control derivatives calculated for each surface.

Table 8.4 - Control Derivatives for all control surfaces*

	Elev. (1)	Elev. (2)	Aft-span Ail.	Ailerons	Rudders
CL_α	**1.9**	**1.7**	neg.	neg.	neg.
CM_α	**-2.78**	**-2.49**	neg.	neg.	neg.
Cl_δ	neg.	neg.	**0.03**	**0.015**	neg.
Cn_δ	neg.	neg.	neg.	**-0.08**	**-0.368**

* Values calculated from Roskam[8.4, 8.5]

8.7. Dynamics and Flight Qualities

An analysis of the dynamic stability was done to determine the handling qualities of the Skyhopper. Table 8.5 indicates that the Skyhopper is able to maintain the necessary flying qualities specified in MIL-F-8785C for a class II aircraft. Implementation of a Stability Augmentation System (SAS) could be incorporated into the Skyhopper's flight control computer to further improve the flying qualities. The SAS would adjust the natural frequency and damping of the short period response to create critically damped stable roots.

Directional and Lateral dynamic stability was investigated as well. Both motions were determined to be stable during all flight conditions, with a steady-state roll rate of 6.6 °/sec, which is comparable to the Boeing 747-100.

Table 8.5 - Longitudinal Handling Qualities

		MIL-F-8785C Class II Category B Level 1 Requirements	Skyhopper
Short Period	**Damping (ζ_{sp})**	$0.3 < \zeta_{sp} < 2.0$	0.866
	Natural Frequency (ω_{sp})	1.5 rad/s < ω_{sp} < 5.7 rad/s	2.45 rad/s
Phugoid	**Damping (ζ_{ph})**	$\zeta_{ph} > 0.04$	0.0708

9. Structures and Materials

9.1. The *V-n* Diagram

Construction of the *V-n* diagram involved the establishment of two different flight envelopes, the maneuver envelope, and the gust envelope. The maneuver envelope is determined by the stall line, limit load factors, and the equivalent dive speed. The stall line indicates the maximum load factor at a particular speed because of the incapability of the wing to produce enough lift to counter the weight of the aircraft. The limit load factors are determined by the mission and type of aircraft being designed. The gust envelope is governed by the stall line, possible gust velocities in turbulent air, and characteristics of the aircraft. The development of the *V-n* diagram is described below (Niu[9.2]).

The stall speed and stall line of the aircraft are calculated from the following equations. All values are assumed to be worst case and taken at sea level conditions.

$$V_{Stall} = \sqrt{\frac{2\left(\frac{W}{S}\right)_{eff}}{\rho C_{L\max}}}$$

$$V_{sn} = V_{Stall}\sqrt{n}$$

The limit load factors were determined in accordance with FAR 25.337. The maximum positive limit *n* was calculated from equation 9.1. In the case of this aircraft, the maximum positive *n* is 2.53. The negative limit maneuvering load factor is equal to –1.0 at speeds up to Vc, and varies linearly to zero at V_D.

$$n = 2.1 + \frac{24000}{TOGW + 10000} \qquad \textbf{(9.1)}$$

The gust envelope is created from gust lines that expand from *n* = 1 and Ve = 0, according to the equation below. K_g is a gust alleviation factor calculated as below, $C_{L\alpha}$ is the lift curve slope of the aircraft, *W/S* is the wing loading, V_e is the equivalent velocity in knots, and U_{de} is the equivalent gust velocity in ft/s. According to FAR 25.341 the values of U_{de} are 28 ft/s for V_D, and 56 ft/s for V_c at sea level conditions (FAA[9.1]). The value of U_{de} for the rough air gust (V_B) is assumed to be 66 ft/s (Niu[9.2]). The mass parameter, μ, is determined from the equation below. Gust lines were created for both the takeoff/landing (vectored), and the cruise configurations of the aircraft, because of the extreme differences in the effective wing loading.

$$n = 1 \pm \frac{K_g U_{de} V_e C_{L\alpha}}{498\left(\frac{W}{S}\right)_{eff}}$$

$$K_g = \frac{0.88\mu}{5.3 + \mu}$$

$$\mu = \frac{2\left(\frac{W}{S}\right)_{eff}}{g\,\bar{c}\,\rho C_{L\alpha}}$$

The combined *V-n* diagram (Figure 9.1) is a composite of the maneuver and gust envelopes. In the Skyhopper, the maneuver envelope is dominant over the entire airspeed range.

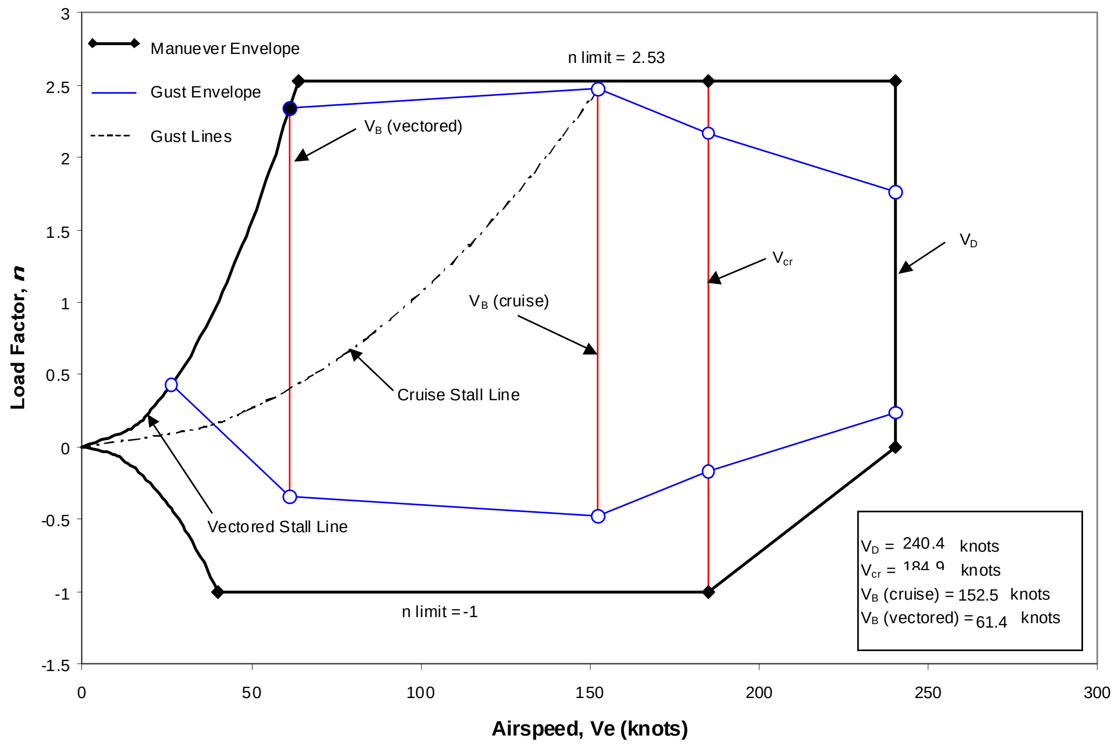


Figure 9.1 - Combined *V-n* Diagram

9.2. Materials

Structural materials were chosen with the aid of Niu[9.2] and Raymer[9.3]. Aluminum, Kevlar composite, and steel were chosen in the design for various components of the aircraft. Because of both military and commercial use, the more stringent military criteria was used in material selection of the different components. This should minimize production and logistic costs. Table 9.1 shows values for strength per weight and strength per U.S. dollar for the different materials. Aluminum 2024-T3 was chosen for the fuselage and wing skin because of rapid and easy reparability in quick turnaround conditions. FOD from vectored exhaust blown debris on takeoff and landing was also a consideration.

Aluminum-Lithium 2020 was chosen for the spars, bulkheads, longerons, and internal members of the wing box. This material has a weight saving of 15% over conventional Aluminum 2024 with a 10% increase in stiffness and strength. Currently Al-Li 2020 is three times the cost of Al 2024 but should decrease by production year 2005. Aluminum-Lithium was chosen over composites mainly because of manufacturing costs of composites and reparability.

