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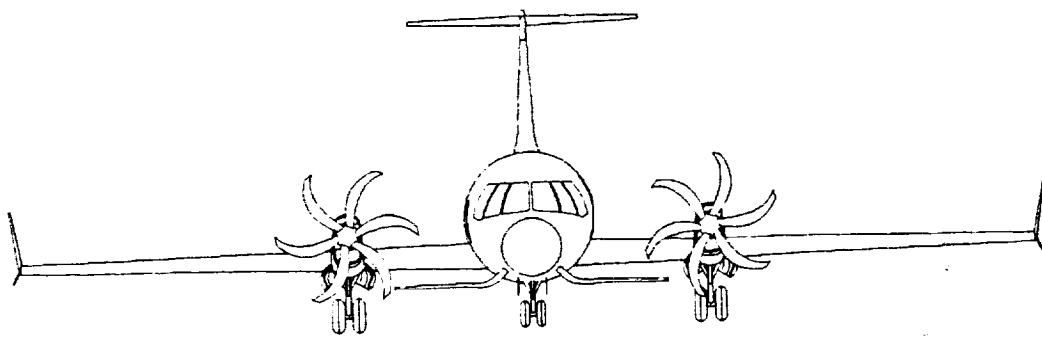
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# The AC - 120

## The Advanced Commercial Transport



Preliminary Design Of A  
100 to 150 Passenger Commercial Transport

N94-24966

Unclas

Presented To: Professor Robert van't Riet

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## **ABSTRACT**

The main objective of this design was to fulfill a need for a new airplane to replace the aging 100 to 150 passenger, 1500 nautical mile range aircraft such as the Douglas DC9 and Boeing 737-100 airplanes. After researching the future aircraft market, conducting extensive trade studies, and analysis on different configurations, the AC-120 Advanced Commercial Transport final design was achieved. The AC-120's main design features include the incorporation of a three lifting surface configuration which is powered by two turboprop engines. The AC-120 is an economically sensitive aircraft which meets the new FAA Stage 3 noise requirements, and has lower NO<sub>x</sub> emissions than current turbofan powered airplanes. The AC-120 also improves on its contemporaries in passenger comfort, manufacturing and operating cost.

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## INTRODUCTION

Presently there are nearly 2,100 commercial transports which 20 years or older and nearing their average lifetime limit of 25 years. In addition, newer and more stringent environmental regulations (i.e. Stage 3 Noise regulation) the need to replace the aging Douglas DC9, Boeing 737, and Fokker 100 aircraft will occur during the next ten years. Therefore, a new and economical aircraft needs to be designed to carry 100 to 150 passengers 1,500 nautical miles to offset the expected future aircraft retirements.

Numerous preliminary designs were analyzed to find their feasibility and the practicality to solve the problem of introducing a new commercial transport. One design involved using a forward swept wing (see Appendix A for further details) and a second design incorporated a rear swept mid-wing with a composite wing box (see Appendix B). Both these designs were found to be technologically impractical and economically unfeasible, therefore continued work on these designs was halted in order to proceed with a workable aircraft. It was decided upon that a different approach should be taken in arriving at a solution for the problem for new short range transport. This approach involved conducting trade studies to analyze different sections of an aircraft to achieve a optimum design for a particular aircraft section. This process would likewise be conducted on major sections and brought together in the end to produce a better aircraft than those currently flying.

Due to the large amounts of time that was used in conducting analysis on the early configurations, a detailed analysis of the final configuration of the AC-120 (The Advanced Commercial Transport) will not be found in this report. Rather this report will focus on the trade studies and the method that was used to achieve a better overall commercial transport.

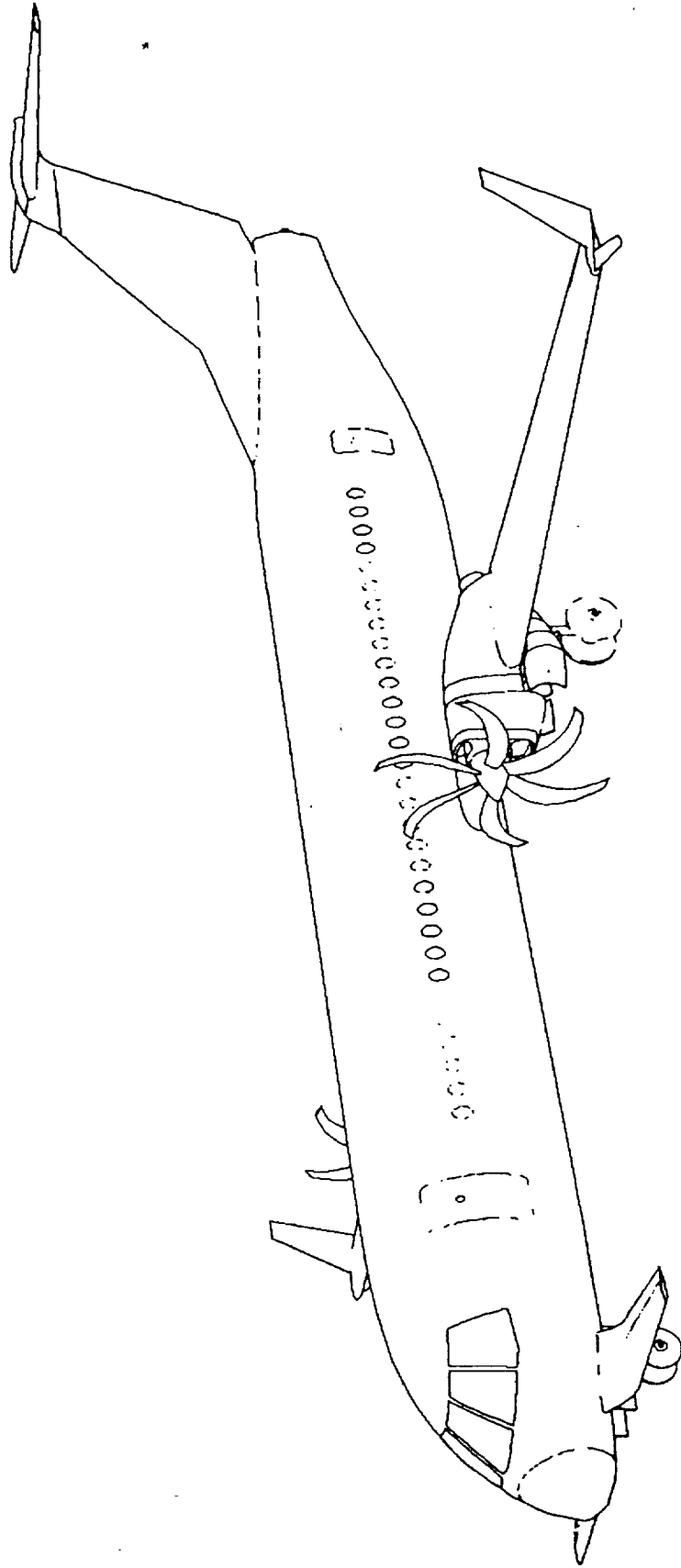
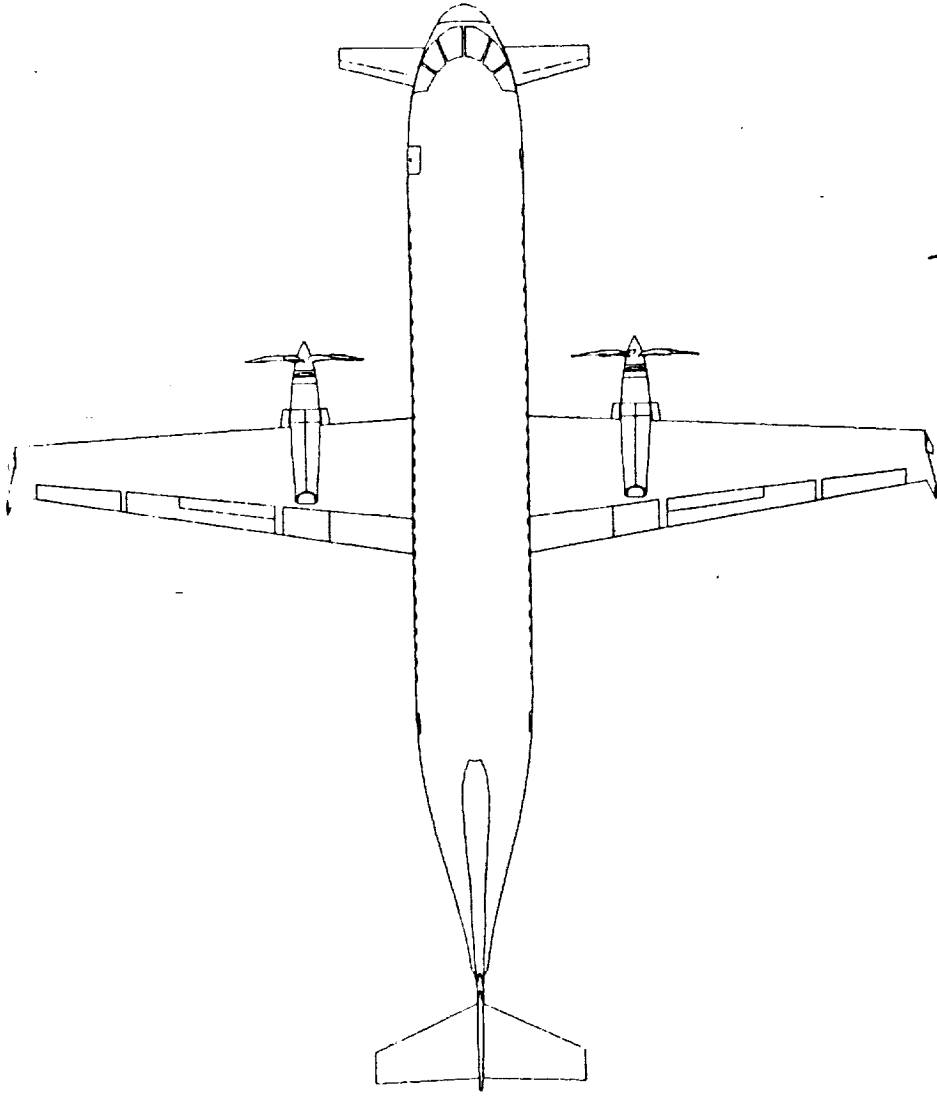


Figure 1. AC-120 Perspective View.





Fuselage Length	=	115 ft.
Cabin Length	=	66.8 ft.
Fuselage Diameter	=	12.5 ft.
Wing Span	=	98 ft.
Aspect Ratio	=	9
Wing Area	=	1060 sq. ft.
Canard Span	=	24.3 ft.
Horizontal Tail	=	22.3 ft

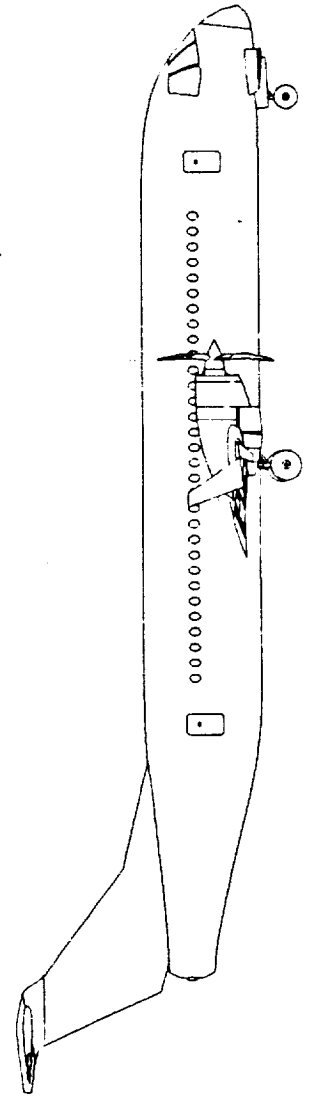
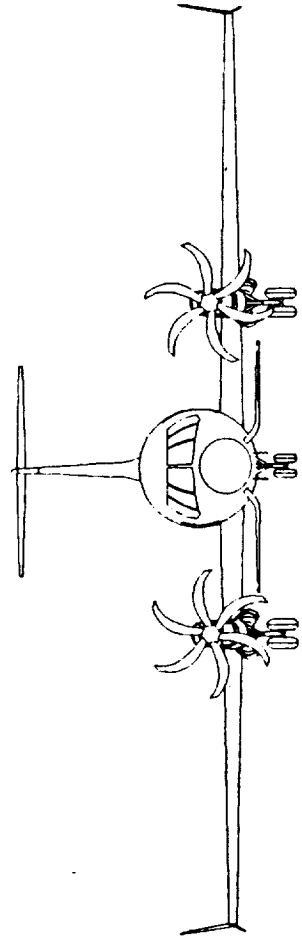


Figure 2. AC-120 Three-View.

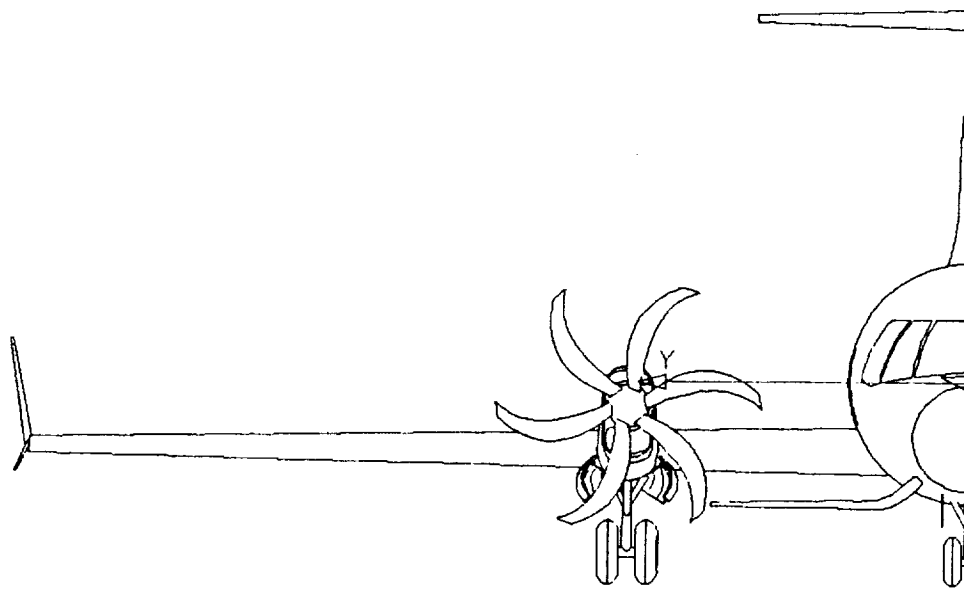
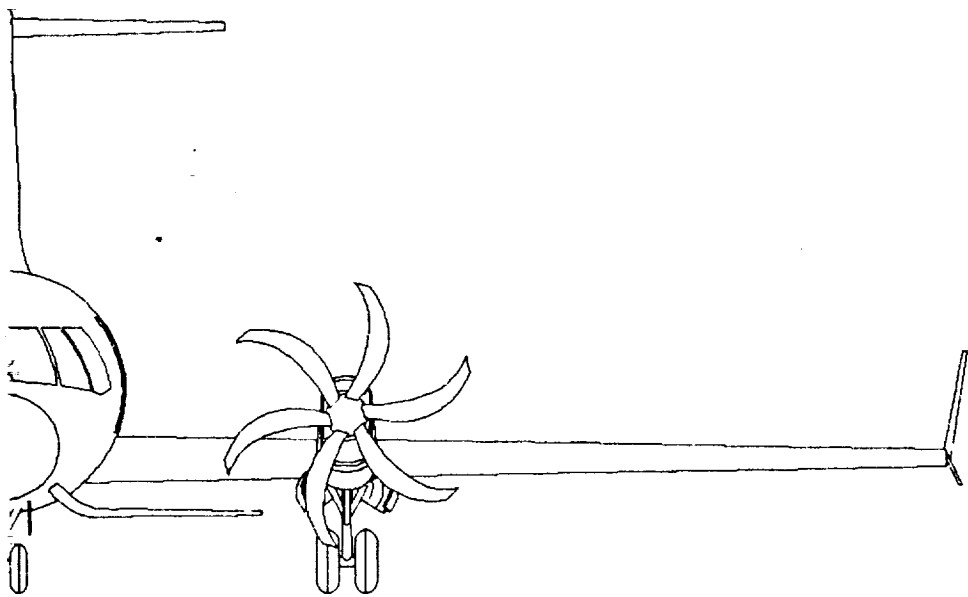
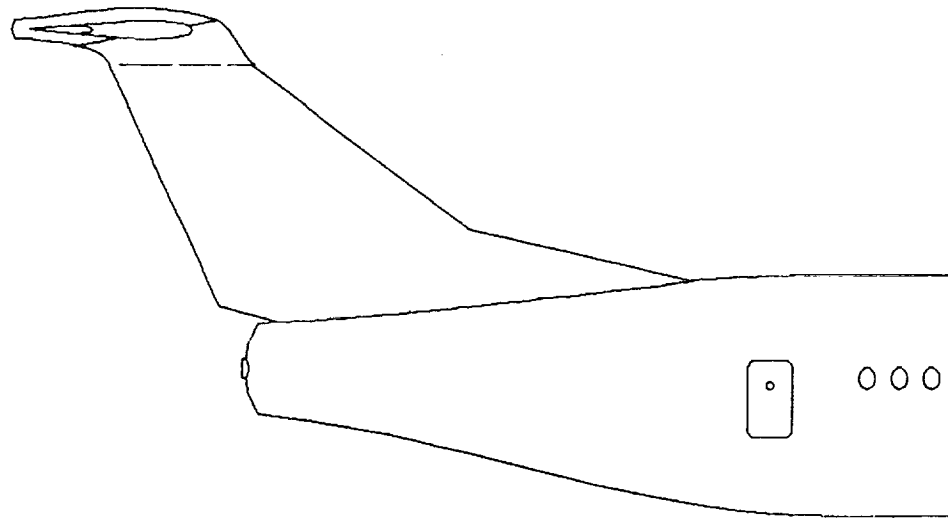