Table 9.1 - Cost vs. Strength Trade Study (Niu[42])

Material	Stiffness per Unit Weight (10^6 inches)	Stiffness per Unit Cost (10^6 lb*psi/Dollar)
Aluminum	106	1.985
Steel	102	13.488
Kevlar	240	0.667

Tails, flaps and control surfaces will be made of Kevlar composite because of weight per unit strength along with damage and corrosion resistance. Also, Kevlar is unaffected by contact with fuel and has desirable fatiguing properties. This is an advantage for areas that are difficult to inspect. The cargo floor will be made with primarily the same composite material, but with an aluminum 2024 top skin. Five full length integral aluminum tracks are installed flush with the floor. These tracks accommodate track insertable tie down fittings for cargo. These fittings will have a tie down strength of 5000 lbs for inertia loads from cargo. This provides a weight savings of 25% compared to a complete Al 2024 without loss of durability for military cargo applications.

Because of high concentrated impact loads, the landing gear will be constructed of carbon steel. Although steel has a lower strength to weight, the higher ultimate strength is required to support the loads on takeoff and landing.

9.3. Structural Arrangement

The primary load bearing aircraft structure is segmented into three main parts; the fuselage, wing, and tail empennage. The main fuselage structure consists of a semi-monocoque construction with eleven bulkheads and the fuselage skin. The bulkheads are located at large point load positions as called out in Figure 9.2 and Table 9.2. The skin will carry shear loads from external forces and cabin pressure. With a maximum service ceiling of about 44,000 feet, and a 8,000 feet cabin pressure, the skin is designed for a pressure differential of 8.7 psi. Four longerons, two at the floor level and two above the doors and below the wing, run the length of the fuselage and carry the major portion of the fuselage bending moment.

An additional structural concern was for emergency landing situations. For safety considerations during emergency carrier landings at mid sea, provisions for an arresting tail hook were added to the design. Although disallowed by the RFP, the tail hook necessitated larger bottom longerons in the aft fuselage to take the landing impulse loads.

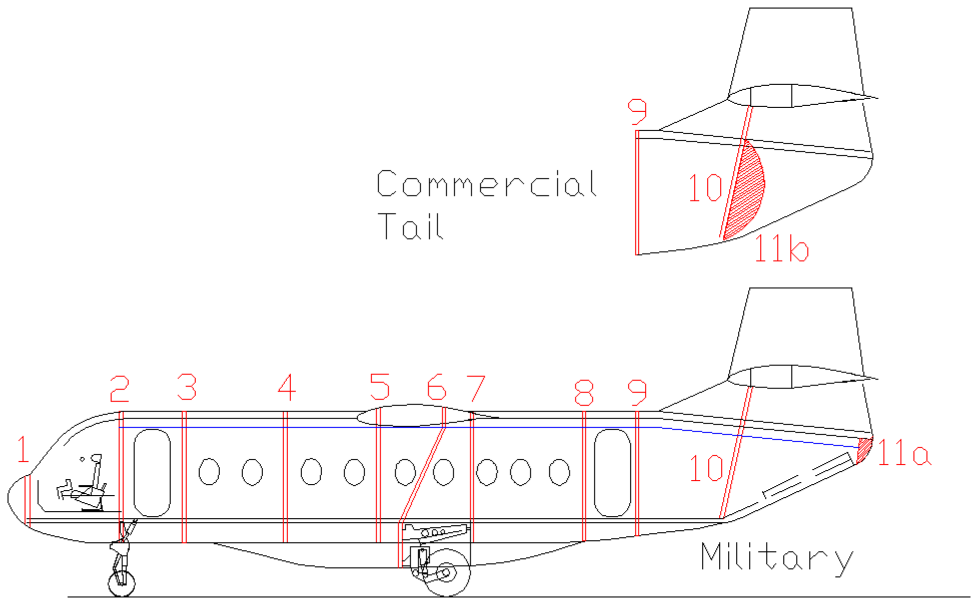


Figure 9.2 - Bulkhead Locations

Table 9.2 - Bulkhead Location Information

Bulkhead Number	Reasoning
1	Forward pressure bulkhead.
2	Nose gear loads, pilot cabin aft wall, and cabin door support.
3	Cabin door support.
4	Mid fuselage support.
5	Forward spar and wing loads.
6	Aft spar, wing loads, and main gear loads.
7	Main gear loads
8	Cabin door support.
9	Cabin door support. Commercial/Military tail section modular build location.
10	Cargo door hinge (military), and forward spar tail loads.
11a	Rear pressure bulkhead, includes ramp door (military).
11b	Rear pressure bulkhead (commercial).

Bulkhead number 6 serves a dual role, transferring loads from both the main landing gear and the aft spar portion of the wing box. By shaping the spar at the longeron attachment positions, the structure was able to accept loads from different lengthwise positions. This decreased the total number of necessary bulkheads along with the structure weight.

The structural arrangement for the wing of the Skyhopper included provisions for wing folding, tilting engine mounts, and other dual-use design aspects. The wing planform was similar in shape to the Grumman X-29 forward swept wing fighter aircraft. The fore and aft spars were placed along the span at constant chord lengths for manufacturing ease at 15%, and 60% of the chord length, respectively. The spars were also arranged to allow sufficient space for the nose droop, lift dumper, and flap attachment and actuation of the double slotted flap system. The wing ribs were arranged to support loads and maintain the aerodynamic contour shape of the skin panels. Figure 9.2 and Table 9.3 illustrate the wing structure of the aircraft. The ribs are colored in red, while the spars are blue.

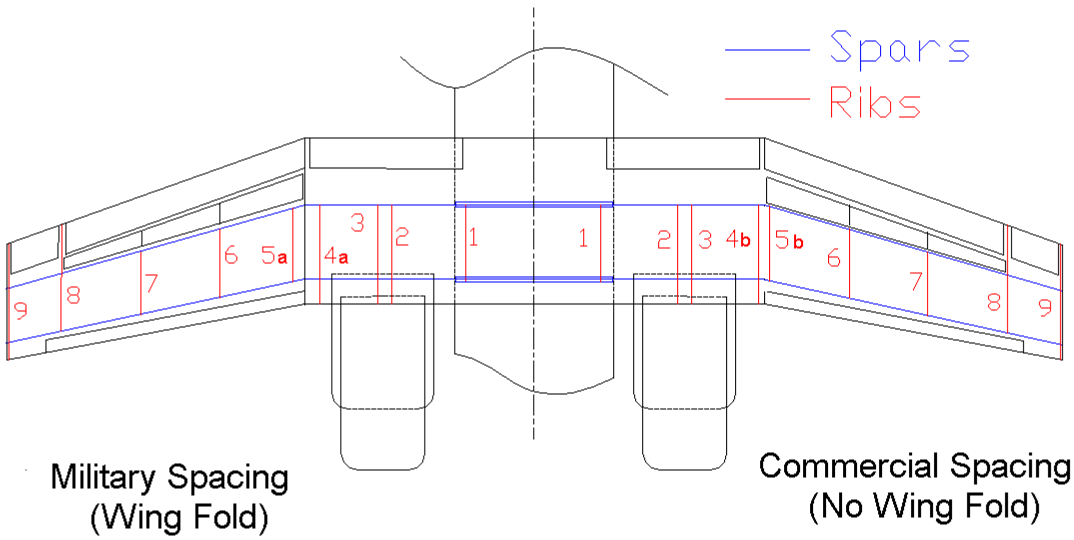


Figure 9.3 - Wing Structure Diagram

Table 9.3 - Rib Location Information

Rib Number	Reasoning
1	Wing box root fitting, flap hinge location.
2	Tilting engine mount position.
3	Tilting engine mount position.
4a	Flap hinge location, wing fold location (military).
4b	Flap hinge location, spar bend location (commercial)
5a	Flap hinge location, wing fold location (military).
5b	Flap hinge location, spar bend location (commercial)
6	Flap hinge location.
7	Flap hinge location.
8	Flap and aileron hinge location.
9	Aileron hinge location.

Two ribs were allotted for the tilting engine mount position due to the complexity of the system and concentration of lifting forces. The cruise fan tilting actuators are also located between these two ribs.

The only change in the wing structure of the military design was the addition of an extra rib for the wing fold in the outboard wing section. This led to an additional weight increase over the commercial design.

The H tail section is made up of the horizontal tail and two vertical tails. The horizontal tail is constructed of two main spars and an aft false spar. The two main spars make up the spar box and are in line with the vertical tail spars. The aft false spar takes bending loads across the span from the elevator. Elevator loads are transferred to the spar box through six central ribs. The two vertical tails are mounted on the two most outboard ribs. Figure 9.4 is a structural drawing of the H tail section.

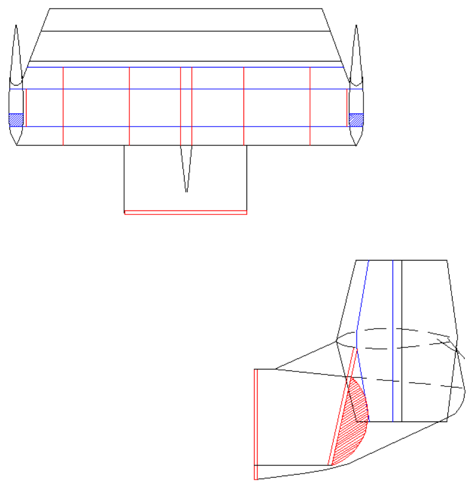


Figure 9.4 - H Tail Section Structure

10. Systems and Avionics

10.1. Landing Gear

The landing gear selected to best suit the design of the Skyhopper was similar to that of the BAe 146. The layout consisted of tricycle type geometry with hydraulically retractable main and nose gear. In order to minimize the storage cavity the main gear retracts inboard in the manner shown in Figure 1.1. The simple telescopic nose gear strut retracts forward where it is housed beneath the cabin floor. This forward retraction enables the nose gear to free-fall and lock securely in the case of a malfunction. The gear are retracted immediately after lift off to avoid the cruise fan exhaust impinging on the main gear and doors. Both the main gear and the nose gear are equipped with oleo-pneumatic shocks, the main gear which pivots on a trailing axle. For taxiing maneuverability the main gear was designed with a single wheel on each strut which pivots on a trailing axle. The nose gear was designed with twin wheels to ensure stability and minimize tire size. The nose unit is steerable ±70°, which enables the aircraft to pivot directly around either of the main gear tires. This results in a nose-wheel turning radius of 23.9 feet, and enables the aircraft to safely traverse 180^{o} on a taxi strip with a minimum width of 41.1 feet. The turning radii for ground handling on crowded airport aprons or carrier decks is shown in Figure 10.3. The landing gear was positioned on the Skyhopper to meet the tipback and turnover angle requirements of a carrier based aircraft, shown in Figure 10.3. The tires for the aircraft are B.F. Goodrich type VII tires. The main gear tires are size 40 x 14, with a pressure of 175 psi, and the nose gear tires are size 22 x 6.6-10 with a pressure of 190 psi. Other features of the landing gear system include a self-jacking unit for tire changing, and shackles for tie down options. The nose wheel can be extended to its oleo maximum limit and locked to lower the aft end of the aircraft. This asset, similar to that used on the Navy A-6 aircraft, allows for easier cargo loading.

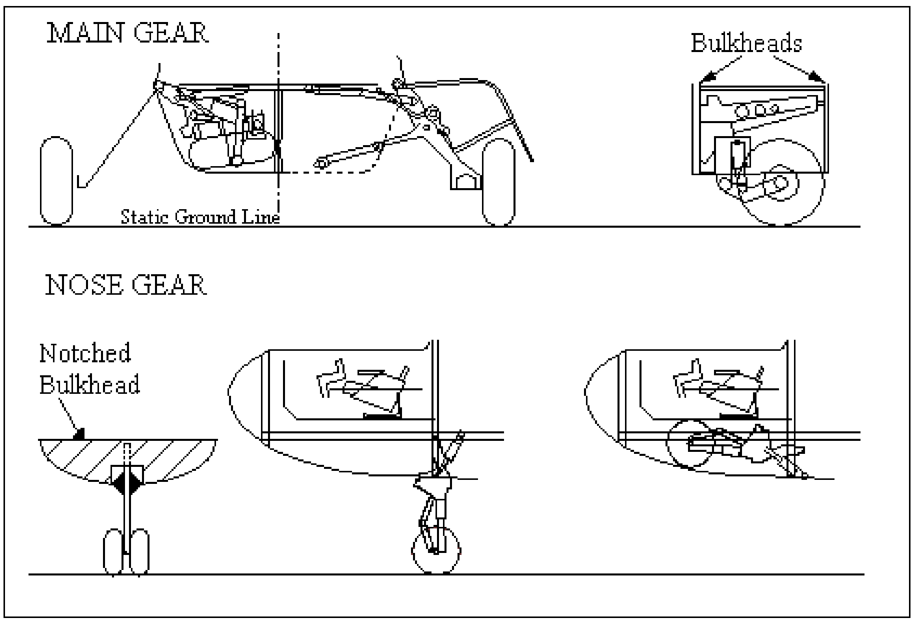


Figure 10.1 - Landing Gear Configuration

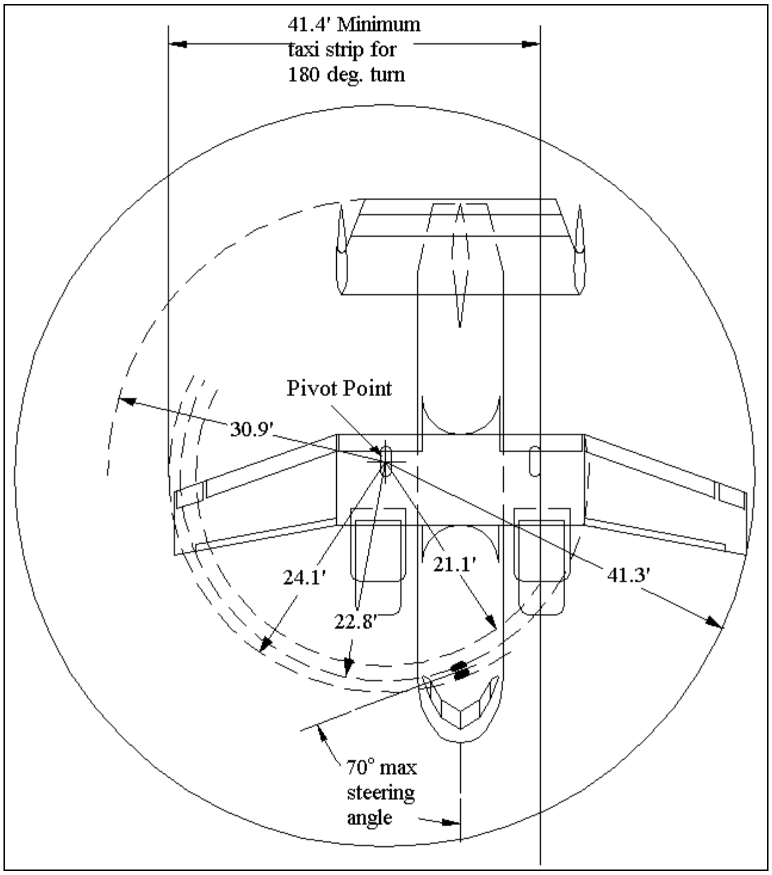


Figure 10.2 - Ground Maneuvering Dimensions

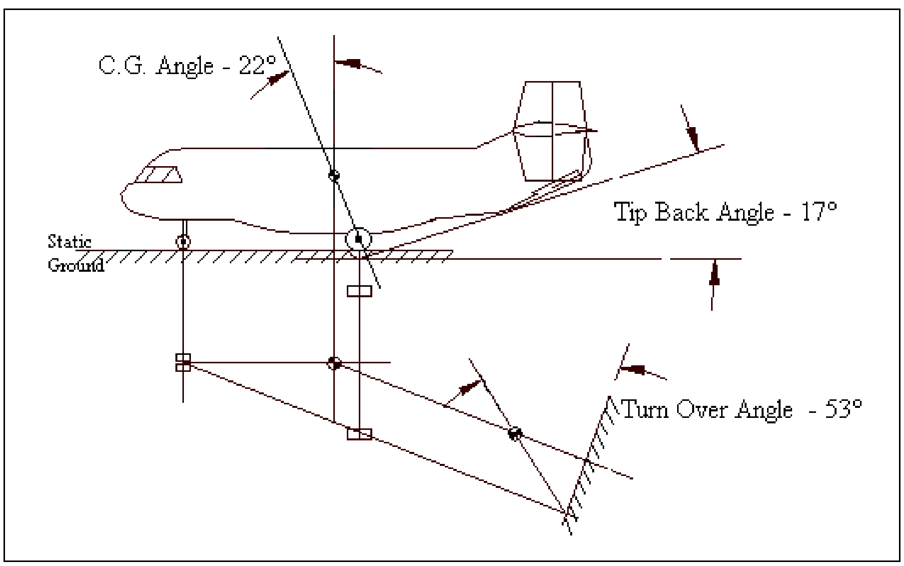


Figure 10.3 - Tipback and Turnover Angles

The possibility of incorporating an electrical braking system in this aircraft was considered. However, the fact that electrical braking systems are still in testing makes it difficult to obtain data concerning their performance. Considering that the Skyhopper already has hydraulically powered steering, and gear retraction, it was concluded that hydraulic braking would be the most practical system for this aircraft. To provide maximum braking, even under wet runway conditions, the aircraft was equipped with anti-skid carbon brakes.