Figure 3. AC-



120 Front View.



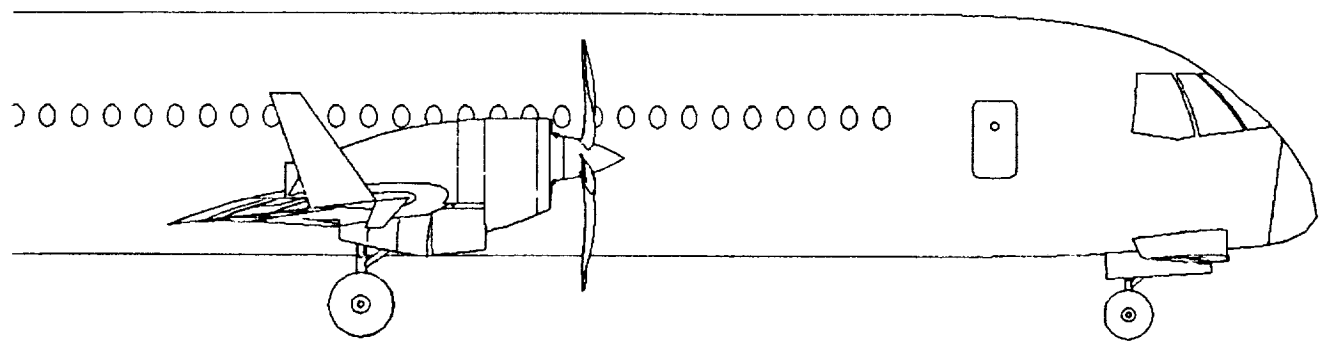
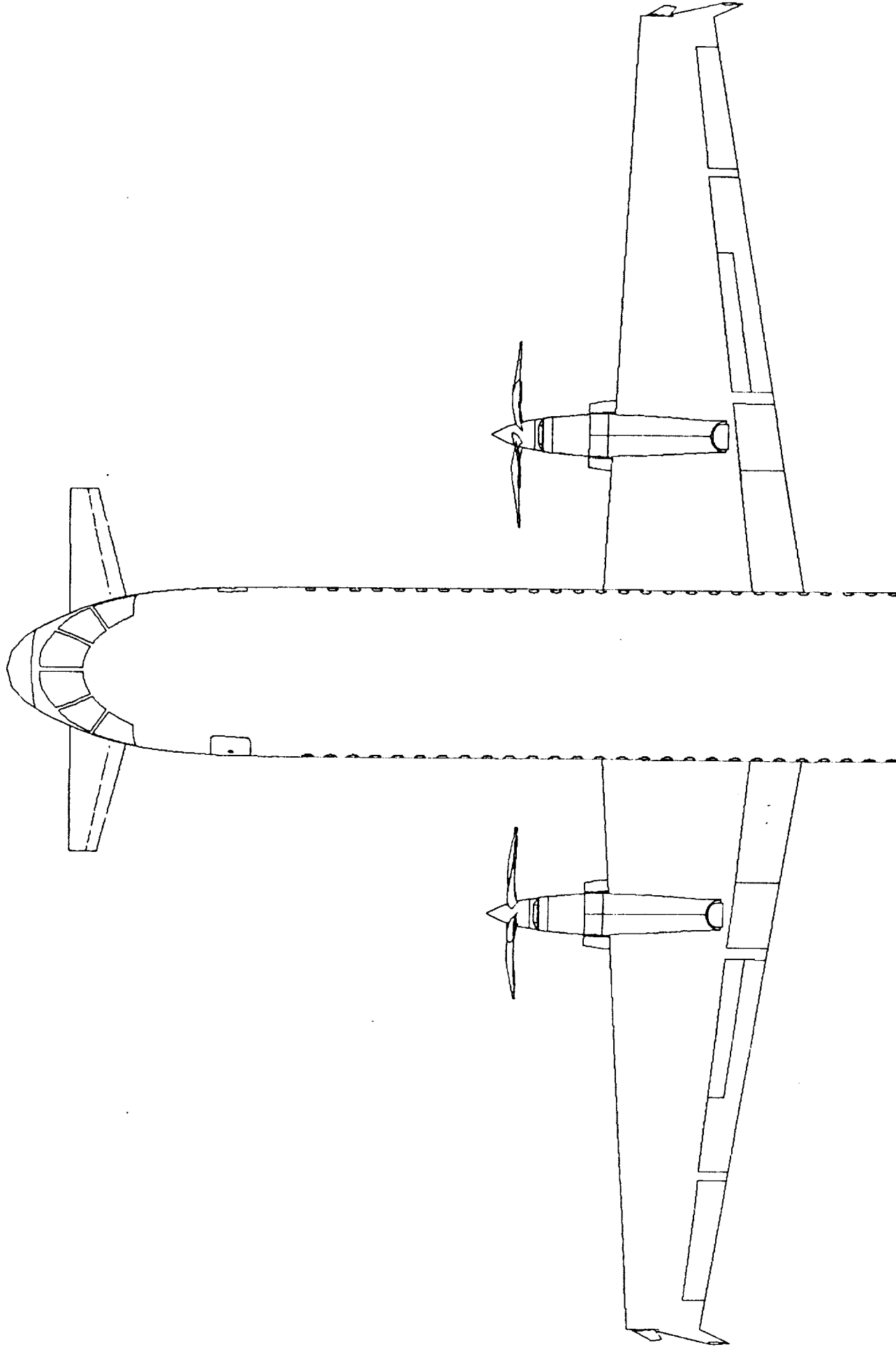


Figure 4. AC-120 Side View.

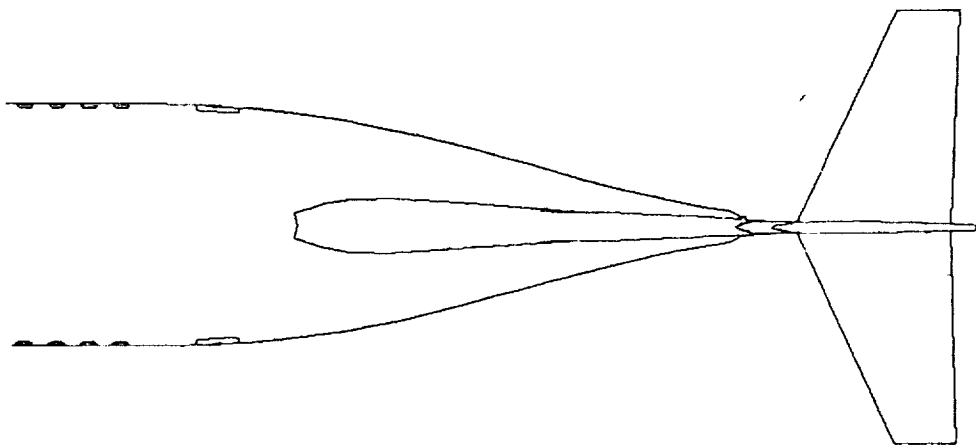
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FOLDOUT FRAME



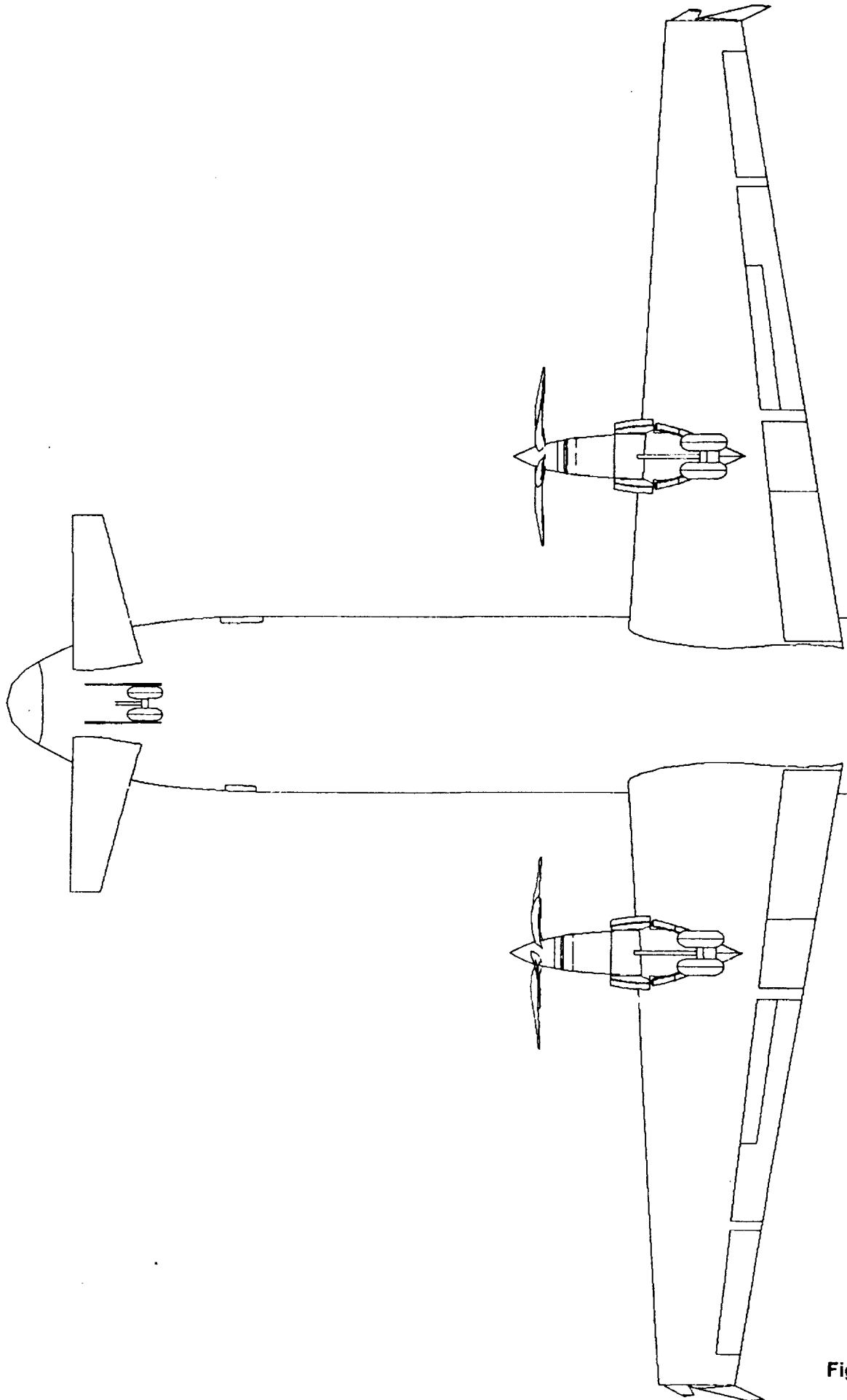
Figure

2.

FOLDOUT FRAME



FOLDOUT FRAME

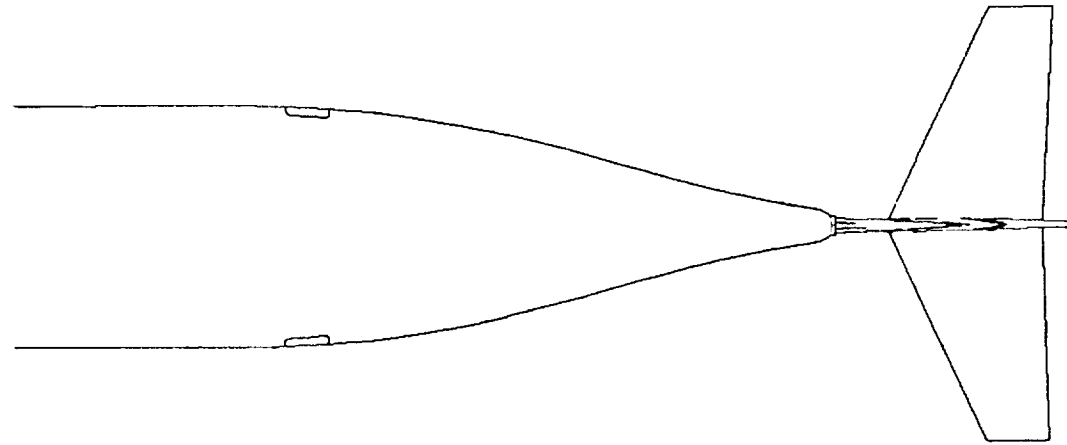


Figure



2

**FOLDOUT FRAME**



e 6. AC-120 Bottom View.

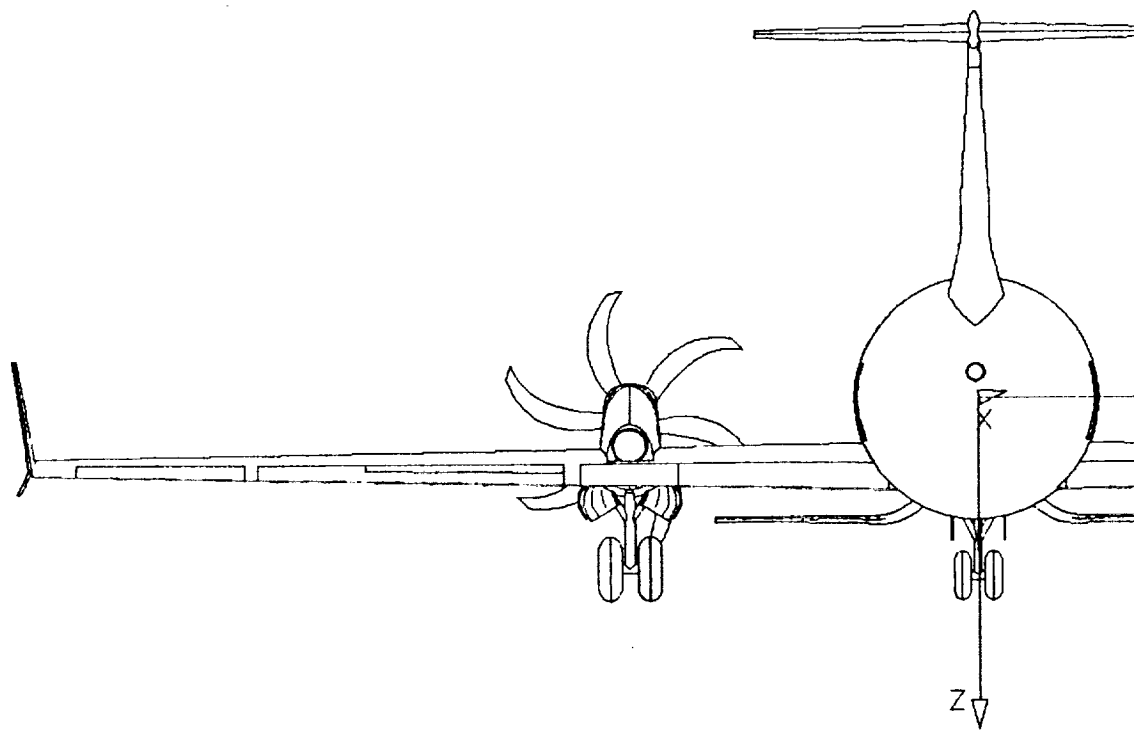
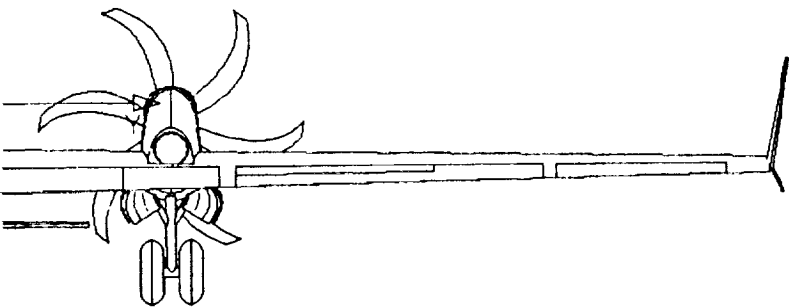


Figure 7. A



-120 Rear View.

## **STUDY OF MISSION SPECIFICATION**

The market for the medium range, 100 to 150 passenger aircraft is already saturated with aircraft such as the Boeing 737, MD 90, Fokker 100, and Airbus A321. All of these were designed by airframe companies with the intention of producing the most successful aircraft in the market. For each of the new aircraft technological advances were introduced but, as a rule, the new aircraft were a derivative of previous aircraft; by designing new aircraft around previous aircraft a smaller amount of research and effort was needed, resulting in savings in time and money. The airframe manufacturers designed new aircraft mainly by the replacement of engines, improvement of the wing design, and wider use of computer applications.

In order to introduce a competitive aircraft to this market, the manufacturer would have to study fuel price trends, allow for long range and altitude flexibility, consider noise and environmental issues, and field length requirements. Because today's airplanes use a non-renewable source of energy with no prospect of having new sources developed in the near future, an airplane to be designed to fly for at least 20 years has to take in consideration the expectation of large increase in fuel prices. Added to this concern is the fact that most of the world's fuel reserves are controlled by a few mostly unstable countries.

With airlines flying aircraft on missions ranging from a 45 minute short hop to the maximum allowed aircraft range, a new aircraft would have to be profitable at all of this ranges in order to be successful. A designer has to keep in mind that if the aircraft was optimized for a single range it may become a failure on all the other ranges, which translates into being a failure in sales. The range should also allow an airline to fly the aircraft from any hub city to another hub city; so when maintenance is needed, the airline will be able to easily schedule a passenger flight and make a profit instead of ferrying the aircraft and losing money. The altitude flexibility is tied up with the range flexibility because it would not be needed nor economically sound to climb to high altitudes when flying the aircraft on short range missions. But for longer missions a high

cruise altitude would be expected in order to fly above any adverse weather and be able to fly at higher speeds.

With noise and emissions becoming a greater concern not, only in the US but around the world, many countries are introducing tight regulations to protect their environment. An aircraft designer must carefully consider a new aircraft's emissions and noise characteristics. A new aircraft should have a state-of the art engine which would not produce large amounts of Carbon byproducts, a function of the combustion pressure, nor Nitrogen byproducts, a function of combustion temperature. An aircraft, specially a aircraft in the category of the aircraft previously described, should have very low noise characteristics because it would be flying in and out of airports located in smaller communities. These communities are getting more concerned about the noise and emissions an aircraft produces when flying overhead and are able to pass laws limiting the operational hours of an airport and the amount of noise and emissions an aircraft can emit when flying into their airport. An airline operating at such a community would highly consider these emissions when buying an aircraft.

A short range aircraft should also be able to fly airport of various field length. Large field would not present a problem to a small aircraft, but a study on short field should be done. An aircraft carrying up to 150 passengers may be needed to fly in and out of very short runways. These runways may be encountered at places where there are geographical limitations and in countries where there is little money to be spent on upgrading airport facilities. A new aircraft should be designed to be able to fly into shorter runways pleasing not only US. airlines flying into small places but also airlines in less fortunate countries which are likely to be operating at smaller airports.

It was proposed by the faculty of the Aeronautical Engineering Department of California Polytechnic State University at San Luis Obispo, that a reasonable set of performance characteristics for an airplane of this type would be:

- cruise at Mach 0.76.
- cruise at high altitudes to fly over bad weather (cruise altitude of 36,000 ft).
- be able to fly in and out of fields as short as 5,000 ft (Sea Level, 95°F).
- have a range of 1,500 nmi for a fully loaded aircraft.
- have a large center of gravity flexibility.

After considerations, some of the above characteristics were changed because no reason to keep them was found. For the fact that a 1,500 nmi range aircraft would not be able to service an important route such as Chicago to Los Angeles (1513 nmi), the range of the aircraft was to increase to 1,550 nmi. This increase would not change the aircraft design by any substantial amount but not having this range would not allow an airline to fly from hub city to hub city with only one stop. It is important for an airline to be allowed the possibility of flying hub routes because the maintenance facilities are located at the hubs. Not allowing an airline to reschedule and aircraft into a route where it would be able to carry passengers while going to maintenance would impose a financial burden, reducing the market for the aircraft.

Though the aircraft was to have a range of 1,550 nmi, it was expected that the airlines would be flying this aircraft mainly on missions ranging from 500 nmi to 800 nmi. For this range, it would not be necessary, useful or economical to climb to 36,000 ft because the aircraft would not be flying at this altitude for more than a few minutes. The decision of was made to lower the maximum ceiling of the aircraft to 33,000 ft, an altitude where the aircraft would still be able to fly over any adverse weather while being economically feasible.

The suggested 5,000 ft landing and take-off field was also investigated and it was concluded that the field length could be increased to as high as 6,000 ft without losing competitiveness. One of the reasons for this was that the shortest major international airport found during the research was the Berlin's Tempelhof airport with a runway length of 6,942 ft at

an elevation of 164 ft. Additionally, the most stringent airport in the US. where an airline would have an interest of flying this aircraft would be Colorado's Telluride airport with a runway length of 5,900 ft at an altitude of 6,000 ft. Considering that it would also be possible to have this airplane compete in the smaller aircraft segment of the market, where it would be expected to have an aircraft that would be able to get into and out of shorter fields, and considering the runway on less developed countries a 5,500 ft runway was chosen.

The changes on the performance characteristics were:

- maximum cruise altitude reduced from 36,000 ft to 33,000 ft.
- take-off and landing field length increased from 5,000 ft to 5,500 ft (Sea Level, 95°F).
- fully loaded range increased from 1,500 nmi to 1,550 nmi.

## MISSION PROFILE

A typical mission for the AC-120 will be to fly from a major airport hub such as Atlanta, Georgia to such destinations as Washington DC, Boston, Massachusetts, and Miami, Florida. It is likely that the AC-120 will be used as a short hop aircraft or a feeder airplane for the major airlines to supply passengers for longer haul flights out of major cities.

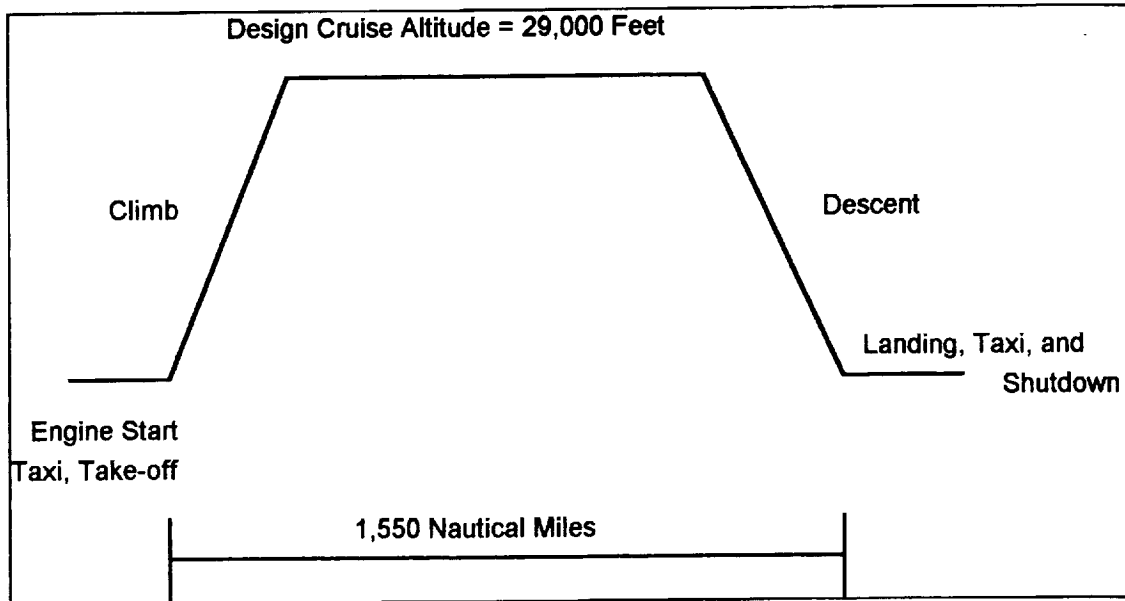
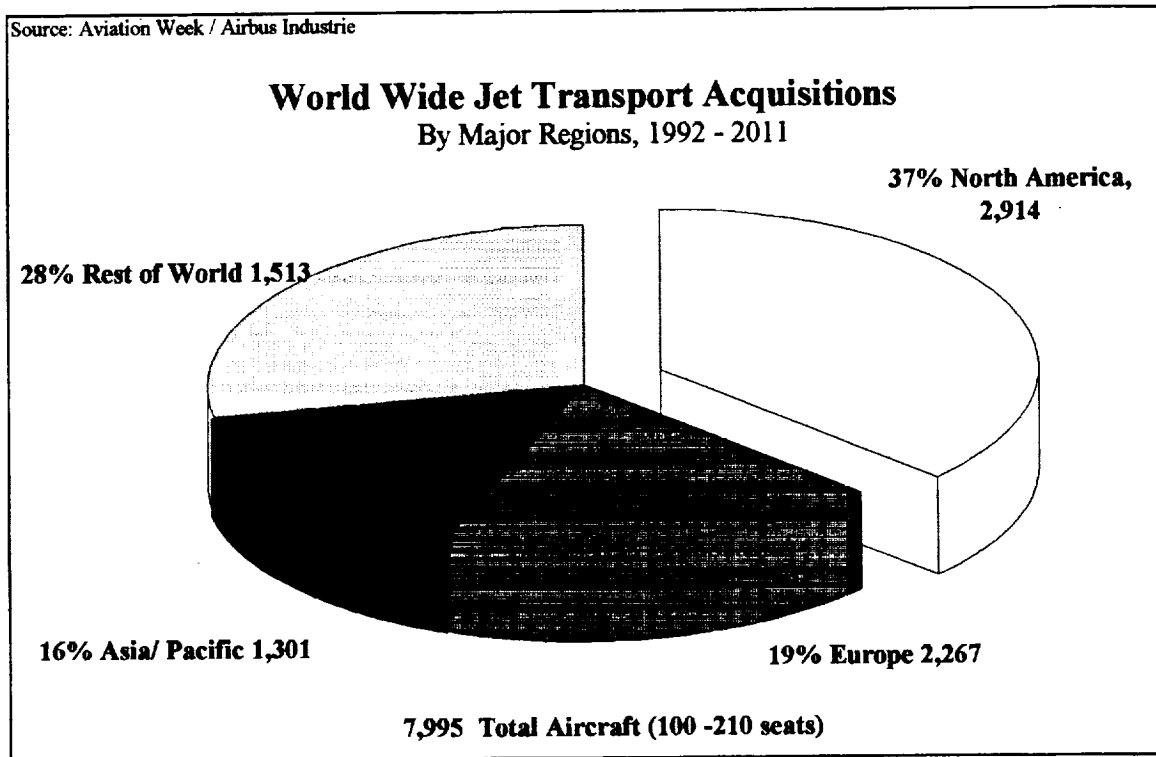


Figure 8. Mission Profile.



## AIRCRAFT FORECAST

Earlier this year, Airbus Industrie released its latest market projections in which a growth of 2.3% in North America, 2.5% in Europe, and 4.9% in Asia (AW&ST, March 1993). Figure 9 shows the anticipated world wide acquisitions of 100 - 210 seat commercial aircraft in to the next century. A large majority of future sales are anticipated to be in North America (37%) and Europe (19%), but the Asian/Pacific (16%) market is growing rapidly. It is projected that nearly 3000 aircraft will be sold to the Asia/Pacific market in the next 20 years, from which 1200 aircraft are expected to be narrow body transports.



**Figure 9. World Wide Jet Transport Acquisition.**

The largest average growth in air travel is expected to be in the Asia/Pacific sector (8.4%) and intra-Asia traffic, in which the AC-120 is designed to operate, is expected to be 21% of the world air travel growth through the year of 2010 (Proctor, AW&ST 4/15/93). If this trend continues the AC-120 can fill the void in the 100 -120 passenger market since the only other

aircraft in this market will be a possible entry of the proposed 120 seat RJX, a joint effort between DASA /Aerospaziale/Alenia (Sparaco, AW&ST 4/15/93). It is expected that the 100 - 150 seat transport class aircraft, doubling to 4,600 aircraft, will be the largest aircraft group in North America and Europe as airlines move towards increased hub operations and new regional operations (Proctor, AW&ST 4/15/93).

A large majority of the new transport acquisitions will be due the retirements due to more stringent noise requirements, age, and the high cost of operating cost of the older inefficient jets. There is currently over 2,100 commercial transports over 20 years of age and only 315 new aircraft are expect to be delivered at the end of the century (Proctor, AW&ST 4/15/93). This creates a market of potentially 2,700 new aircraft that will need to be purchased in order to replace those being taken out of service. Therefore the AC-120 will be entering a growing aircraft market in which a demand for inexpensive and low operating cost aircraft will dominate in sales.

## **BENEFITS OF A THREE LIFTING SURFACE CONFIGURATION**

The three lifting surface configuration offers several benefits, all of which are utilized by the AC-120. Among these benefits are the ability to achieve the ideal trim angles for the aircraft, for any CG. position; greater freedom for the designer in positioning the aircraft's aerodynamic center; and reduction in skin friction drag through smaller control surfaces.

The ideal trim angle for the aircraft is that angle applied to the trimming surface(s) that results in zero control surface induced drag. For a conventional or canard aircraft configuration, this means that the load on the control surfaces must be near zero. In the case of the conventional aircraft, the ideal trim angle occurs when the tail has a very slight positive lift, and the moment of the wing is balanced primarily by the mass of the aircraft. In the case of the canard layout, it occurs when the canard carries a slight download. Both of these cases represent unstable aircraft, furthermore, the ideal trim angle in both cases occurs at a unique CG configuration.

In contrast, a three lifting surface configuration can be ideally trimmed for any CG position, and thus for any static margin as well. This phenomenon can be viewed from several different perspectives. The first results from viewing induced drag as a component of lift acting tangent to the free stream. In trimming a three surface airplane, one of the surfaces is set at a positive angle of attack, and the other at a negative angle of attack. Since there are an infinite number of combinations of trimming angles for the canard and horizontal stabilizer, a set can be found such that the opposing induced drag vectors of the two surfaces exactly cancel. If induced drag is viewed in terms of circulation, the ideal trim condition can be viewed as that trimmed condition that results in the cancellation of the wing tip vortices generated by the two control surfaces. Either way this is viewed, the result is the same: no induced drag from the control surfaces.

Another advantage to the three lifting surface configuration is that it offers the designer an infinite number of possibilities for the control surface sizes, in positioning the aircraft's CG.

This fact was used extensively in designing the AC-120. In attempting to position the CG, wing-fuselage AC, and aircraft AC, all at one location, it was known at the start of the design process that the AC could be located at virtually any location on the aircraft without moving the wing. In conventional designs, an unanticipated CG location, discovered late in the design process, often forces the designer to consider desperate fixes such as moving the wing forward or substantially rearranging the aircraft's fixed equipment. With a three lifting surface configuration, the designer can either leave the CG problem as is, taking advantage of the configuration's robust toleration of CG shifts, or he can change the area of either of the control surfaces.

One of the fundamental means by which the AC-120 achieves superior drag figures is through reduction in wetted control surface area. This is achieved by flapping the Canard and minimizing CG shift (see Center of Gravity Travel of this report). With the canard used primarily as a trimming entity, the entire span of the canard can be fowler flapped, leading to higher lift coefficients and smaller areas. Canard configurations can also be flapped, but a canard aircraft that is anything less than wildly unstable has extremely large pitching moments in the landing configuration. The result is that a reduction in wetted surface area is not realized.

Three lifting surface configurations offer significant advantages in reducing wetted surface area, design freedom, and trim drag. If a new aircraft design is to penetrate a market that is already dominated by strong competitors, that design must make use of non-utilized technologies that offer promise. AEROCOM believes that the three lifting surface configuration is one such technology, and accordingly, included it among the features of the AC-120.

## PROPULSION SYSTEM

### BACKGROUND

Historically turboprops have not enjoyed favor with the major airframe manufacturers. This is primarily the result of perceived difficulties to be encountered with turboprop sales, speed inferiority to jets, and noise.

Much of the unfavorable attitude toward turboprops can be attributed to prejudice resulting from financial losses suffered by several manufactures in the early 1960's, who attempted to pit turboprops directly against jets; the Vanguard was a major loss for the Vickers company (43 sold); the Bristol 175 Britannia fared marginally better due to its early arrival (82 sold); and Lockheed redeemed the Electra's commercial sales (168) with the P-3 maritime patrol aircraft. All of this, in hindsight, could have been anticipated. Why, then, would aircraft companies with strong reputations such as Bristol, Vickers, and Lockheed risk their companies' fortunes in a fool hardy gambit with turboprop aircraft? The answer is that in terms of pure logic these companies had the right answer. The Britannia, Vanguard, and Electra all could be operated with costs per passenger mile well below their competition, and their engenders believed this was a formula for a successful aircraft. Unfortunately, the flying public of that day had been flying on propeller aircraft for nearly four decades, and was thoroughly enamored with the jet age. In contrast, today jets are the status quo, and props are the novelty, if only in a nostalgic sense.

Of course, the standard reason given for the failure of these "end of the propeller era" aircraft is that they were too slow. While it is true that these aircraft were not as fast as their jet competition, they were amazingly fast for large propeller driven aircraft. They ranged in speed from the "slow" Vickers Vanguard (425mph) to the "really slow" Bristol 175 Britannia (405mph). On long range flights this speed deficiency resulted in delays that were quite significant (New York to London, 40 minutes). On shorter flights, however, the delay was so small that operators of the Lockheed Electra found it possible to schedule the same block times for flights between

Los Angeles and San Francisco as the jets. Nonetheless, the passengers of the day would have nothing of it; non-replenishable resources were not the issue of the day.

Of these issues, the least important, historically, has the greatest implications today: noise. The turbojets in use on early models of the Boeing 707, Hawker Siddely Comet, and DC-8, were hardly noise improvements on turboprop powered aircraft. In fact, of the two types, the large turboprops of yesterday would be much more welcome in today's airspace than the turbojets. Since then, however, turbojets have been superseded by turbofans, which are in many cases quieter than large propfans. Like the jet, the turboprop has also changed since the 1960's, and the new technology developed has likewise resulted in a reduction in noise.

#### **THE TURBOPROP COMES OF AGE**

There appears to be a resurgence in the popularity of turboprop aircraft. Many low volume routes that were until recently, served by jet powered aircraft, are now being served by smaller turboprop aircraft. The reasons for this are several: first, these aircraft are extremely efficient, when compared to their fuel hungry jet counterparts; second, the third generation turboprop aircraft being used on these routes are fast, when compared with older turboprops; and finally, turboprops offer maintenance and operational efficiency unrealizable by jets.

The demise of the large turboprop powered transport took place in the heyday of the 429 cubic inch V8 automobile engine - fuel price was not a big concern. Despite the current lull in fuel prices, the fuel hungry automobile and airplane will not return. Will Rogers once said, "Buy land, they aren't making any more of it." The same wisdom can be applied to fuel prices: Fuel prices may go up and down, but fossil fuel's non-replenishable nature assures that the trend will always be up.

This greater concern for fuel savings is reflected in the aircraft the airlines have been choosing to fly shorter routes, where speed sacrifices can be made. Until recently, flights from Los Angeles to San Jose could be flown on Boeing 737, or similar aircraft. Now however, these flights are served by smaller more efficient turboprop aircraft, operating in the same airport environment the jets had been. Similarly, flights from New York City to Hartford, have evolved in

aircraft from the Boeing 737 to the Shorts 330 turboprop. In all these cases, the motivator has been fuel cost.

Another reason for the reappearance of turboprop transports, operating side by side with the jets at major airports, is technological improvements resulting in near jet speeds for propeller driven aircraft. The cutting edge of these advances is represented by the SAAB 2000. This aircraft utilizes swept-blade propellers, which allow considerably higher airspeeds, while reducing noise during the landing and takeoff phases of flight considerably. The result of this type of aircraft's superior performance is that they can operate from major airports served by jets without impeding the flow of traffic. Their higher speed also brings into question the justification for operating jets on routes that could be served by this type of aircraft: why should an operator pay higher fuel bills for 4 minutes of time saving?