Concerning the possibility of brake failure, flat tires, or power approach problems on landing the option of adding an arresting hook to the COD version of the Skyhopper was considered. Structural provisions were made to longerons in order to meet the requirements of adding an arresting hook at the base of the rear cargo door. Figure 10.4 shows the arresting hook and dashpot assembly on the Skyhopper.

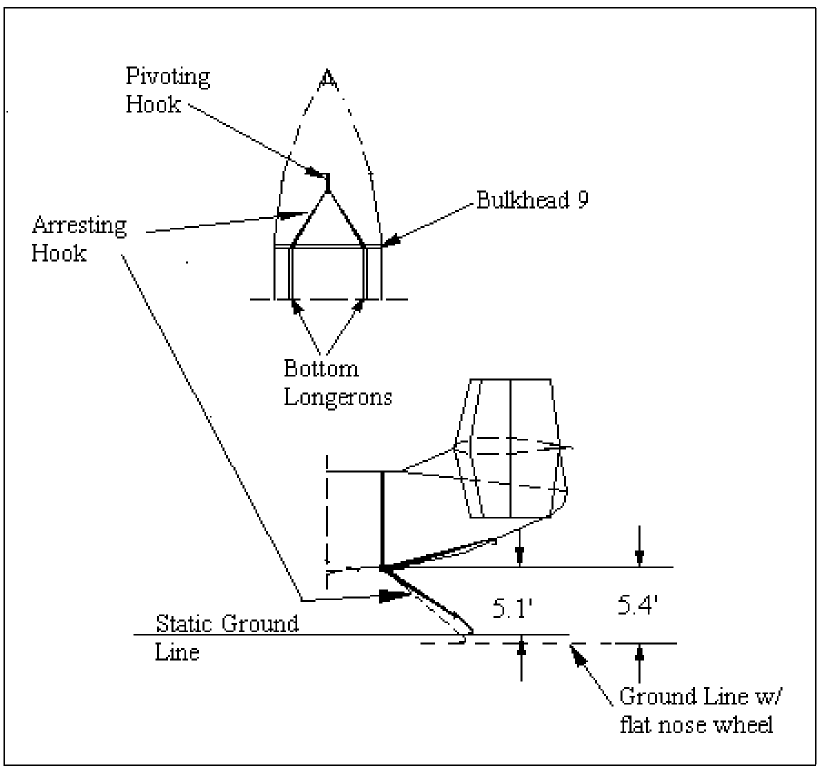


Figure 10.4 - Arresting Hook Option

10.2. Support Systems

Each propulsion pod contains an electrical generator powered by one of the two engines. Each generator in turn powers a hydraulic pump. These hydraulic pumps provide pressure for both local and opposite engine tilt actuators. This setup allows for engine rotation in the case where one hydraulic system fails. When power is not provided by the engines, a 4,000 psi hydraulic unit powered by the APU supplies pressure for all hydraulic systems. The pilot manually controls which hydraulic system is used. Each hydraulic unit is capable of providing pressure for the landing gear operation, including retraction and extension, ground steering, engine rotation, and cargo door operation (on the Military version). For emergency situations a pressurized hydraulic reservoir is integrated into the hydraulic system. This reservoir is located in the landing gear fairing aft of the main landing gear, for easy inspection and maintenance.

The electrical generators located on the engine pods are also used to provide in-flight power for all electrical systems in the Skyhopper. These operate independently for safety, and are also backed up by the Skyhopper's APU.

The fuel system for the Skyhopper includes four main tanks, one in each outer wing, a third in the center wing, and the fourth in a fuel blister below the cabin floor (**Figure 4.5**). The total volume of the four tanks is 298.4 cubic feet. An easily accessible refueling receptacle is positioned just above the fuel blister. From here fuel enters the blister tank and is pressure fed into the wing tanks until all tanks are full. A pressure regulating system prevents tank pressure from exceeding their design limit in extreme weather conditions. Fuel is supplied to the engines from the wing center section tank, which receives fuel from the other wing tanks and blister tank. Fuel pumps on two separate fuel lines draw fuel from the wing center section tank which supplies fuel to the power plants. A crossover fuel line is included to maintain fuel circulation in the case of a fuel pump failure. An in-flight fuel tank venting system to preclude abnormal tank pressure during maneuvers or rapid altitude excursions is located at the trailing edge of the tail mounting pylon. An emergency fuel dump nozzle is also located there at the base of the pylon.

Several accommodations were made to overcome adverse weather conditions. An anti-icing system as seen in Figure 10.5 uses thermal air circulation to prevent a buildup of ice on the leading edges of the wing, tail surfaces, and engine and cruise fan inlets. Hot air for this system is provided by engine bleed air, with air temperature controlled by an inline thermostat. Monitoring systems and controls for the de-icing system are located in the cockpit for pilot access.

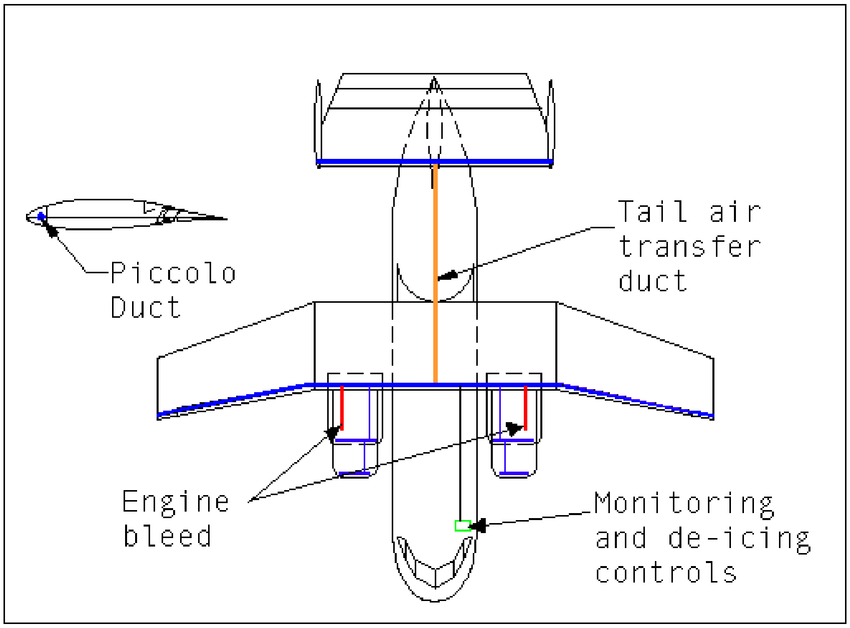


Figure 10.5 - Anti-icing System

To retain pilot visibility under adverse conditions, the Skyhopper is equipped with heated windshield panels, hydraulic wiper units, and rain repellant solenoids. Separate control units are provided for right and left window panels. An electric heating unit supplies heat to each window panel, which have embedded heating elements, and the pitot-static probes.