Several of the differences in operational practices between props and jets also have a bearing on the speed issue. Delays at the gate have become a big issue with the airlines. Because of this several air carriers, most notably Southwest, occasionally back their jet aircraft away from the gate using thrust reversers in order to avoid ground handling delays associated with towing the aircraft. This practice is a nuisance to airport operations because it can be destructive of property and noisy, since high power levels are necessary. In contrast, propeller driven aircraft can realize a shorter turnaround time due to their ability to directly reverse lower velocity thrust, allowing this practice to occur regularly and without adverse affects.

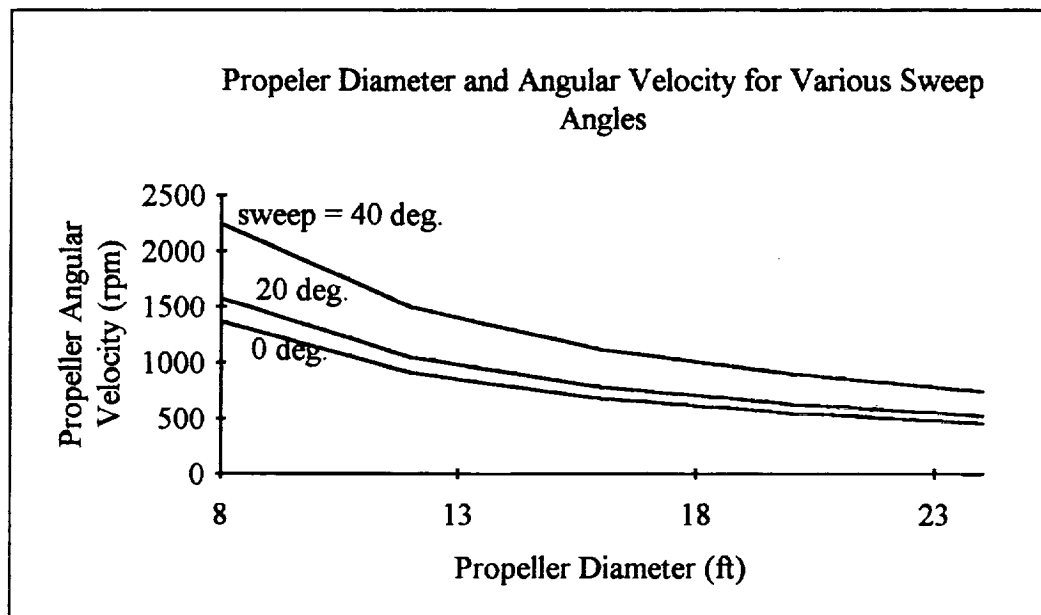
Another issue concerning profitability is the robust nature of the turboprop powerplant. Aircraft do not make money when they are in the hanger. The newer, quieter jet engines are extremely delicate high performance machines that require maintenance by highly skilled people on expensive test apparatus. In contrast, turboprops achieve their efficiency through bypass ratio, driven, in most cases, by a turbojet core that is relatively uncomplicated.

#### **EXTENDING THE CONCEPT**

So far, these success stories have been limited to small aircraft competing at the very short range end of the airline market. After reviewing the obstacles associated with extending the

concept of a low cost, efficient turboprop powered airplane into the 100-150 passenger short-haul transport category, AEROCOM believes that the problems of speed and noise can be overcome.

The Mach number of 0.76, determined to be a standard operating speed for this category of aircraft, can be met, or even exceeded using props. However, this high a velocity would require the use of unducted fans, such as the General Electric UDF, which is a very high technology product. Since simplicity and cost were considered to be two of the most redeeming qualities of propeller driven aircraft, these were ruled out. On the other extreme, straight blade propellers were ruled out because in a maintenance-friendly two engine format, they could not reach an acceptable airspeed see Figure 10.



**Figure 10. Propeller Diameter vs. Angular Speed for Various Sweep Angles.**

The best alternative to these two types of propulsion was determined to be swept-blade props, driven by conventional turboprop powerplants. This format offers the maintenance simplicity of conventional turboprops, with only a moderate increase in cost, due to advanced technology blades.

One obstacle to this format is that it is impractical to meet the standard operational Mach number of 0.76. However, it is possible to come very close: 0.7. Thus, before proceeding with



this format, it was necessary to determine what kind of compromise this would represent in terms of arrival times. A survey of the delays this would cause is summarized in Table 1.

**Table 1. Time Difference between Turbojet and Propeller Aircraft Flying from Atlanta, GA.**

	WASHINGTON D.C.	BOSTON	DENVER
Turbojet @ M=.76	1:05 (hr:min.)	1:52 (hr:min)	2:25 (hr:min)
Propeller @ M=.66	1:11(hr:min.)	2:04(hr:min)	2:40 (hr:min)
TIME DIFFERENCE	6 min.	12 min.	15 min.

These results were obtained by making the assumption that the entire flight would be at cruise speed. This means that these charts over predict the speed advantage of the jets for several reasons. Firstly, all aircraft are held to a maximum speed of 250 knots IAS below 10,000 ft., a speed that both jets and the AC-120 can meet. Secondly, the AC-120 can occasionally expect better treatment in the airport traffic pattern due to its greater altitude and speed flexibility. Finally, a propeller powered aircraft does not need to use a tow vehicle on departure, shortening block to block time. With all these things considered, it is conceivable that the AC-120 would suffer as little as four minutes time loss when compared with its jet powered competition.

To put this in perspective, four minutes is well within the standard deviation of arrival times for this length of flight. Furthermore, four minutes is short enough such that any unanticipated deviance in airport operations will result in this long of a delay. Thus, it is well within reason to expect that with props the AC-120 would on occasion arrive ahead of its jet powered competition.

The other major problem to be considered before proceeding with a propeller driven aircraft was noise. The noise problem to be faced can be divided into two categories: interior and exterior noise.

AEROCOM believes that the interior noise problems associated with turboprops are conquerable with an active noise control system (Antinoise). The Lotus Group in England is

currently involved in the development of such a system for the Cessna Caravan II aircraft, and a representative of that company says that the system in its present form is adaptable to aircraft as large as the Fokker F-27 (Lotus Aim To Silence, Flying 3/93). In terms of cost, antinoise also appears to be an effective solution; the system in use on the Nissan Sunny automobile lists at \$300.

AEROCOM believes that the use of swept-blade propellers will reduce the AC-120's noise to the level that it will be acceptable to the requirements delineated in FAR 25, part 3, and all anticipated changes to these rules. The high pitched whine associated with turboprop powered airplanes is the result of high tip Mach numbers generated by the fan when it is driven at a fine pitch for takeoff. Swept blade propellers produce lower tip Mach numbers at takeoff, due to their sweep, and thus, lower noise. An additional means by which a propeller driven aircraft can meet noise requirements is by virtue of its steeper climb gradient. Noise requirements are measured by placing a fixed microphone a specified distance from the end of the runway, and to the sides. If the aircraft can climb out very steeply, it is farther away from the microphones when the test data is taken.

With the obstacles of noise and speed adequately dealt with, the decision to use swept-blade turboprops to power the AC-120 was finalized. Table 2 summarizes the pros, cons, and solutions that were factored into this decision. Additionally, Table 3 that follows it summarizes the fuel benefits to be reaped from swept-blade turboprops.

**Table 2. Pros, Cons, and Fixes of Propeller Aircraft.**

PROS	CONS	FIXES
very low fuel consumption		
lower maintenance cost		
lower initial cost		
	speed	speed has been determined to be insignificant for short flights
lower emissions due to reduced fuel consumption		
	exterior noise	swept-blade propellers
	interior noise	active noise reduction
lower groundhandling costs because no tow trucks are necessary		
greater speed and altitude flexibility in airport traffic patterns		

**Table 3. Fuel Benefits of Propellers.**

Mission and fuel weight	Propellers	Turbofan	Savings ( $\frac{\$}{\text{passenger} \cdot \text{mile}}$ )
1,550 nmi	13,500 lbs	16,600 lbs	2/3
800 nmi	9,600 lbs	11,500 lbs	1/3

**SPECIFICS TO THE AC-120 PROPULSION SYSTEM**

One specific problem in developing the AC-120 is that no engine currently exists with the horsepower necessary to power a twin-engined aircraft of its size (8,500 HP required per engine - refer to Preliminary Sizing section of this report). Several engines exist from which a derivative engine of the necessary performance could conceivably be produced. The Allison GMA 2100, which is one of the most efficient turboprop engines, was chosen to fill this role. The scaled values of the parameters for this proposed derivative engine appear in Table 4.

**Table 4. Predicted Engine Specifications for an GMA 2100 Derivative.**

Diameter	59 in
Length	140 in
Dry Weight	2010 lbs
Specific Fuel Consumption	.41 lb/hp/hr

The propeller diameter and engine RPM at cruise were determined by using Hamilton Standard propeller performance charts, with the tip Mach number scaled down by the cosine of the tip sweep (the same manner by which the effective Mach number for swept wings is determined). This analysis resulted in the following rough-cut estimates for propeller specifications:

**Table 5. Propeller Specifications.**

Diameter	12 ~ 14 ft
RPM @ cruise	1,200 ~ 1,500
efficiency	0.75 ~ 0.8

**CONCLUDING REMARKS**

The use of swept-blade turboprop technology allows the AC-120 to beat its competition by 30% in fuel savings with only a marginal loss in speed. Numerous other advantages weighed in the decision to power the aircraft with turboprops, as well, including, lower emissions, reduced ground handling expense, and reduced maintenance and purchase cost.

## WEIGHT ESTIMATION

The estimation of the gross take-off weight ( $W_{to}$ ) was computed using fuel fraction method described in Roskam Aircraft Design Part I. The gross take-off weight was made up by three main components: the operational empty weight ( $W_{oe}$ ), fuel weight ( $W_f$ ), and payload weight ( $W_{pl}$ ). Table 6 shows the major assumptions that were made during the process of weight estimation for the airplane.

**Table 6. Assumed Values in Weight Estimation**

Phase	Climb	Cruise
Fuel consumption (lbs/hp/hr)	0.5	0.42
$\frac{L}{D}$	16	18
Propeller efficiency	0.75	0.85
Altitude (ft)	N/A	33,000

Table 7 shows the final results from a Class I weight estimation process. To verify this results a Class II weight estimation process was performed and results were found to be within 3% from the previous method.

**Table 7. Major Component Weight of the AC-120**

Operating Empty Weight (lbs)	59,000
Fuel Weight (lbs)	13,500
Payload Weight (lbs)	32,000
Take-Off Weight (lbs)	104,500

## COMPONENT WEIGHT AND LOCATIONS

The aircraft would be built with proven technologies and equipped with state of the art systems to provide passenger comfort and safety.

Systems sizes and weights were carefully chosen such that they could be fitted to desired locations on the airplane to produced the needed center of gravity location, while still performing efficiently. The empty weight of the aircraft was broken up into major categories: structure, fuel, fixed equipment, crew, passenger, and cargo. These major components are shown in Table 8.

**Table 8. Main Categories Weights and Locations.**

category	weight (lbs)	location from root chord leading edge (ft)
structure	29,050	6.07 aft
fuel	18,400	2.37 aft
fixed equipment	27,400	0.83 fwd
crew	1,050	13.83 fwd
passengers	21,000	2.37 fwd
cargo	7,600	2.37 fwd

The above combination resulted in a maximum gross take-off weight of 104,500 lbs for the aircraft. At this loading, the center of gravity location of the aircraft was 2.37 ft from the datum line.

Each of the above categories consisted of various components. The component break down of each category had to be known in order to calculate the category weight and locations. It was possible to change the location of some of the components of the aircraft such as engine position, wing location, control surface areas and locations. But all the components had limitations and interacted with each other so various configurations were examined in order to obtain the most appropriate combination.

The component weights and locations for the structure and fixed equipment are shown on Tables 9 and 10.

**For the structure:**

**Table 9. Airplane Structure Components Weights.**

component	weight (lbs)	location from root chord leading edge (ft)
fuselage	15,650	6.4 aft
wing	8,000	3.8 aft
canard	190	39.6 fwd
horizontal tail	296	66.1 fwd
vertical tail	700	62.1 aft
forward landing gear	386	35.6 aft
main landing gear	1,300	3.4 aft
engine nacelle	600	3.6 aft

For the fixed equipment:

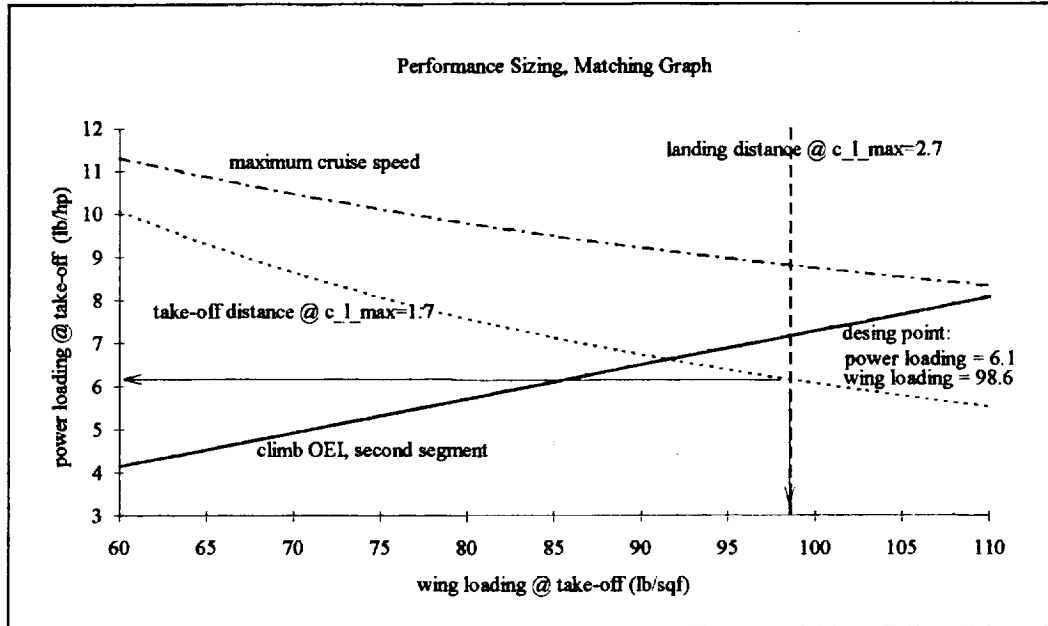
**Table 10. Fixed Equipment Components Weights and Locations.**

component	weight (lbs)	location from root chord leading edge (ft)
Flight Control System	1670	30.7 fwd
Electrical System	1910	14.7 fwd
Instruments and Avionics	1570	39.6 fwd
Air Conditioning and Pressurization System	1120	10.3 aft
Oxygen System	210	50.4 aft
Engines	14500	4.1 fwd
Auxiliary Power System	1050	57.4 aft
Flight Deck Crew Seats	60	36.6 fwd
Passenger Seats	1800	2.4 aft
Cabin Crew Seats	45	2.4 aft
Lavatories and Water	2270	7.9 aft
Food Provisions	220	37.4 aft
Cabin Windows	480	2.4 aft
Baggage and Cargo Equipment	340	30.4 aft
Paint	210	4.4 aft



## PRELIMINARY SIZING

The preliminary sizing was done using Roskam's method, as described in Airplane Design Part I to begin the design process. A design plot was then constructed with the assumptions: the clean lift coefficient of 1.5, take-off and landing distance of 5,500 ft each; the plot is shown in Figure 11.

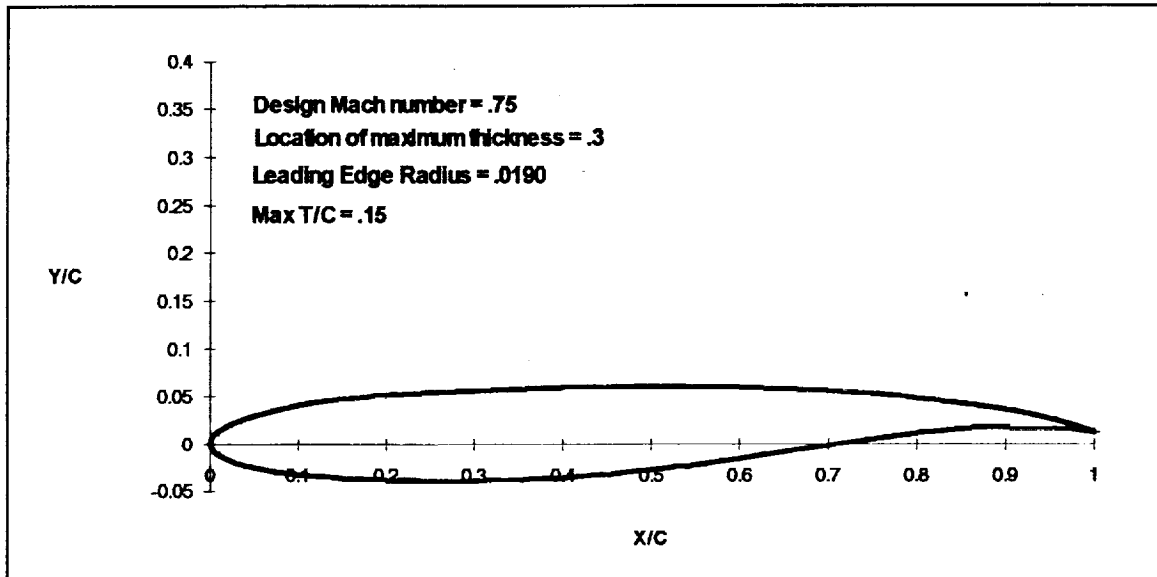


**Figure 11 . Sizing Plot Showing the Most Constraining FAR Regulation and Design Point.**

The sizing plot shows a required power loading of 6.1 lbs/hp and wing loading of 98.6 lb/sqft are needed in order to meet the aircraft specifications. From the power loading value and the take-off weight of 104,500 lbs, it was calculated that the AC-120 would need 17,000 hp of thrust at take-off; and from the wing loading, it was calculated that the AC-120 would need a wing area of 1060 ft<sup>2</sup>.