To maintain suitable cabin conditions at all flight altitudes, an air conditioning unit and an air pressurization system are incorporated in the Skyhopper. This system is located to the right of the nose wheel well, beneath the cockpit floor. This location allows commonality for the naval and civil versions. During in-flight conditions, those two systems are driven by engine bleed air. If bleed air is unavailable, the APU, which is locate on the opposite of the wheel well, can provide the necessary power. The air conditioning system is monitored by a thermostat and simple airflow control. The system is designed to maintain a cabin and cockpit temperature between 60^o and 80^o F. The pressurization system is designed to provide a maximum pressure differential of 8.7 psi. in order to maintain a 8,000 feet. cabin pressure at altitudes up to 44,000 feet. Service access and instrumentation for all systems is located below the aircraft floor for easy access without the requirement of excess maintenance equipment.

A winch mounted to the nose landing gear support bulkhead beneath the cabin floor assists in rear cargo loading and extraction. The winch, similar to that used in the C-2, has a 6,000 pound capacity and is operated by a handheld pendant for safety of the operator. Evenly spaced tie-down fittings mounted to the cargo cabin flooring aid in loading and securing cargo.

10.3. Cockpit Layout and Controls

Several factors were considered in selecting a cockpit layout for the Skyhopper. To reduce cost in both areas of production personnel training, and logistics, spares keeping aboard aircraft carriers it was necessary to model the cockpit after an existing design. Considering the confined landing and take-off conditions the Bell/Boeing V-22 Osprey cockpit layout is ideal for meeting the demands of the Skyhopper and meets the above objectives. (see Figure 10.6). The V-22 cockpit instrumentation and controls will be duplicated with minimal alterations to suit the Skyhopper design. For optimum visibility, the aircraft is equipped with multifunction glass-panel cockpit displays. To accommodate pilot visibility in adverse flight conditions, a Heads-up Guidance System (HGS) is also integrated into the flight control panel. The avionics duplicated from the V-22 Osprey include:

- VHF/AM-FM, HF/SSB and UHF secure voice com
- IFF
- Texas Instrument AN/APQ-174 terrain-following multifunction radar in offset nose thimble
- Tacan
- VOR/ILS, AHRS, radar altimeter and digital map displays
- Jet Inc ADI-350W standby attitude indicator
- Aydin Vector data acquisition and storage system
- Two Control Data AN/AYK-14 mission computers, with software
- Pilots' night vision system and Honeywell integrated helmet display system

Additionally, provisions are also made to accommodate self-defense systems including anti-missile and radar/infra-red warning systems (Defense Industries[10.2]).

Figure 10.6 - V-22 Cockpit* : To Be Duplicated for Skyhopper

*Source: Defense Industries[10.2]

The Skyhopper is controlled by a fly-by-wire system. Multiple digital channels link the control surface actuators to the base system from where the pilot controls the flight envelope. Each channel consists of its own memory, input/output functions, discrete failure logic, processor, digital data bus and serial link to other channels (Brinkman[10.1]).

To reduce hydraulic links in the aircraft, the Skyhopper is equipped with linear and rotary electrohydrostatic actuators, which are activated by electrical signals from the fly-by-wire system from pilot controls. Electrohydrostatic actuators, in accordance with the commands of the integrated avionics system, deflect each control surface. Unlike the control surfaces, the engine/cruise fan tilt mechanism involves hydraulically powered irreversible rotary screw actuators. The pressure for this actuator is received from the hydraulic unit for the landing gear systems. The motion of this actuator is also integrated into the digital flight commands. For all channels of the fly-by-wire system there is a manual override option for emergency conditions. Manual flight controls for the pilot, include a variable feel stick and throttle control. Other controls include a pistol grip stick for nose-wheel steering, manual landing gear retraction and extension lever, and dual braking pedals. The pilot's visibility angles permitted by the cockpit seating arrangement can be seen in Figure 10.7.

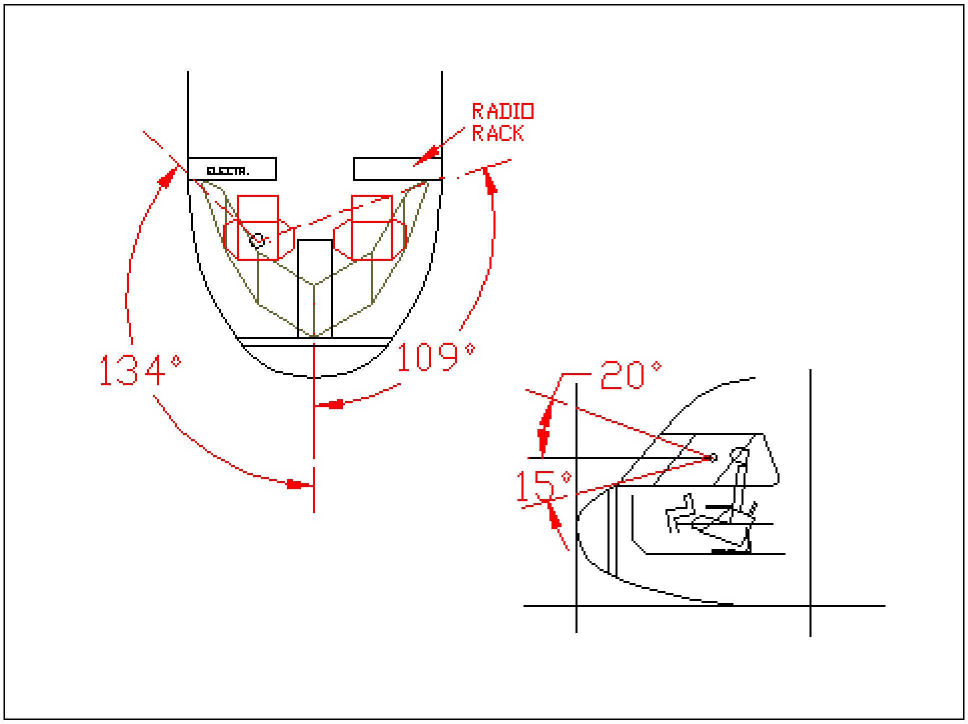


Figure 10.7 - Pilot Visibility Angles

10.4. Engine Tilt Mechanism

The hydraulically powered irreversible screw actuator for the tilt engine mechanism is mounted to the rear spar of the wing shown in Figure 10.8, and is free to pivot at both ends. As the actuator shaft extends, the engine pivots at a point near the top of the front wing spar. The actuator is capable of locking the engine at any rotated position. Engine rotation is incorporated in the fly-by-wire command with manual override control by the pilot.

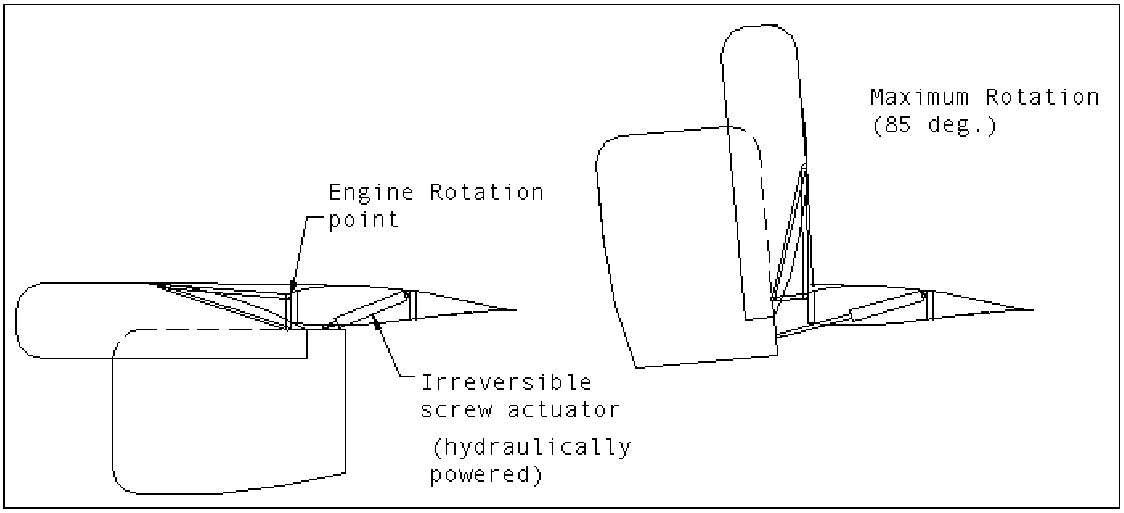


Figure 10.8 - Tilt Engine Configuration

11. Financial Strategies

11.1. Fly-Away Cost

As required in the RFP, the flyaway cost was calculated for the production of 750 Skyhoppers using the methods described in Roskam[11.2]. This method is based on historical data and the teams estimation of certain scale factors. The flyaway cost was divided into two distinct components; Research, Development, Test and Evaluation Cost and the Manufacturing and Acquisition Cost.

The Research, Development, Test and Evaluation Cost (RDT&E Cost) was further divided into seven categories: Airframe Engineering and Design, Development Support and Testing, Flight Test Airplanes, Flight Test Operations, Test and Simulation Facilities, RDT&E Profit, and Cost to Finance. In the RDT&E estimate, it was assumed that the military and commercial versions of the aircraft would not have any differences that would constitute a change in any element of this cost. The breakdown of the RDT&E cost is shown in Figure 11.1 and Table 11.1.

Table 11.1 - Research, Development, Testing, and Evaluation Cost Breakdown

Airframe Engineering and Design	$	208,716,837
Development Support and Testing	$	64,247,024
Flight Test Aircraft	$	682,838,094
Flight Test Operations	$	11,544,738
Test and Simulation Facilities	$	233,346,843
RDTE Profit	$	116,673,422
Cost to Finance the RDTE phase	$	175,010,133
Total RDTE Cost	**$**	**1,166,734,217**
RDTE Cost per Aircraft	**$**	**1,543,299**

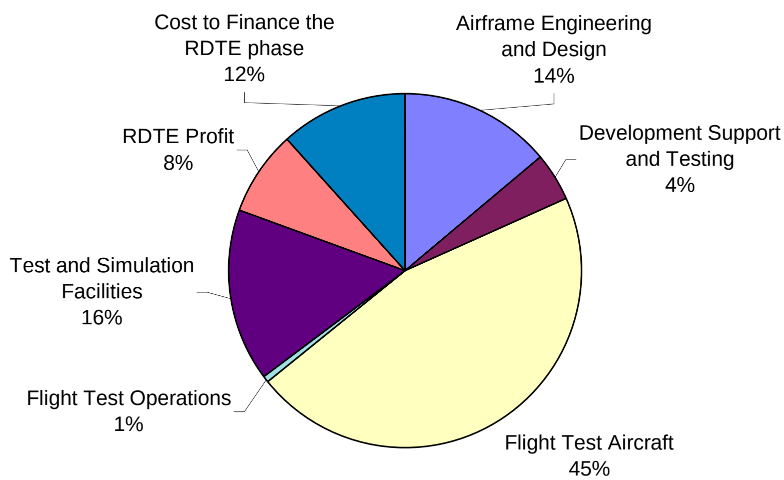


Figure 11.1 - Research, Development, Testing, and Evaluation Cost Breakdown

The flight test aircraft cost consumed almost 50% of the total RDT&E cost. It was assumed that four flight test aircraft, two static and two dynamics, would be necessary in this design case to test both the passenger and cargo versions. The total for the RDT&E, $1,166,734,217 ($1,543,299 per aircraft), is added to the Manufacturing and Acquisition Cost to get the total flyaway cost.

The Manufacturing and Acquisition Cost is also broken into several parts: Airframe Engineering And Design, Airplane Production, Production Flight Test Operations, and cost to finance. By eliminating the rear loading tail door and wing folding on the passenger aircraft, the weight was reduced by 1782 pounds, thus reducing the material and associated equipment cost in the Airplane Production. These airframe reductions plus other reductions shown in Table 5.1**,** reduced the weight of the passenger aircraft further providing additional material and manufacturing reductions. The change in the production line to accommodate for the new tail section, would be an extra cost and was accounted for in the manufacturing cost. The material savings minus the extra production cost resulted in an over all savings of around 525 million for the 750 aircraft run, or 700 thousand per aircraft. (Figure 11.3, Figure 11.4: Table 11.3, Table 11.4)

Table 11.3 - Manufacturing and Acquisition Cost Breakdown

(Passenger Aircraft)

Airframe Engineering and Design Cost	$	305,332,107
Aircraft Production Cost	$	12,688,776,736
Production Flight Test Operations Cost	$	112,500,000
Cost of Financing the Manufacturing	$	2,051,982,938
Total Manufacturing and Acquisition Cost	$	15,205,426,924
Manu. and Acquisition Cost per Aircraft	$	20,273,903

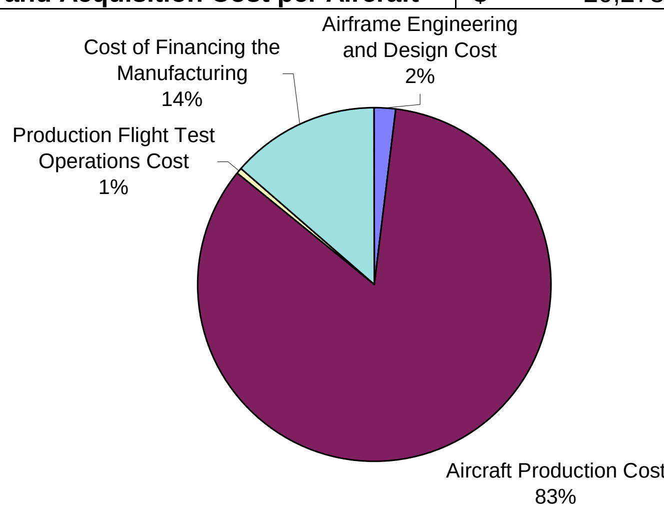


Figure 11.3 - Manufacturing and Acquisition Cost Breakdown
(Passenger Aircraft)

Table 11.4 - Manufacturing and Acquisition Cost Breakdown

(Cargo Aircraft)

Airframe Engineering and Design Cost	$	352,167,250
Aircraft Production Cost	$	13,215,219,005
Production Flight Test Operations Cost	$	112,500,000
Cost of Financing the Manufacturing	$	2,051,982,938
Total Manufacturing and Acquisition Cost	$	15,731,869,193
Manu. and Acquisition Cost per Aircraft	$	20,975,826

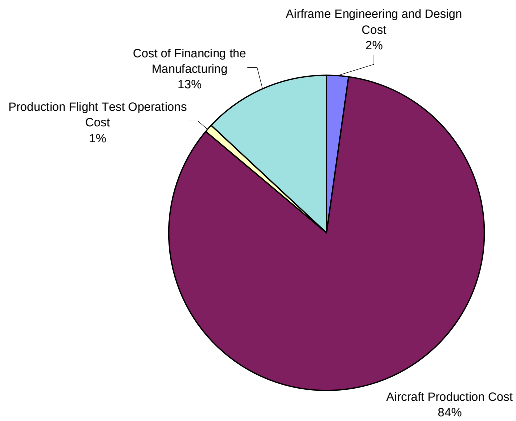


Figure 11.4 - Manufacturing and Acquisition Cost Breakdown (Cargo Aircraft)

The production run was completed for 750 cargo and 750 passenger aircraft. In the actual manufacturing of the aircraft the Aircraft Production would not be split into two separate runs, but be one continuous production line. This split was done in the cost estimation because there is no good way, at this point in the design process, to accurately estimate the number of cargo versus passenger versions that would be produced. In the actual production run, the fixed cost of manufacturing and materials would be divided equally for each of the aircraft. The cost of production would only change when the passenger version began production. So this shows that the estimated production costs shown in Table 11.3 and Table 11.4, the cargo aircraft production cost was overestimated and the passenger cost underestimated.

The fly-away cost of the two aircraft where found by adding the Manufacturing and Acquisition cost to the RDT&E cost and marking that cost up 5%, the industry standard (Table 11.5). The prices for the 2005 estimations were found by estimating the consumer price index for that year and were checked against the Dow Jones Company's estimates.