## AIRFOIL

The airfoil chosen for the airplane is the supercritical airfoil which is shown in Figure 12. A supercritical airfoil was used because of its high lift coefficients and high divergence Mach number. Supercritical airfoils also have less abrupt stall characteristics than conventional airfoils, higher maximum lift coefficients, and higher lift curve slope than NACA airfoils of similar thickness ratio. An added benefit observed on supercritical airfoils was the even distribution of the thickness along the chord. With an even thickness distribution, more freedom is allowed on the structural design of the wing. The main disadvantage of employing a supercritical airfoil is the manufacturing of such an airfoil costs slightly more than a conventional airfoil. Secondly, due to the higher lift generated by the wing, an increase in induced drag will result.



**Figure 12. The 75-07-15 Supercritical Airfoil Used on the AC-120.**

The choice of airfoil is the 75-07-15 (chosen from Bauer, 1972), which is an airfoil with a divergence Mach number of 0.75, a design lift coefficient of 0.7 and a maximum thickness of 0.15. Since not all of the values of the lift curve were given, it was necessary to employ an interpolation technique (Roskam, Part VI) to attain the missing values.

The 75-07-15 airfoil has a lift curve slope of 5.86 per radian, a  $c_{l,max}$  of 1.9 at a Mach number of 0.75. It can also produce a  $c_l$  of 0.23 at no angle of attack, and its characteristic curve can be seen in Figure 13.

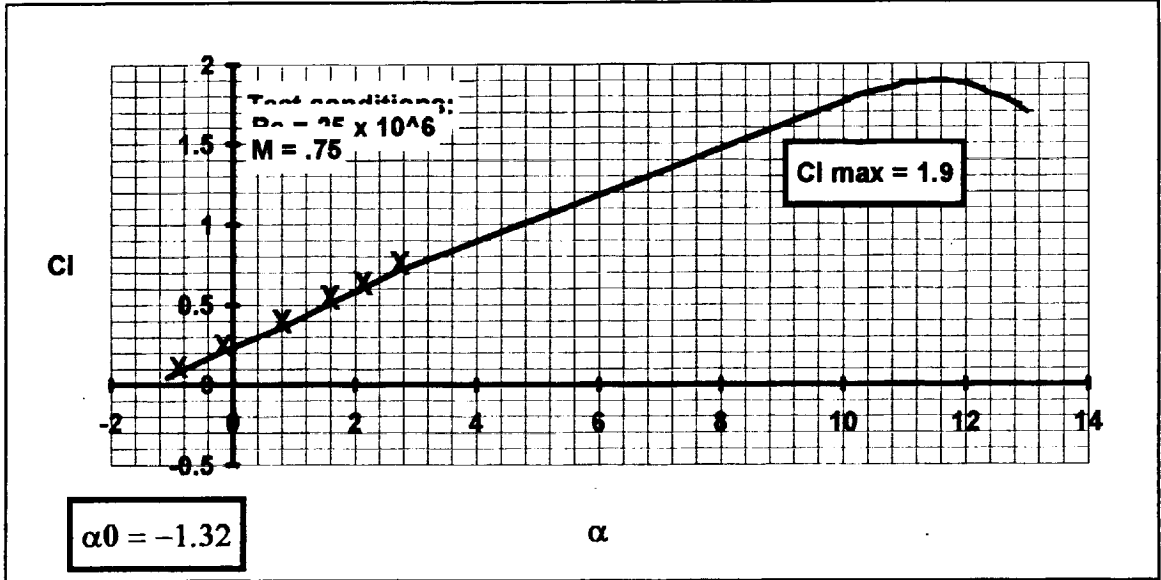


Figure 13. Lift Curve to Angle of Attack of the 75-07-15 Airfoil.

## HIGH LIFT AND CONTROL SYSTEMS

The high lift systems chosen have the maximum lift coefficients given in Table 11 and values for the geometry and position were found using Roskam Part II as a reference.

**Table 11. CL max for different conditions.**

$D_{Cl_{max}}$ (Clean)	.1
$D_{Cl_{max}}$ (Take Off)	.31
$D_{Cl_{max}}$ (Landing)	1.2

The geometry of the high lift devices is shown on Tables 12, 13, and 14.

### FLAPS SELECTION

#### Fowler flaps

**Table 12. Flaps Geometry.**

deflection @ landing	30°
deflection @ take-off	10°
flapped wing area	55%
percentage of wing chord	30%
location	0.13 to 0.63 semi-span

#### Ailerons

**Table 13. Ailerons Geometry.**

Outboard	
percentage of wing chord	30%
location	0.75 to 0.95 semi-span

#### Spoiler

**Table 14. Spoiler Geometry.**

percentage of wing chord	20%
location	0.38 to 0.61 semi-span

Many types of high lift devices were considered for the use on the AC-120. Plain flaps would require a large percentage of the wing span, double slotted flaps had a complexity that was impractical due to the cost involved of installing such devices, so Fowler flaps were then chosen because of their lower cost and lower complexity relative to the other choices.

The supercritical airfoil chosen has the required clean maximum lift coefficient ( $C_L = 1.9$ ), which is being used as a base to size the high lift devices. Using the 75-07-15 airfoil, a landing coefficient of lift of 2.7 could be achieved on a small commercial transport without large and complex high lift surfaces. To attain higher lift coefficients the use of either larger Fowler flaps or leading edge slats would have been necessary. The simpler high lift system translated into savings not only in aircraft weight but also production and maintenance costs. A summary of different high lift devices implemented on the AC-120 wing is shown on Table 15.

The lift curves for the wing were generated.(Roskam Part VI) and Figure 14 shows the lift coefficient curve for the clean wing and the landing configuration. It can be seen that a maximum lift coefficient for the clean configuration was attained at an angle of attack of  $12.2^\circ$ . For fully deflected flaps, the maximum lift coefficient was attained at  $9^\circ$ .

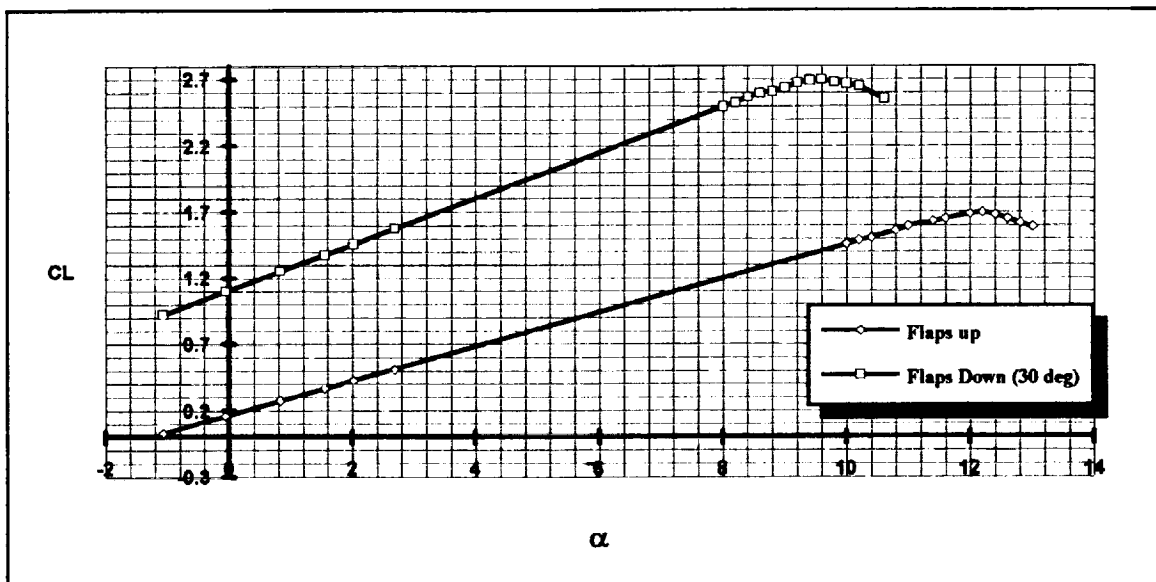


Figure 14. Coefficient of Lift vs. Angle of Attack for Clean Wing and for Landing Conditions (Fowler Flaps @  $30^\circ$ ).

By using the same Fowler system at a smaller deflection, a take-off lift coefficient of 1.7 could be easily obtained. A larger flap deflection at take-off would have allowed the use of a smaller wing area, but would have greatly increased the drag and requiring added engine power.

The positioning of the ailerons on the outboard sections of the wing allow the pilot to use them for trim, lateral controls and when the auto-pilot is engaged. Spoilers were added mainly for increasing the aircraft's angle of descent into crowded airspace or when landing in urban areas.

**Table 15. Coefficient of Lift of the Wing for Different High Lift Devices (For Constant Flapped Wing Area).**

Type of High Lift Device	CL <sub>max</sub>
Supercritical Airfoil	1.6
Plain Flaps	2.1
Leading-edge Slats	2.1
Split Flaps	2.4
Fowler Flaps	2.7
Single Slotted Flaps	2.8
Double-Slotted Flaps	3.0
Double-Slotted Flaps with Leading Edge Slats	3.2
Addition of Boundary Layer Suction	3.5

## WING DESIGN

### WING SUMMARY

The final wing configuration has the geometry described in Table 16 and Figure 15. These parameters were decided upon based on the method outlined below, in the sub-sections, Determination of Design Conditions and Determination of Wing Parameters.

**Table 16. Wing Geometric Parameters.**

Wing Area	1060 ft <sup>2</sup>
Aspect Ratio	9
Taper Ratio	0.33
Span	97.7 ft
Mean Average Chord	11.76 ft
Root Chord	16.28 ft
Tip Chord	5.43 ft
$\frac{1}{4}$ Chord Sweep	0.0°
Leading Edge Sweep	3.18°
Spanwise A.C. Location	20.35 ft from $\zeta$

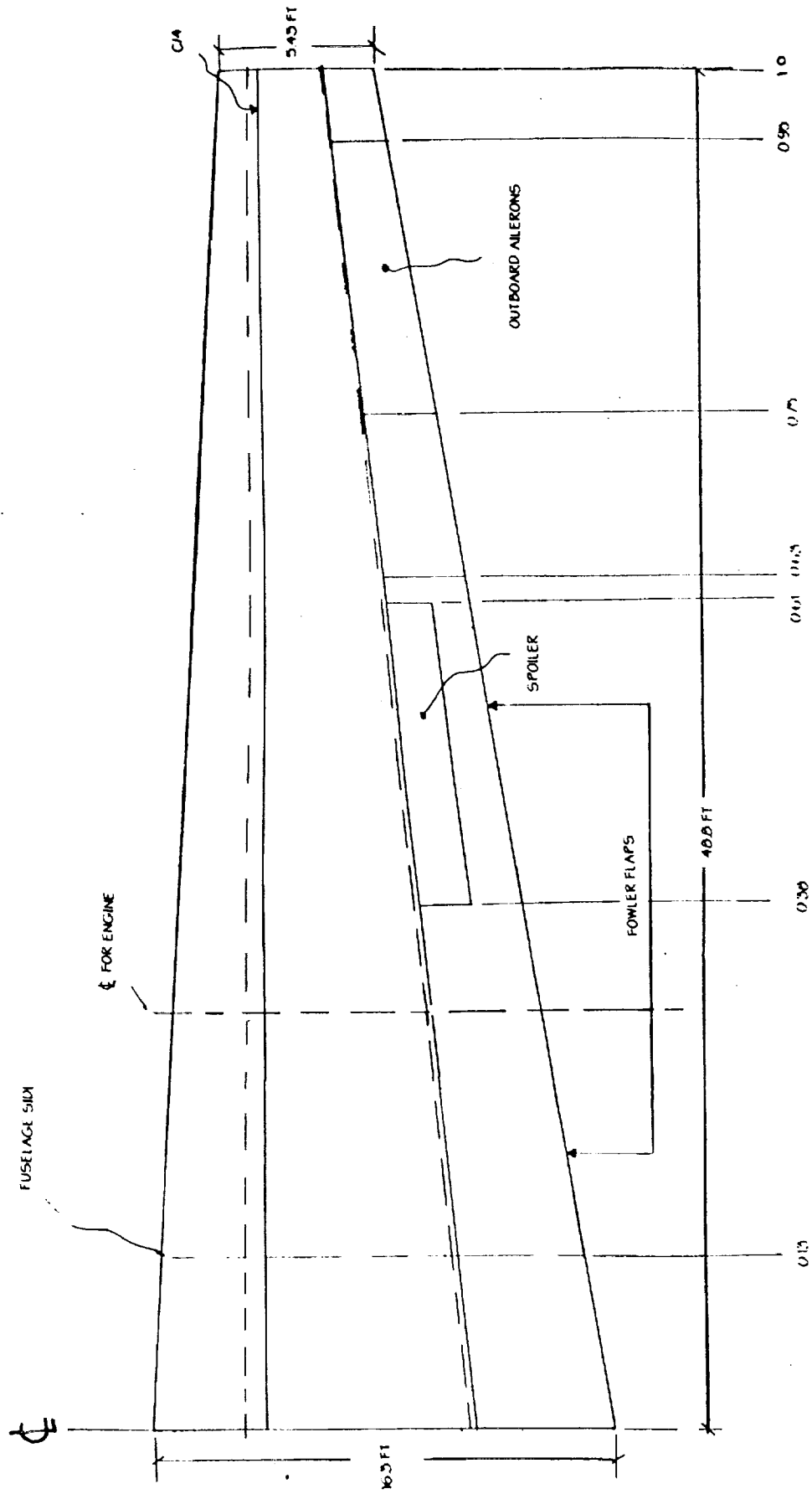


Figure 15. Wing Geometric Parameters Showing Flaps, Spoiler, Ailerons, and Engine Location.



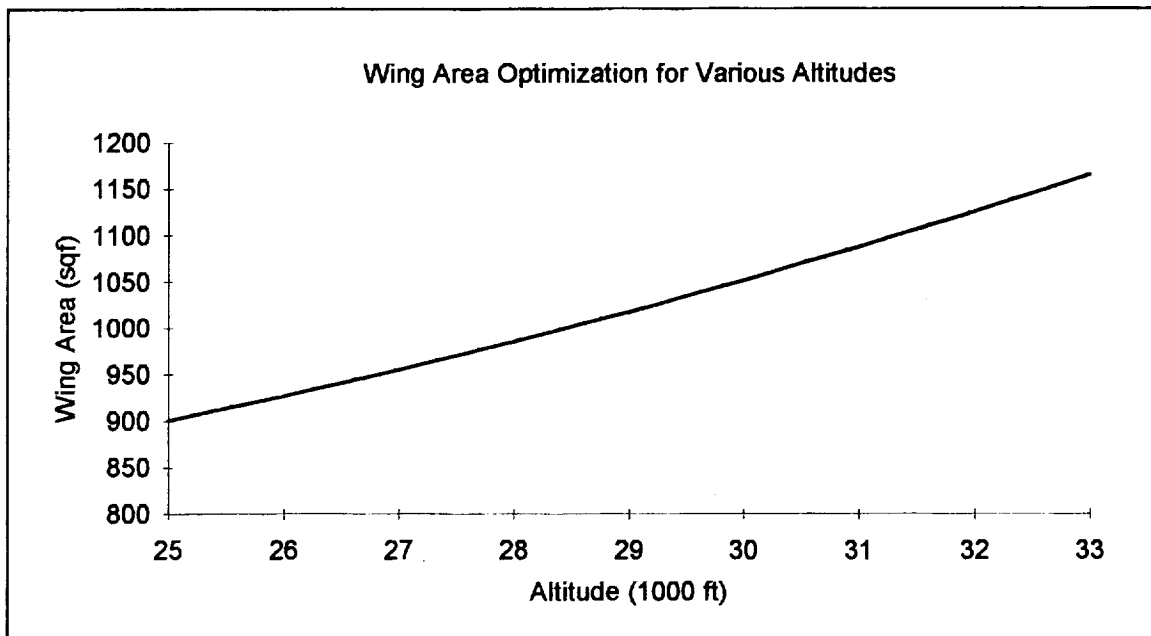
## DETERMINATION OF DESIGN CONDITIONS

In order to design the wing for the aircraft it was necessary to determine the range of altitude the aircraft would be flying at. Though a maximum range of 1,550 nmi, ( $\approx 3.5$  hr) was considered necessary to satisfy airline needs, typical missions would be as short as 500 nmi ( $\approx 1$  hr), where it would not be economical to climb to a high altitude. Additionally, the decision to power the aircraft with turboprops limited the speed to  $\text{Mach} \leq 0.7$  and the flying altitude to less than 33,000 ft because of adverse effects on propeller efficiency. Considering the maximum altitude, maximum speed, and range flexibility, a variance in flying altitude of 25,000 ft to 33,000 ft was determined to be a realistic range in operating altitude for the AC-120.

The next step in the wing selection process was to determine what design altitude between twenty five and thirty three thousand feet would result in the best average wing performance throughout this range. The simple answer would be to design the wing for the average of the expected altitude range, 29,000 ft. Curiosity motivated an investigation with the aim of determining whether this hueristical approach is in fact correct. The first step was to optimize wing area for every 1,000 ft interval between twenty five and thirty three thousand feet. In this case, optimization means varying wing area until a maximum lift to drag ratio is observed (mathematically:  $\partial(Cl/Cd)/\partial S = 0$ ). The wing areas used in performing this calculation are shown in Table 17 and also in Figure 16.