Table 11.5 - Approximate Flyway Cost of Aircraft

Cargo Aircraft (1999)	$	23,580,262
Cargo Aircraft (2005)	$	27,153,030
Passenger Aircraft (1999)	$	22,843,243
Passenger Aircraft (2005)	$	26,304,341

11.2. Operational Cost

In addition to the flyaway cost, the operational cost of military cargo/passenger, civilian cargo and civilian passenger aircraft were calculated. The methods described in Roskam[11.2] were utilized again. It was assumed in this estimation that all aircraft purchased by a particular operator are purchased in the same year and at the same price. In a typical situation, an operator would receive and pay for only a few of their ordered aircraft. A twenty-year operational life was also assumed in each of the three cases. These costs were also found in 1999 dollars. To attempt predicted fuel costs, labor rates, and insurance cost for the year 2005 would cause too much possible compounding error to be able to call any results an accurate prediction. For example, the fuel cost per gallon has fluctuated by 90 cents over the last 30 years. The actual prices and wages for 1999 were found and used in these estimates.

The civilian operational cost is found by adding the estimated direct (DOC) and indirect operational (IOC) costs. The DOC estimate for the commercial aircraft was broken down into five separate costs: Flight, Maintenance, Depreciation, Landing and Navigation Fees and Landing Taxes, and Financing Cost. The elements of the Flight Cost are the fuels, lubricants, crew salaries, and airframe insurance. The cargo and passenger aircraft's DOC breaks down into relatively the same proportions, Figure 11.5. The passenger aircraft reduces its DOC with its lighter weight, but has higher insurance rates and the need for a flight attendant. All direct operational costs are found per nautical mile flown (Table 11.6, Table 11.7).

Table 11.6 - Direct Operational Cost Civilian Passenger Aircraft ($/nm)

Flight	$	2.82
Maintenance	$	4.89
Depreciation	$	2.97
Landing and Navigation Fees, Registry Taxes	$	0.07
Financing	$	0.81
Total DOC	$	11.44
Total IOC	$	8.00
Operational Cost	**$**	**19.44**

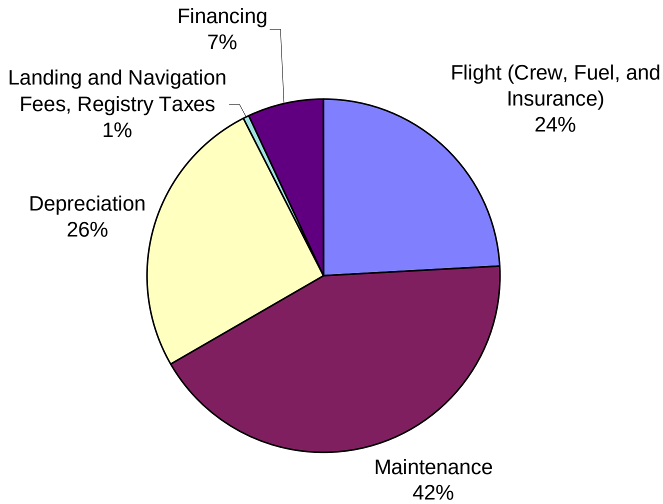


Figure 11.5 - Direct Operational Cost Breakdown Civilian Passenger Aircraft

Table 11.7 - Operational Cost Civilian Cargo Passenger Aircraft ($/nm)

Flight	$	2.43
Maintenance	$	4.89
Depreciation	$	2.65
Landing and Navigation Fees, Registry Taxes	$	0.07
Financing	$	0.76
Total DOC	$	0.80
Total IOC	$	6.48
Operational Cost	**$**	**17.28**

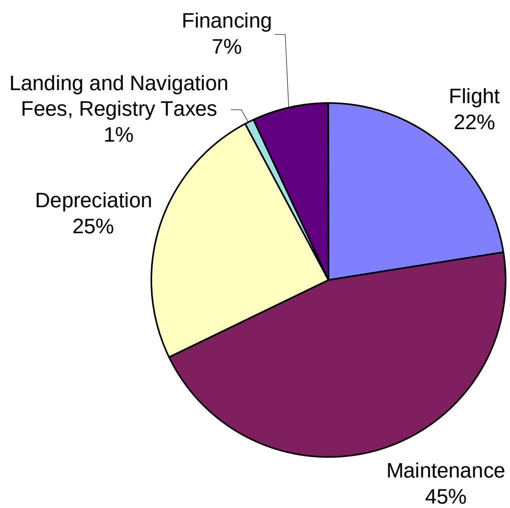


Figure 11.6 - Direct Operational Cost Breakdown Civilian Cargo Aircraft

The IOC for the commercial aircraft consist of all cost not directly related to the flight of the aircraft. A few examples of these costs would be, passenger meals, cabin attendants, baggage handling, sales and reservations, maintenance of ground facilities and equipment, promotion and sales, and administration. The cargo version of the civilian aircraft does not have the IOC associated with passengers, therefore a lower IOC. The IOC is a very hard number to approximate, because items like administration expenses, maintenance, and promotion vary greatly between operating entities. For this reason it is Roskam's suggestion to use a historical average of 70% of the DOC. The 70% was to be used for a passenger aircraft, with the removal of IOC associated with passengers, an estimate of 60% of DOC was used for the cargo version. These costs are reported in dollars per nautical mile. (Table 11.6 and Table 11.7)

The operational cost for a military aircraft is calculated in a different fashion then the civilian version. The military operational cost is broken down into different section because of the difference in the way a military aircraft is stored and operated. Military operational cost is broken down into Direct Personal; Indirect Personal; Fuel, Oil, and Lubricants; Maintenance Support, Training, and Other Support Equipment; Maintenance Materials; Spares and Depots. The military aircraft's operational costs were calculated in dollars per flight hour. For the design mission of 1500 nm, the operational cost of $9,451/flight hour is almost equivalent to the civilian passenger version's 19.43/nm.

11.3. Marketability

To determine the market potential of the Skyhopper, it was again necessary to split the analysis of the 750 aircraft production run into the three categories: Military, Civilian Passenger and Civilian Cargo. One of the primary missions of the military version was carrier on board delivery. With only 12 U.S. carriers, 1 British, 3 French and 1 in Brazil, this part of the sales could reach 40 aircraft. With the other possible military uses of the Skyhopper such as; Emergency Supply/Evacuation, Anti-Submarine Warfare (ASW), Airborne Early Warning (AEW), Insertion/Extraction of Special Forces and In-Flight Refueling Tanker; an optimistic estimate of 150 military aircraft could be sold. This leaves 600 aircraft to be sold in the civilian market.

The operational cost of an aircraft is a major point of consideration for a company that is looking to buy a new aircraft. This cost determines ticket prices, cargo-shipping prices, and determines if a company using this aircraft can be competitive in the market. To determine if the Skyhopper could be a competitive force in the airline industry, two things were determined; the city to city range and the possible ticket prices. The design of range of 1500 nautical miles makes the Skyhopper more than just the puddle hopper that its 30-passenger capacity suggests. It is possible for the Skyhopper to reach all major airports in the United States and Europe with only one lay over in a major city. (Figure 11.7 and Figure 11.8)

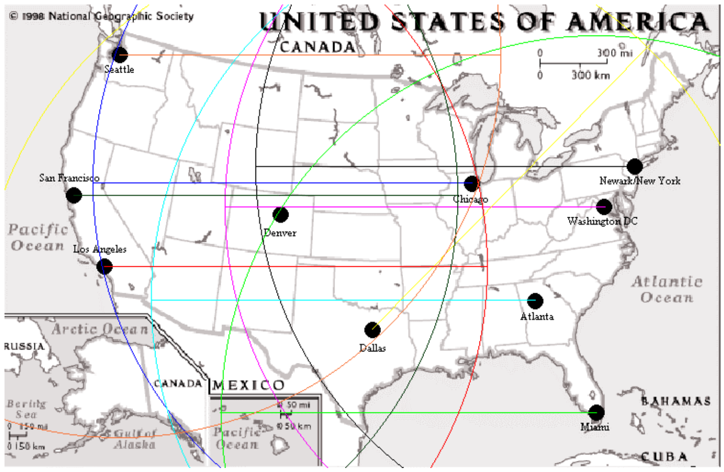


Figure 11.7 - Skyhopper's U.S. City to City Range

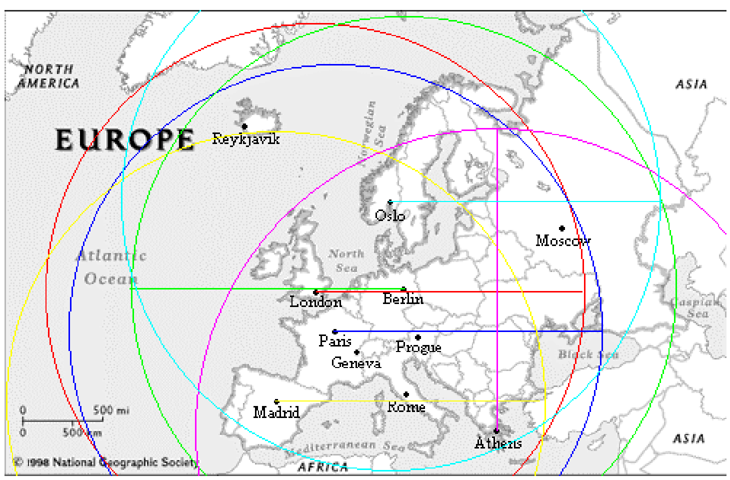


Figure 11.8 - Skyhopper's European City to City Range

With a sufficient range to make any major flight path in the United States and Europe, the next thing to look at was if the ticket prices could be made competitive. According to Roskam[11.2], ticket prices are usually determined by a derivative of the operational cost. The operational cost is divided by the average number of filled seats on a typical flight to get the seat-mile cost. This cost is multiplied by the distance of the trip and given an average of a ten-percent mark up to determine the ticket price. The Skyhopper's possible ticket prices from major city to major city were compared to advertised prices of the larger airlines in the United States and Europe (Table 11.8). It was assumed that the Skyhopper would be

75% full on its average flight. The ticket prices of the Skyhopper are very competitive in almost all cases, but why would an airline buy a smaller aircraft to fly these routes and earn less revenue per flight. This is where the Skyhopper's short takeoff and landing capabilities come into effect. The typical airport is 10 to 15 miles from the city it serves and most major city centers are located on bodies of water. If an airline was willing to commit to the Skyhopper and build small air terminals on these bodies of water, it would be possible to give passenger direct city center to city center access. The air terminals would not have to be full service airports, they would act more like a bus stop. All major aircraft repairs, refueling, maintenance, and storage can be handled at the airlines facilities at the regular airports. The air terminals would just consist of passenger loading and unloading and skeleton maintenance crews. These air terminals would be a major selling point to businessmen and day-trippers to these cities. The necessity for car rentals and/or long cab rides would be eliminated. If it would be possible to keep the ticket price down between two very close cities, i.e. Philadelphia and New York, the Skyhopper's routes would become a competitive force with the train systems. An Amtrak ticket between Philadelphia and New York cost $38.00 for the hour and half trip. The Skyhopper could make this trip in under a half an hour for only $60. The Skyhopper could make 4 to 5 stops in these city center "bus stops" before the need to refuel.(Figure 11.3) The new terminals could also be a major source of tourism and commerce for the cities. This would give the city's governments incentive to support the building of these terminals.

Table 11.8 - Ticket Price Comparison

	United States				
	American Airlines	US Air	TWA	Delta	Skyhopper
New York to Chicago	$ 514.00	$ 524.00	$ 516.00	$ 515.00	$ 536.25
New York to Atlanta	$ 588.00	$ 588.00	$ 590.00	$ 588.00	$ 557.70
New York to Philadelphia	$ 133.00	$ 167.00	$ 150.00	$ 135.00	$ 58.34
Dallas to Denver	$ 616.00	$ -	$ -	$ 599.00	$ 491.63
San Francisco to L.A.	$ 205.00	$ -	$ -	$ 125.00	$ 256.54
	Europe				
	British Airways	Air France	Lufthansa	Alitalia	Skyhopper
London to Paris	$ 268.00	$ 270.00	$ 425.00	$ -	$ 158.73
Paris to Berlin	*$ 799.00*	$ 499.00	$ 525.00	$ -	$ 405.83
London to Berlin	$ 420.00	*$ 610.00*	*$ -*	*$ -*	$ 430.72
Rome to Paris	$ -	$ 580.00	$ -	$ 575.00	$ 517.37
Rome to London	$ 425.00	*$ 600.00*	*$ -*	$ 425.00	$ 668.38
Lay over					

Figure 11.9 - Possible Skyhopper City to City Route

The civilian cargo version has a somewhat limited market because of it smaller size. The current parcel delivery aircraft are larger in size than the Skyhopper. If the center city “bus stops” could be made to handle the parcel delivery, this would open up a whole new area for the Skyhopper. The quick delivery time to city center business would be a huge selling point for these companies. It would cut down the time and prices of their overnight and next day package deliver services. The civilian cargo version could also be utilized as an emergency supply and evacuation aircraft and possible used in forest fire suppression.

12. Conclusion

As shown in Table 12.1 the Skyhopper satisfies or exceeds all RFP requirements and additional design criteria. Furthermore, the Skyhopper can complete them all under engine out conditions. The Skyhopper's Super STOL capability features a minimal noise footprint in comparison to a conventional transport aircraft. The rear cargo door makes the aircraft capable of air drops of cargo, personnel, and/or ground roll unloading. In addition, The flight performance characteristics of the Skyhopper exceed that of the Grumman C-2A Greyhound, making it a viable replacement option.

The tip turbine cruise fan propulsion system of the Skyhopper has been tested and proven in flight. Coupled with the extensive Naval service of the Rolls Royce Adour Mk. 781 engine in the T-45A Goshawk, this propulsion system allows for total conventional control surfaces. The four engine configuration also increases the mission reliability of the aircraft, and eliminated the need for high risk cross ducting of the propulsion system. These features make the Skyhopper a minimal technology risk, enhancing the safety of the aircraft.

The minimal noise footprint, proven and practical propulsion system, and low cost are helping the Skyhopper pave a new direction in commuter travel. By providing city center to city center service the Skyhopper offers a preferred transportation option for the frequent traveler.

Table 12.1 - RFP Requirement Check

RFP Requirement	Military	Commercial	
Takeoff within 300 ft ground roll	300 ft	300 ft	☑
Minimum cruise speed of 350 knots	372 knots	372 knots	☑
Minimum cruise range of 1500 nmi	1500 nmi	1500 nmi	☑
Land with fuel reserves within ground roll of 400 ft	400 ft	400 ft	☑
Minimum capacity of 24 passengers	30 passengers	30 passengers	☑
Provide overhead stowage space	N/A	Yes	☑
Maximum acceleration $\leq$ 0.4 g	N/A	0.4 g	☑
Meet spot factor requirements of 60 ft by 29 ft	Yes	N/A	☑
Carry two GE-F110-400 engines	Yes	N/A	☑
Max payload of 10,000 lbs.	10,000 lbs	N/A	☑
No arresting hook for landing	Optional	N/A	☑
All RFP Requirements Met or Exceeded.			☑

13. The Skyhopper – A Vision for the Future

Imagine yourself stepping out of an aircraft directly into the exciting streets of a major metropolitan center. Just a few hours ago, your boss told you to get to City X to meet a very important client for dinner. You debated whether or not to take the train or to catch a commuter flight at the airport. In the end, you decided to take the new Skyhopper service located down by the river. As you exit the aircraft, you realize how happy you are that you decided to take the Skyhopper. Not only was it a quick and comfortable ride, you were invigorated by the thought that you were riding in the same aircraft that the Navy Seals use. Arriving well before the train would have gotten you there, you will have plenty of time to relax before your dinner meeting. In the short cab ride to the restaurant you hear on the radio that traffic is backed up for miles out towards the airport because of the baseball game. Another plus for the Skyhopper, as you wonder if the client will be able to make the meeting on time. You hope so, because with the Skyhopper's new terminal so close to your office, you will be able to make it home before the kids go to bed.

The ability to conveniently connect cities has been a dream of metropolitan dwellers since the beginning of the urban center. The Skyhopper SSTOL capabilities make this and many other things possible. From the simple convenience of a trip to a major city, to the insertion of troops or supplies to war torn areas, the Skyhopper is the future of convenient and effective air travel.

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