**Table 17. Wing Areas for Optimum Performance at Altitude.**

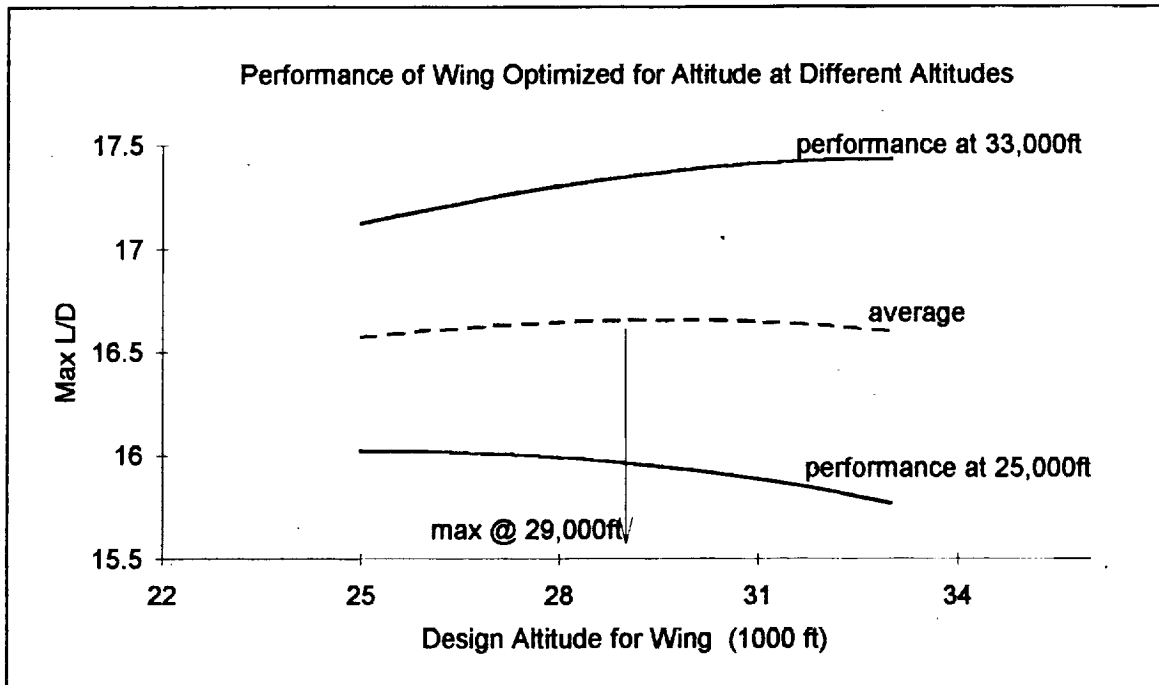
altitude (ft)	area (sqf)
25,000	900.4
26,000	926.5
27,000	955.1
28,000	985.5
29,000	1017.6
30,000	1051.5
31,000	1087.3
32,000	1125.2
33,000	1165.3



**Figure 16 - Wing Areas for Optimum Performance at Altitude.**

The results show, as expected, that, for an increase in flying altitude, the optimum wing area necessary in order to obtain a maximum Lift-to-Drag ratio increases. In order to determine a design altitude that would result in a wing with the best range of altitude performance, a study of how each of the wing areas would perform at the other altitudes had to be conducted. This involved calculating the performance for each of the above wing areas at 25,000 ft and 33,000 ft, to determine how each of the wings would perform at the extremes of the AC-120's design

altitude range. The average between the two values was taken and the results are shown in Figure 17.



**Figure 17 - Study on How a Wing Optimized for Altitudes Ranging from 25,000 ft to 33,000 ft Would Perform at 25,000 ft and 33,000 ft.**

The results shown in figure six confirm that the common sense expectation is valid, as a rule of thumb, since the maximum appears to occur at approximately 29,000 ft. However, a closer examination of the peak of the graph reveals that the true maximum does not occur exactly at the average altitude. The maximum is subtly skewed to the high side, in other words, a slightly larger wing than one designed for the average altitude will result in fractionally better performance over the entire range surveyed. Since this difference is well within AEROCOM's ability to accurately predict wing performance, 29,000 ft. was chosen as a design cruise altitude for the wing.

## DETERMINATION OF WING PARAMETERS

### Wing Area Selection

With a design altitude for the wing solidified, the next step was to determine what area would provide the best lift to drag ratio at cruise. The ratio of lift to drag can be varied in many different ways. The most common is the so called "drag polar," which is obtained by varying an aircraft's velocity, and has a maximum at

$$\partial(Cl/Cd)/V_{\infty} = 0$$

this maximum is commonly referred to as the best L over D.

Another method is to vary lift to drag ratio by changing  $C_l$ . This maximum occurs when the parasite drag,  $C_{d0}$  is equal to the induced drag,  $C_{di}$ :

$$\partial(Cl/Cd)/\partial C_l = 0 \text{ when } C_{d0} = C_{di}$$

In the derivation of the above result, it is assumed that parasite drag is not a function of  $C_l$ . This is true if, and only if,  $C_l$  is varied by changing lift, since parasite drag is very dependent on the wing area. This result is apparent from the functional relationships below:

$$C_l = C_l(\text{wing area, lift, density, velocity}) \quad C_{d0} = C_{d0}(\text{wing area, .....})$$

$$\text{Assumption: } C_{d0} \neq C_{d0}(C_l)$$

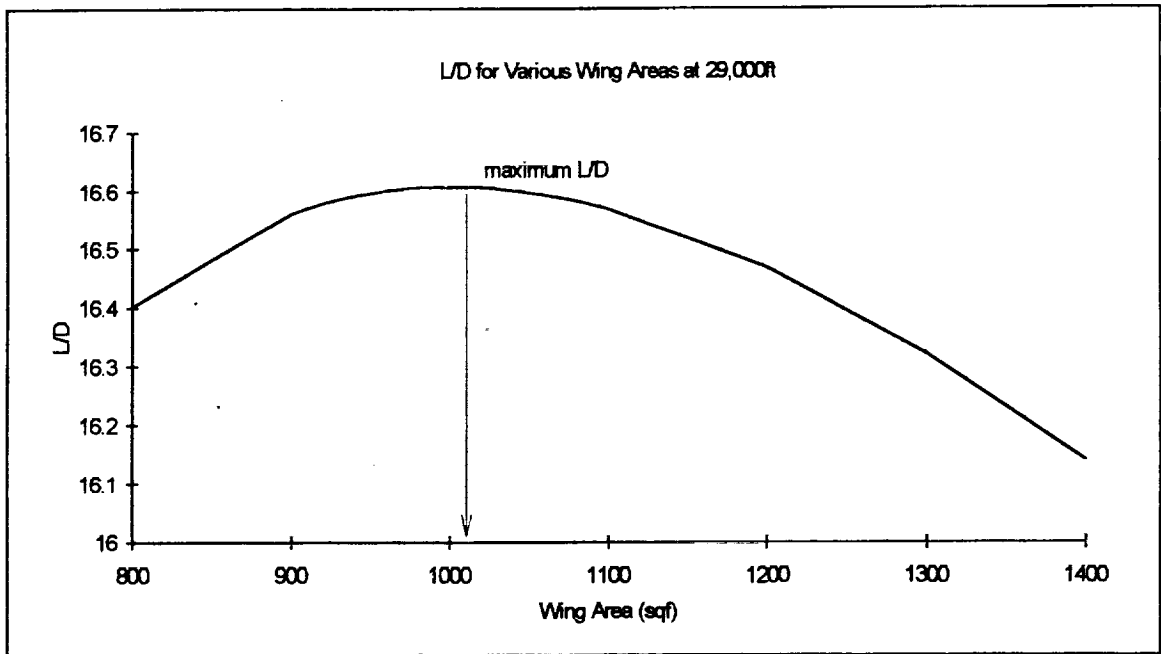
During cruise, the lift of the aircraft is equal to its weight, so the maximum of this equation really shows what aircraft weight will produce the best lift to drag ratio - not a very useful result. The method used by AEROCOM in varying lift to drag ratio, was to vary wing area. This results in a maximum represented mathematically by:

$$\partial(Cl/Cd)/\partial(\text{wing area}) = 0$$

This equation has a solution where

$$C_{di} = C_{d0} + \partial C_{d0}/\partial(\text{wing area})$$

This differential equation has a closed form solution that results in an non-determinable constant, so the maximum must be found by trial and error. In order to find an iterative solution, the lift-to-drag ratio was calculated for wing areas ranging from 800 ft<sup>2</sup> to 1400 ft<sup>2</sup> at the design altitude. The results of the study is shown on Figure 18.



**Figure 18. Optimization of the Wing for 29,000 ft.**

As seen on Figure 18, for an altitude of 29,000 ft an increase in wing area resulted in an increase in Lift-to-Drag ratio up to the maximum, which occurred at 1017 ft<sup>2</sup>. Thus, 1017 ft. became the design wing area for cruise.

Cruise, however, is only one condition of many that has an effect on the choice of wing area. Another crucial factor in sizing the wing area is the take-off and landing conditions. The choice of wing area must allow the aircraft to takeoff and land without requiring the use of extremely high thrust or clumsy high lift devices, that would result in substantial cost increases. The values for the maximum lift coefficients expected to be produced by the selected high lift devices were calculated in High Lift Control and Control Systems, and are  $C_{l,max} = 1.4$  for cruise,  $C_{l,max} = 1.7$  for take-off, and  $C_{l,max} = 2.7$  for landing. Since these values are all functions of wing area, the results shown required an iterative solution in conjunction with all of the methods outlined in this section.

A sizing program was used to obtain power ratio,  $W/P$ , as a function of the wing load,  $W/S$ , with curves showing the lift coefficients for landing and take-off, and the constraints

necessary for compliance with Federal Aviation Regulations. The take-off weight of the aircraft was 104,500 lbs and was computed in Component Weight and Locations.

The most constraining FAR requirement is for a single engine climb, which was easily met by the AC-120. This requirement is represented by the solid line in Figure 19. Other influential parameters include balanced field length on takeoff (dotted line), and landing distance (vertical line). Utilizing data computed for the maximum lift coefficients in the landing and takeoff configuration (again, this is the final result of an iterative process), the design point was chosen at the point where both the landing and takeoff lift coefficients could be met. This resulted in a power loading of  $W/P = 6.1 \text{ lbs}/\text{hp}$  and wing loading of  $W/S = 98.6 \text{ lbs}/\text{ft}^2$ .

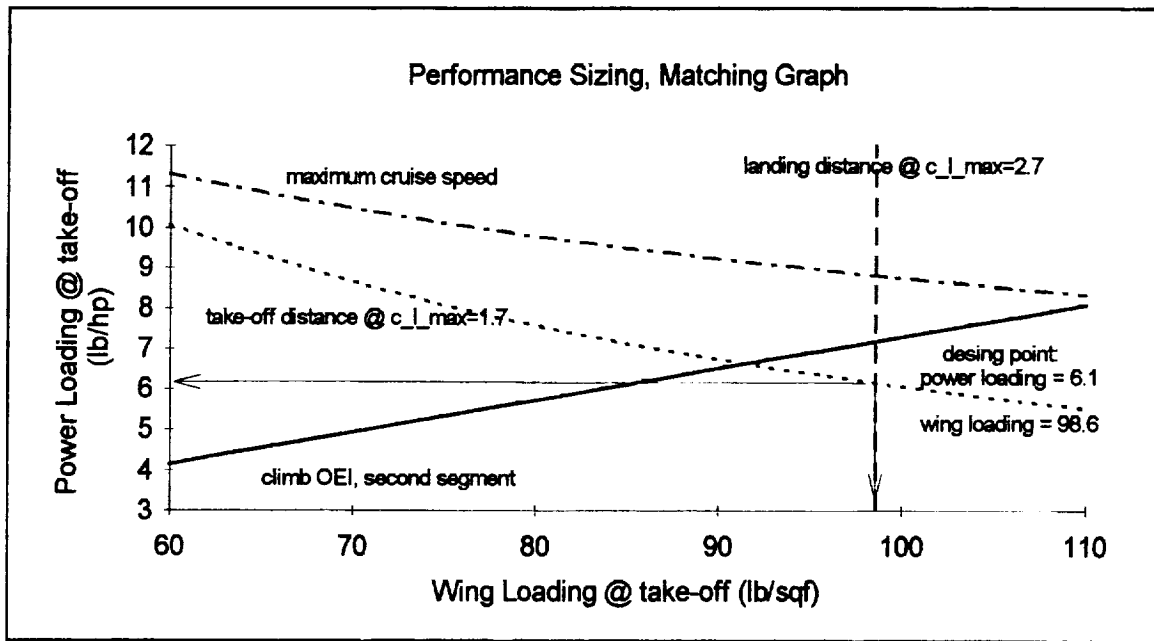


Figure 19. Sizing Plot Showing the Most Constraining FAR Regulation and Design Point.

With a power loading of  $W/P = 6.1 \text{ lbs}/\text{hp}$  and a wing loading of  $W/S = 98.6 \text{ lbs}/\text{ft}^2$ , the maximum take-off weight is 104,500 lbs, and the wing area needed to meet the take-off and landing field requirements is 1060 ft<sup>2</sup>.

At this point a very mild trade-off had to be made with wing area. It was intended to have the wing area of 1017 ft<sup>2</sup> optimized for 29,000 ft, but this would not satisfy the landing and take-

off requirements. In order to satisfy the requirements the wing area was increased to 1060 ft<sup>2</sup>. Since, AEROCOM's ability to predict wing performance is probably not within the tolerance represented by this difference in wing area, this was not considered to be a major sacrifice.

### **Taper Ratio Selection**

Another step in the iterative process leading to the definition of wing parameters was the determination of the taper ratio. An elliptical planform wing generates an Oswald's efficiency factor of about 1, the minimum induced drag factor realizable for ordinary wings. Historically, very few elliptical wings have ever been produced due to their cost. In contrast, a straight, tapered wing is the cheapest to produce, and with the proper choice of taper ratio, results in only a moderate sacrifice in Oswald's efficiency factor. A taper ratio of one-third was selected after research indicated that this value would result in the lowest induced drag factor ( $\delta$ ) (and thus the highest Oswald efficiency factor), for a straight taper wing of any aspect ratio (Anderson, John D., 1991).

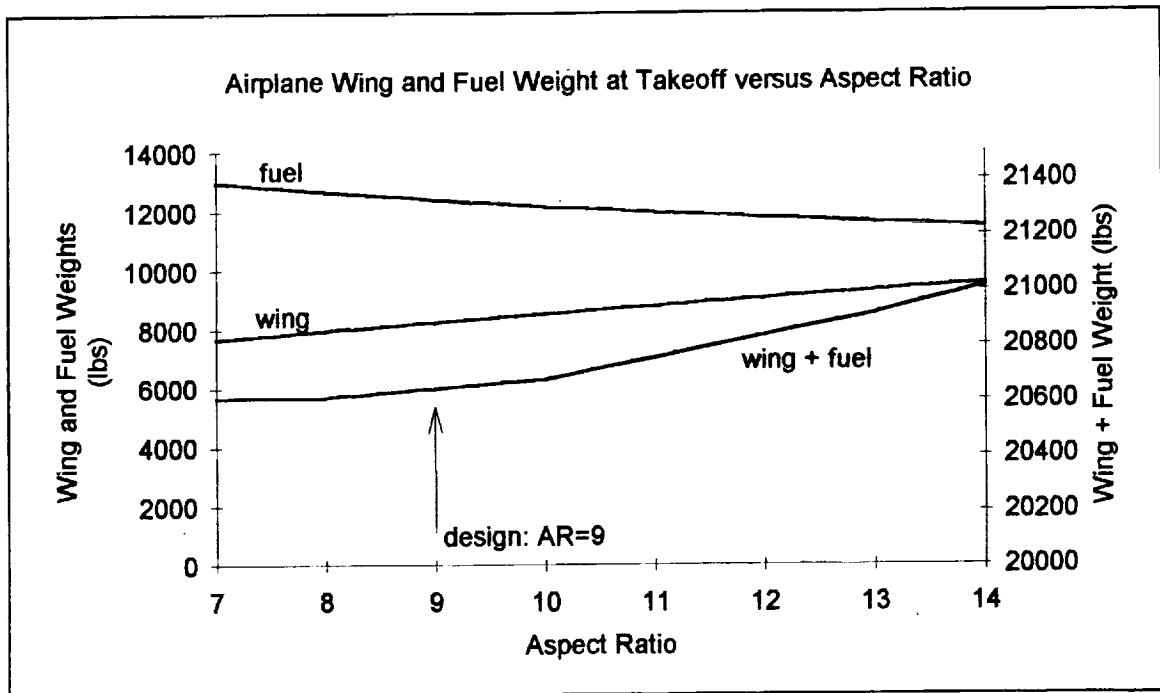
### **Aspect Ratio Selection**

At first it was believed that the best overall aircraft would be achieved with a high aspect ratio. This belief was based on the fact that the induced drag, which has a significant impact on fuel burn, is inversely proportional to the aspect ratio, given by the equation,

$$C_{d,induced} = \frac{c_l^2}{\pi e AR}$$

While the equation above shows a decrease in drag for larger aspect ratios, it fails to take into consideration the increased weight of the wing structure that always accompanies an increase in aspect ratio. In order to better understand the tradeoffs inherent in this relationship, the fuel weight at take-off and wing structural weight were calculated as a function of the wing's aspect ratio. For fuel calculations, a mission of 1,500 nmi was assumed, and the lift to drag ratio, a necessary parameter for determining the mission fuel weight, was calculated. The total fuel needed for the mission was then calculated using the method described in Roskam Part I. The wing structural weight was calculated using the average of two methods described in Roskam

Part V, for each of the aspect ratios chosen as data points. The results of the calculations are shown in Figure 20.



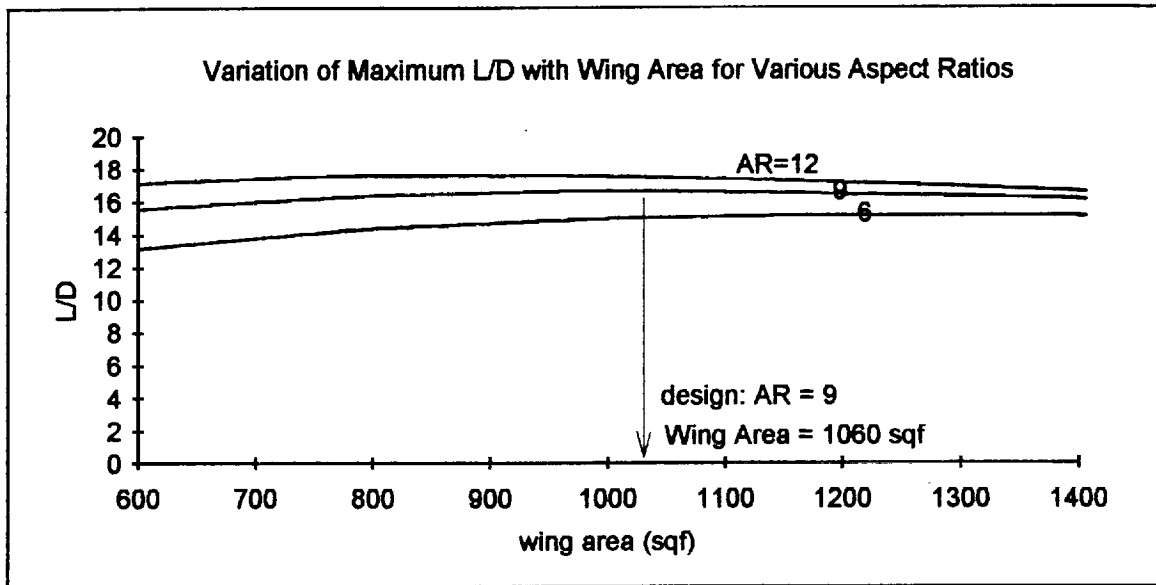
**Figure 20. Wing and Fuel Weight for a 1,500 nmi Mission for Various Aspect Ratios. Also Shown is the Sum of the Wing and Fuel Weights at Take-off.**

The study shows that a minimum in takeoff weight is achieved at an aspect ratio of approximately nine. The slope of the weight curve would increase more dramatically if divergence effects due to aeroelasticity and flutter at high aspect ratios were factored into the wing weight. Another important footnote to Figure 9 is that the chart was calculated for the aircraft's longest mission. On flights of 500-800nm, a more typical mission for the aircraft, the penalties of increasing the wing structural weight would further outweigh the benefits of a lower fuel consumption.

This type of study has become an industry standard method for assessing what aspect ratio will result in the best tradeoff between initial cost and long-term fuel savings. Generally, short-range aircraft are designed on the low side of the curve, since lift to drag ratio benefits in fuel consumption for such a short haul are not worth the increase in initial cost.



In order to deal with the iterative nature of the wing selection process, additional studies were conducted to analyze the wing performance for different aspect ratios. The first of which, shown below in Figure 21, was utilized in determining the wing areas for the previously outlined study on aspect ratio v. weight. The data for the chart was produced in a manner identical to that used to determine the optimum cruise wing area.



**Figure 21. Variation of Maximum Lift-to-Drag Ratio for Various Wing Areas at 29,000 ft Altitude.**

Upon conclusion of these studies AEROCOM decided to finalize the aspect ratio at 9. This means that the aircraft has is slightly toward the lift to ratio side of the aspect ratio versus weight curve. As stated earlier, generally short range aircraft have aspect ratios on the empty weight side of this curve. Since the aircraft's powerplant's are less expensive than comparable jet powered aircraft, AEROCOM felt that a small sacrifice in empty weight was justifiable.

### **Thickness Ratio**

Another reason AEROCOM believes that a slightly high aspect ratio represents the right tradeoff for the AC-120 is the thick wing section chosen for its wing. When the AC-120's power plant was changed to turboprops, the resulting decrease in speed negated the necessity of using super-critical airfoils. Instead of abandoning the use of supercritical airfoils, AEROCOM realized

that by retaining the super-critical wing sections on inboard sections of the wing, a very thick airfoil could be used. A thick section is desirable because it reduces stress on the wing box, and since cost is ultimately proportional to the magnitude of the stress the wing must handle, a thick wing is a cheap wing. Another advantage a thick wing offers is large fuel volume, which, for the AC-120, factors directly into its extraordinary ferry range. The sections that would be used are 15% thick super-critical, and are covered in detail in the Airfoil section of this report.

### **Sweep Selection**

The most common reasons for choosing a swept wing are drag divergence, aeroelasticity, and fuel volume. Drawbacks to a swept wing are production cost, and structural weight penalties. A swept wing would have been necessary if the drag divergence Mach number for the airfoil selected was greater than the Mach number for the aircraft. The airfoil selected, a 75-07-15 supercritical airfoil, shown detail in the Airfoil section, had a divergence Mach number of 0.75. The aircraft was designed to fly at a Mach number of 0.68-0.70, so there was no need to sweep the wings. The fact that swept wings are less susceptible to turbulence because of their lower lift-curve slope was considered in the selection of the wing, but production costs were considered to be more important than the minor benefits be obtained in passenger comfort. Thus, a straight wing was determined to be the best overall solution for the AC-120.

## **WINGLETS**

The AC-120 will implement the use of winglets because of their favorable aerodynamic characteristics and for the fact that they are aesthetically pleasing. Winglet design can significantly influence the cruise performance and handling qualities of an airplane. It has been demonstrated by wind-tunnel and flight tests, that winglets can provide increased aerodynamic efficiency. This efficiency is achieved by the reduction of lift-induced drag without overly penalizing structural weight (Van Dam, 1984).

Some of the most important design guidelines for winglets are: (1) A low cruise drag coefficient; (2) High maximum lift coefficient; and (3) Docile stall characteristics. The first factor provides a low crossover lift coefficient of airplane drag polars with winglets off and on. The second and third factors prevent the nonlinear changes in airplane lateral-directional stability and control characteristics. Another important fact is minimizing adverse interference due to shock waves in the wing-winglet junction. The use of a supercritical airfoil would minimize the adverse Mach number effects, hence minimizing the adverse interference. The airfoil also follows the design guidelines outlined above, making it a good choice for winglet implementation.

## PASSENGER CABIN

The AC-120 passenger cabin is designed to provide the maximum passenger comfort in a narrow body commercial transport. The width of the interior passenger cabin was kept to a minimum, while not comprising passenger comfort. Figure 22 shows how fuel cost will rise with an increase in seat width. This in turn will cause the fuselage diameter to increase, thereby creating more drag and a higher direct operating cost for the airplane.

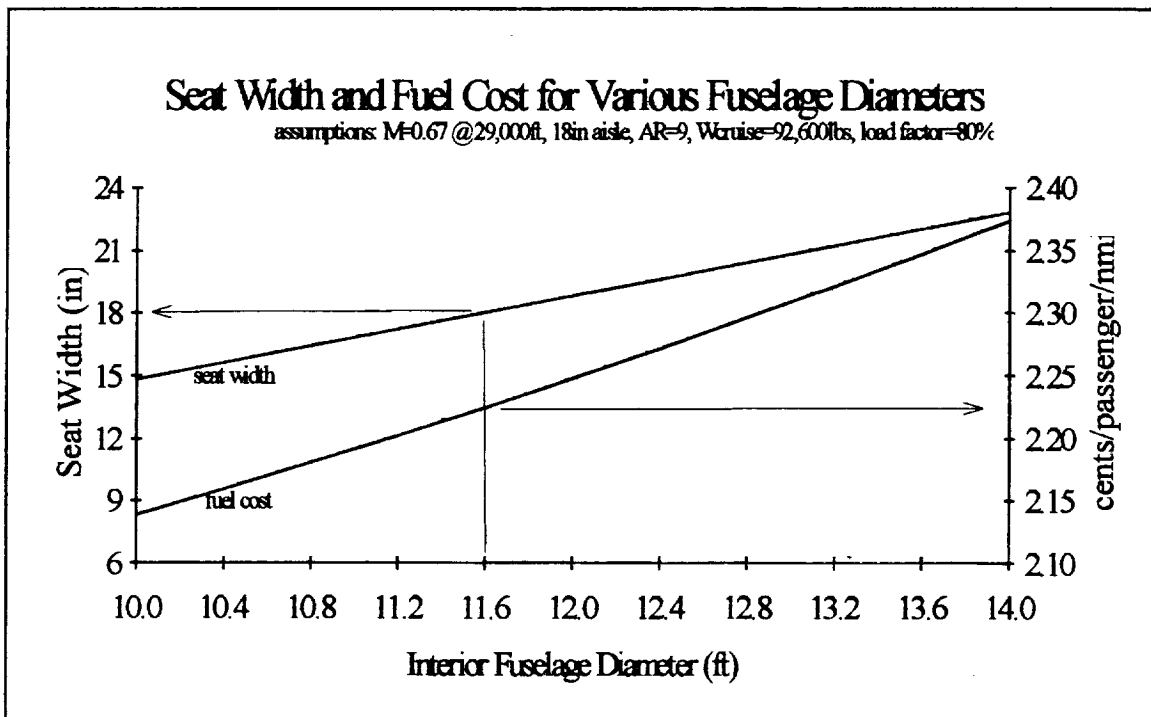
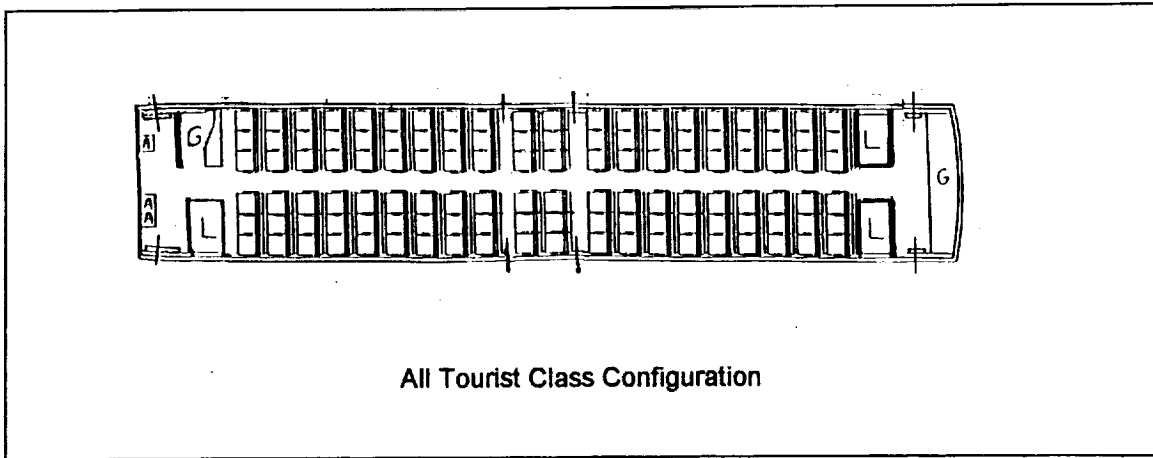


Figure 22. Variation of Seat Width and Fuel Cost for Various Fuselage Diameters.

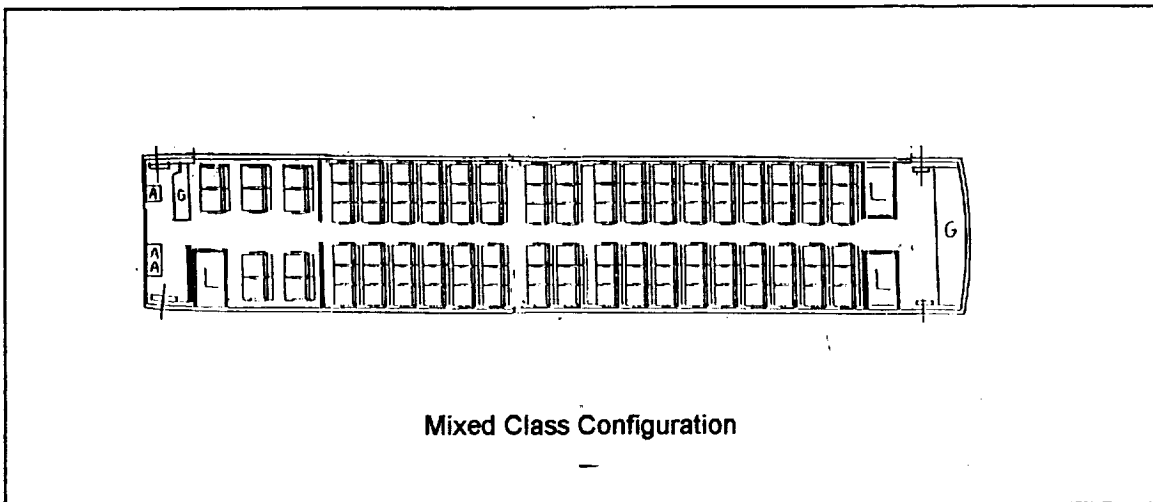
The standard passenger layout is configured to seat 120 passenger in an all-tourist class arrangement (Figure 23). The seats are arranged in 20 rows of seats in a six abreast configuration and are in a 31 inch seat pitch throughout the entire cabin. With a width of 18.5 inches and 18 inch aisles, the cabin provides the widest economy seats available, comparable only to the economy seats to be seen on the Boeing 777.



All Tourist Class Configuration

**Figure 23. Seating Configuration A**

The mixed class layout is configured to carry 110 passengers, 10 seats in business class and 100 in tourist arrangement (Figure 24). The business class seats are situated in a four abreast arrangement and are in a 36 in pitch with seats being 21 inches wide and 25 inch aisles, providing a comfort level equal to that of the Boeing 747 first class. The economy seating is similar to the all tourist class configuration with 18.5 inch seats, 18 inch wide aisles, and are at 31 in. pitch in a six abreast arrangement.

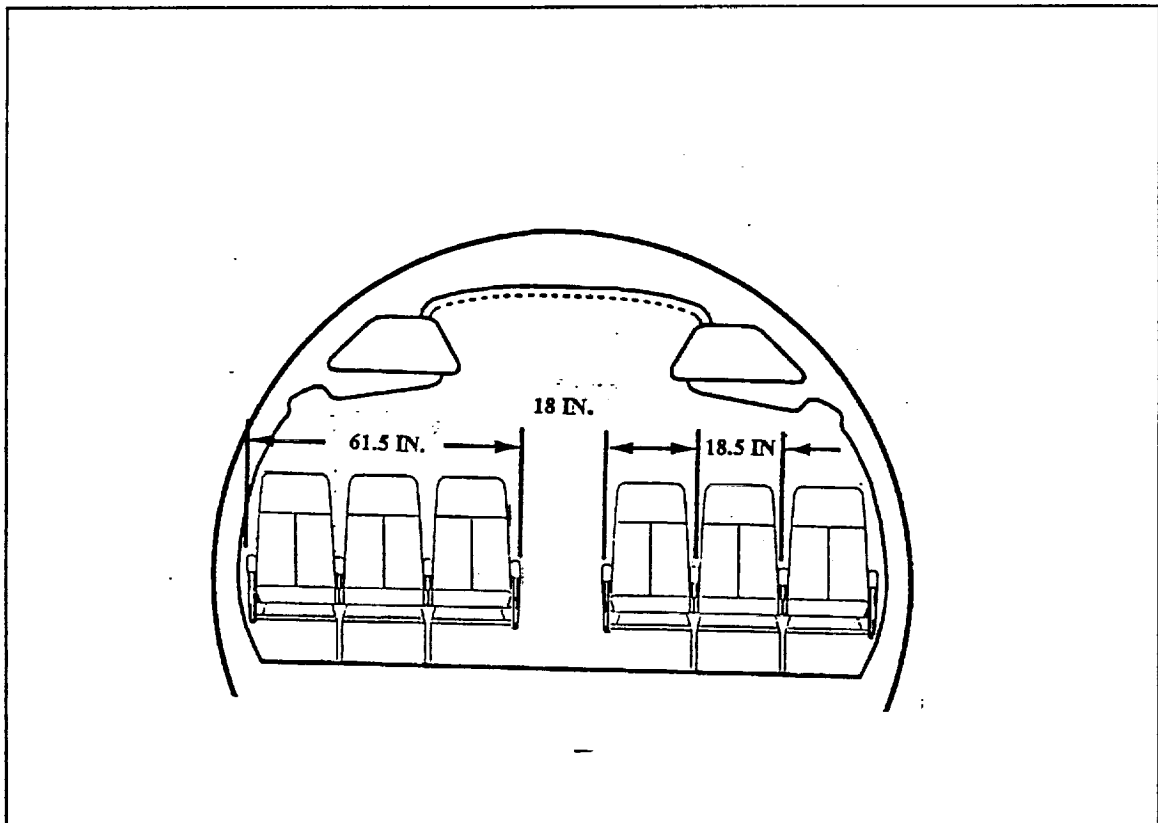


Mixed Class Configuration

**Figure 24. Cabin Seating Configuration B.**

The interior of the passenger cabin contains removable walls that serve as class dividers and large equipment such as lavatories and the small forward located galley are of a modular

design that enables easy removal by airline maintenance crews. In both cabin arrangements three lavatories come standard, each measuring 33 inches wide, one in the front of the airplane and two located in the aft section of the airplane. Each aircraft has provisions for seating of up to four flight attendants and the airplane is equipped with two galleys, one small galley in the forward section of the cabin and one full size galley located against the rear cabin pressure bulkhead. The small galley in the front of the airplane is intended to service the business class passengers, but it can be removed to provide the option for more seats or to install a mini-office that would provide a fax machine, airphone, and small computer. One standard feature of the AC-120 is a built-in airstair to allow passengers to unload quickly after landing in airports that may not be equipped with jetways.



**Figure 25. Cabin Cross Section.**

The main passenger door measures 36 by 72 inches providing ample room for loading and unloading of passengers. The AC-120 satisfies all FAA regulations by providing two Type I and one Type III doors on each side of the cabin. Service doors measure 24 by 48 inches and are located one in the front right hand side and two at the rear, one on each side servicing the rear galley. The Type III doors are located over the wing (Two on each side) to provide emergency evacuation of passengers and all doors have the minimum required unobstructed access distance, 36 inches for Type I and 18 inches for Type III.

## **SYSTEMS**

### **CONTROL SYSTEM**

The advantage in producing a neutral stable aircraft (Figure 26) is the lower induced drag due to smaller control surfaces. If an aircraft was to become neutrally stable in flight, a minimum amount of control surface deflection could create a large change in aircraft attitude, a potentially dangerous situation. A fly-by-wire system (FBW) makes use of an on board computer and is used to alleviate this problem. This system can process data from the control surfaces, attitude indicators and pilot input prior to deflecting the surfaces when performing a maneuver. If a problem is detected, the computer can readily override the pilot's input or deflect control surfaces to correct it.

The FBW system can provide many benefits for the AC-120. Crew workload is reduced through the use of maneuver demand control laws and envelope protection functions. The need for inherent stability can be relaxed to save structure weight and improve aerodynamic performance. Maintenance is reduced by decreasing the numbers of mechanical and hydraulic components of the aircraft. For safety reasons, the AC-120 will utilize a triple redundant fly-by-wire control system. This system will be integrated with hydraulic actuators used for all primary, secondary, and high lift control surfaces. Pilot inputs will be sent to the flight control system and electronically converted to control surface position commands. The commands will be transmitted to surface actuators via three independent systems. These systems are located on both sides and floor of the fuselage in order to reduce the chance of simultaneous accidental failure in more than one system. Additionally with system redundancy, each control surface is divided into three separate surfaces, and activated by separate actuators. These smaller control surfaces allow for smaller actuators reducing unit cost and weight.

### **FUEL SYSTEM**

AC-120 Fuel System (Figure 27) carries 365 ft<sup>3</sup> of fuel. The majority of the fuel is located in the left and right main tanks outboard each engine to provide for stability (Figure 27).



The rest is carried in the two auxiliary tanks located inboard each engine, where the fuel system is capable of transferring fuel via the crossover tubes located in the dry center of the fuselage for cruise trim purpose. Fuel lines run from the main tank to the engine and to the auxiliary tank. Fuel pumps are located in the left and right auxiliary tanks to enable fuel delivery during extreme aircraft attitudes. Sump tanks are near the inboard section of the wing to release contaminants from the fuel tanks. Surge tanks are located at the outermost part of the wing area to condense fuel vapor before releasing it overboard. The fueling port is located on the right main tank for compatibility with airport facilities. Dry bay's are located at both engine and landing gear area's to prevent a catastrophic condition in case of a fuel line rupture or broken gear strut.

### **HYDRAULIC SYSTEM**

Layout of the AC-120 Hydraulic System is shown in Figure 26. The hydraulic system is powered by two independent 3000psi engine generators along with two pumps. The system independence is necessary in case of failure in either generators or pumps. Each system is capable of powering the ailerons, elevators, rudder, spoilers, flaps, main gear, nose gear, steering, and brakes. The AC-120 is also provided with a auxiliary power unit capable of long duration stand-by power to operate the hydraulic system during ground operations. Its also runs flight controls, environmental, and fuel systems when parked in airport facilities.

### **ENVIRONMENTAL SYSTEM**

The Environmental System located in the center portion of the fuselage is comprised of two Air Conditioning units and a Mixing and Distribution unit. These units produce 6000 ft cabin altitude for an aircraft cruise altitude of 33,000 ft. This is sufficient cabin conditions at high altitudes for passenger comfort. The environmental system is run by bleed air pumps located on each engine . The bleed air from the engines are then fed through both the air conditioning units and the mixing station. Air leaves the mixing station into the main air distribution source located in the top portion of the fuselage, which extends throughout the entire cabin including the cockpit area see Figures 28 and 29. Air from the main distribution source is then fed to individual air ducts located in the cabin compartment for passenger use. Air is then collected at the floor

level were it is sent through the mixing and distribution bay for filtration and recalculation. The air conditioning lines are also fed through the cockpit, flight control system and lavatories where air supply is needed more.

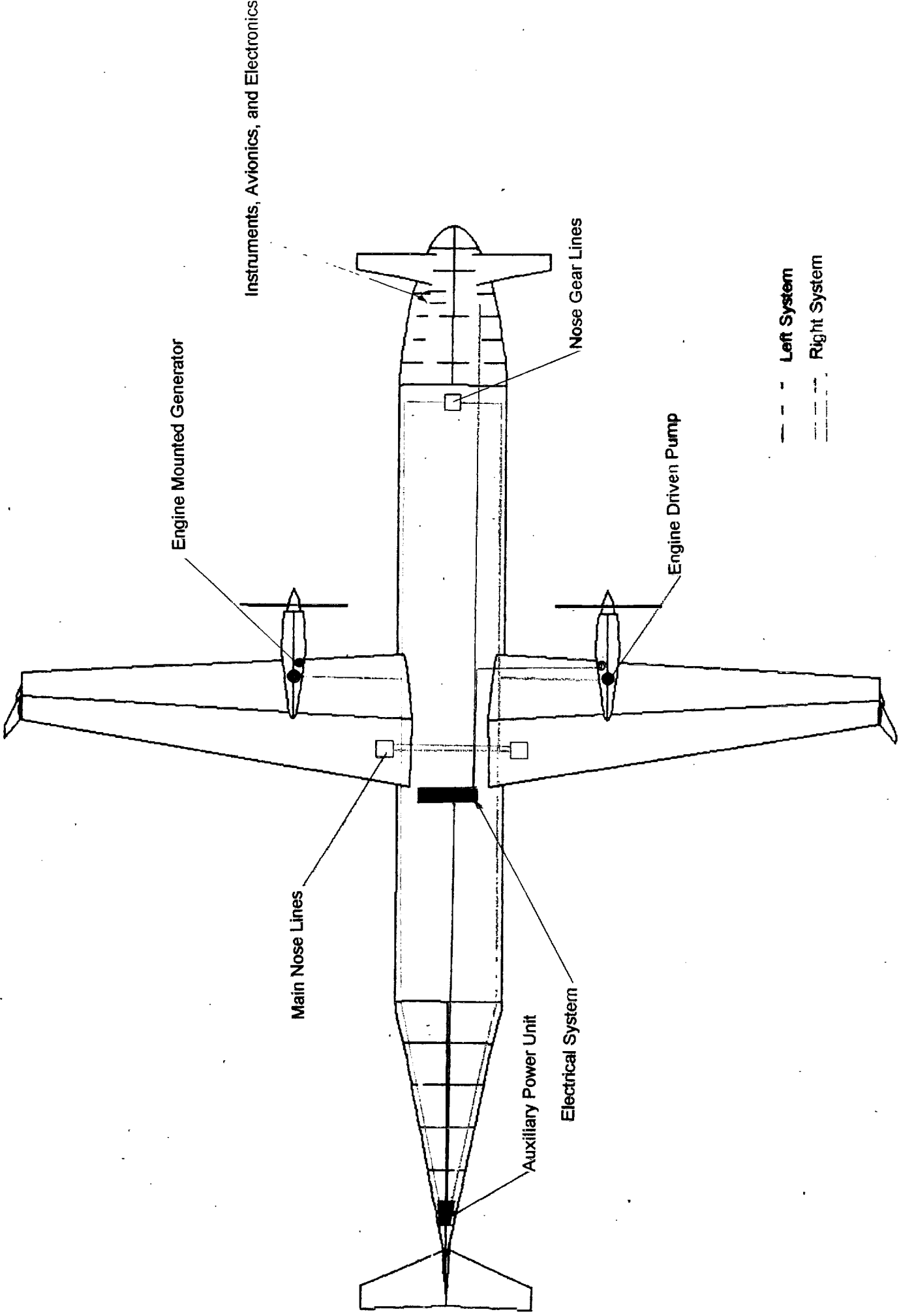


Figure 26. Electrical and Hydraulic Systems.

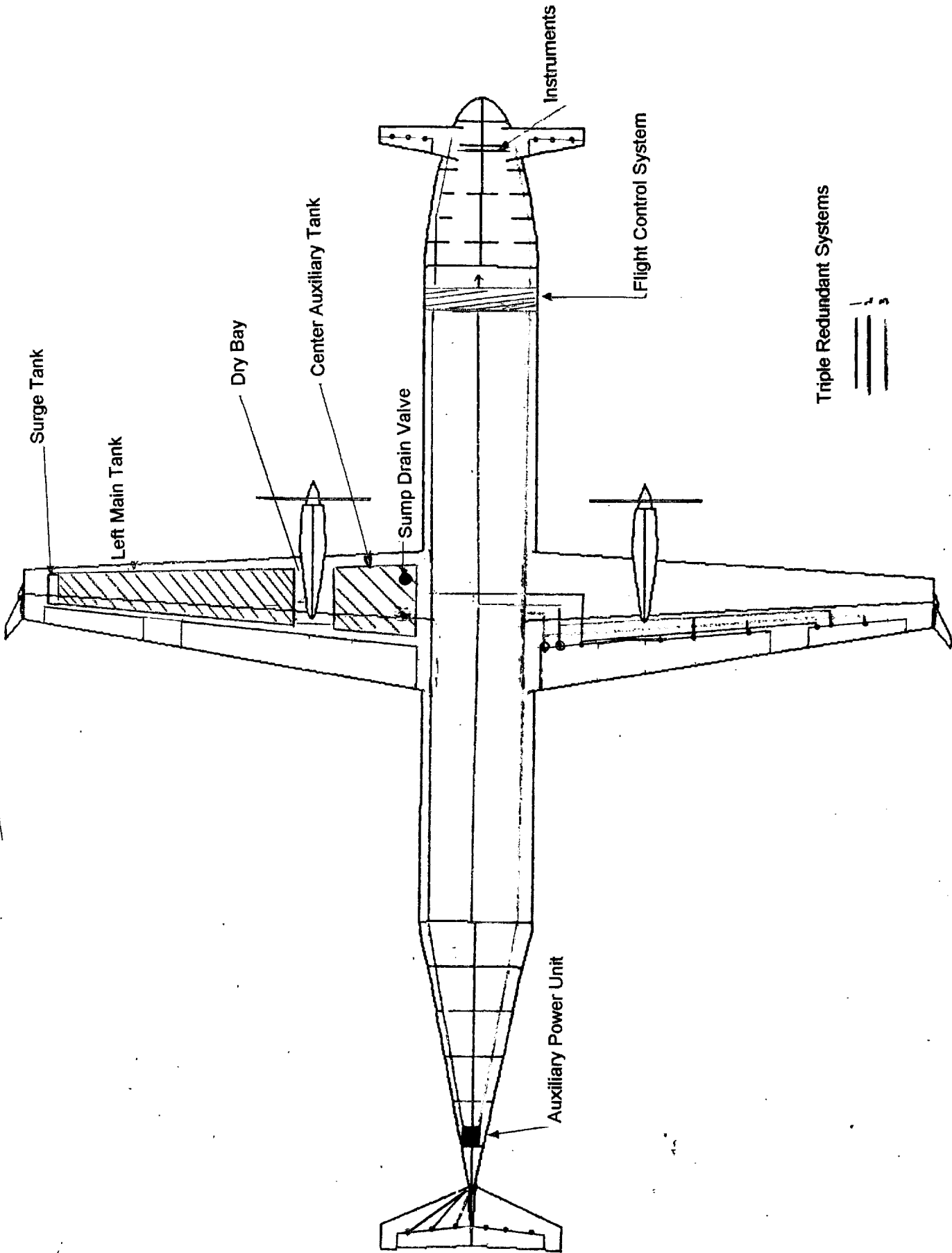


Figure 27. Control and Fuel Systems.

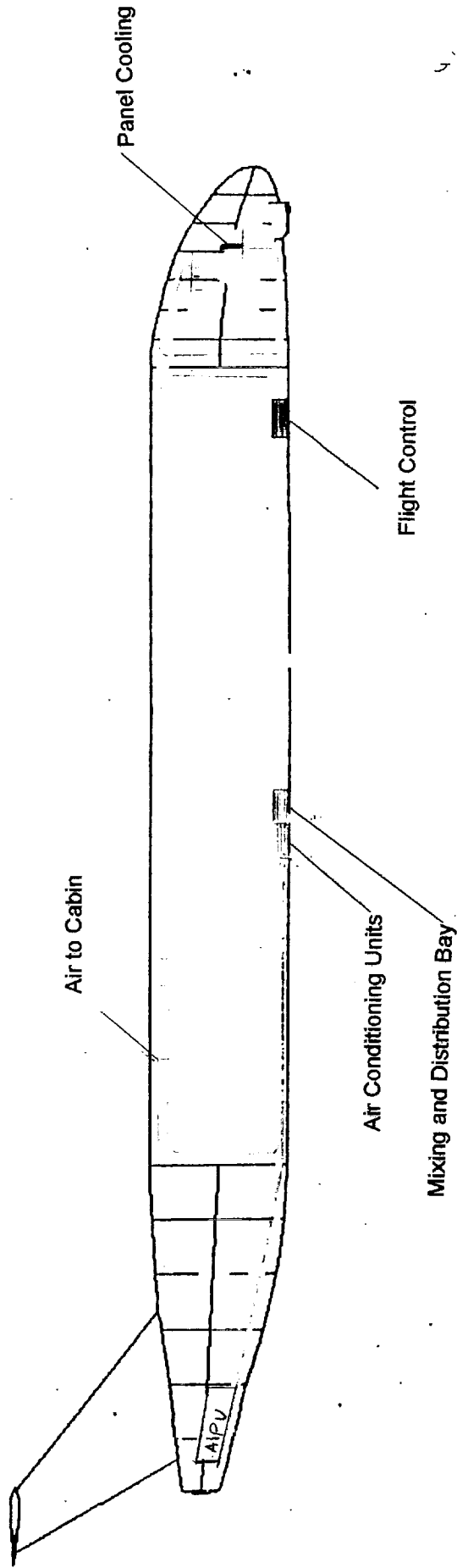


Figure 28. Environmental Systems.

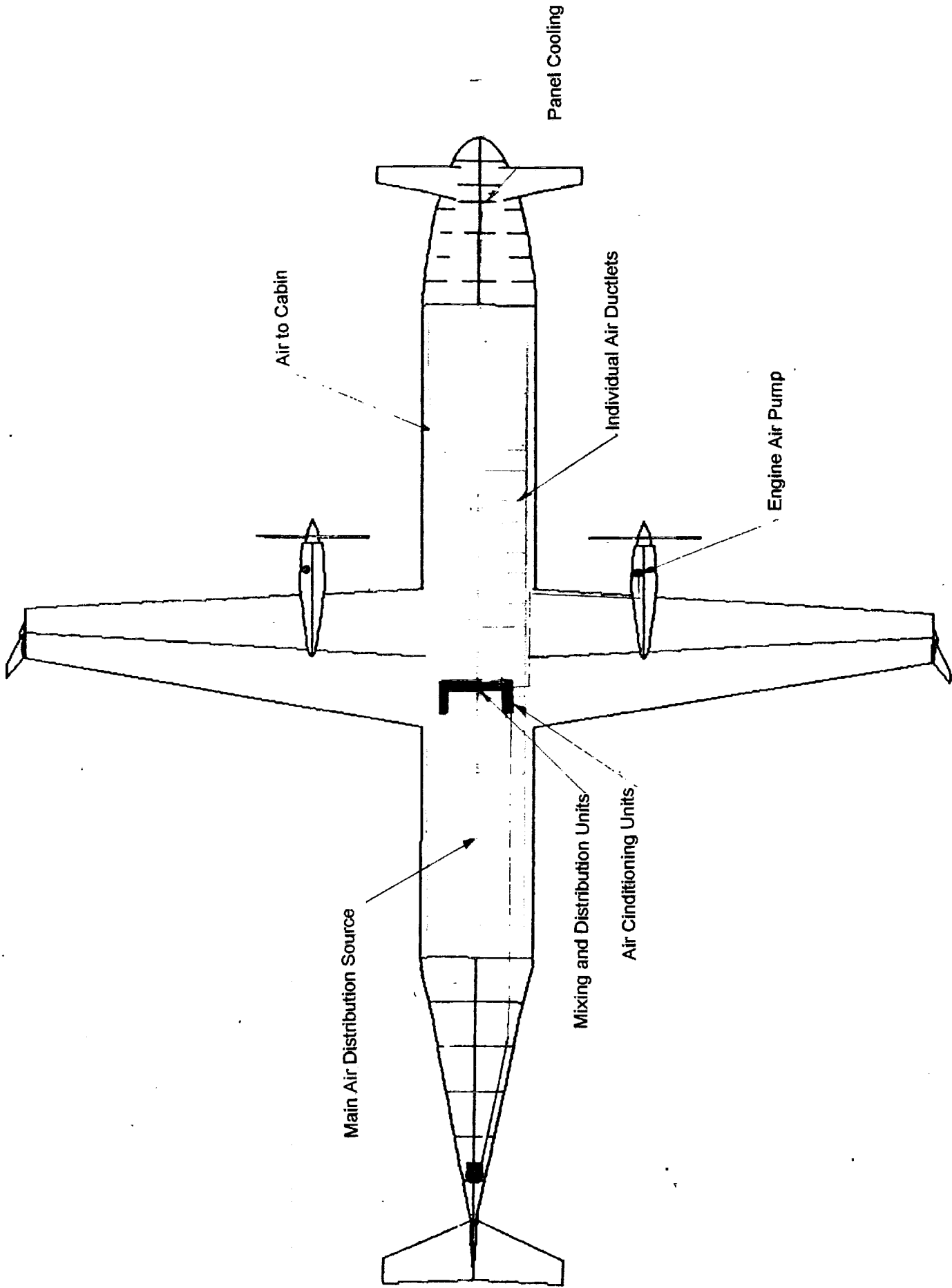


Figure 29. Environmental System, Top View.

## PERFORMANCE

### PAYLOAD RANGE

The AC-120 was designed to satisfy a 1,550 nmi mission while carrying 120 passenger with 35 lbs of luggage each, a crew of five, and 4,000 lbs of payload. The fuel reserve increases the range to 1702 nmi while still carrying the full payload described above. If a longer range is to be expected of the aircraft, a compromise with the payload would have to be made. It was calculated that at 42 % payload, the AC-120 will be able to reach 2,600 nmi. If there was to be no load aboard the aircraft, such as in the case of ferrying the aircraft overseas, the aircraft would be capable of reaching 3,300 nmi. As shown in Figure 30.

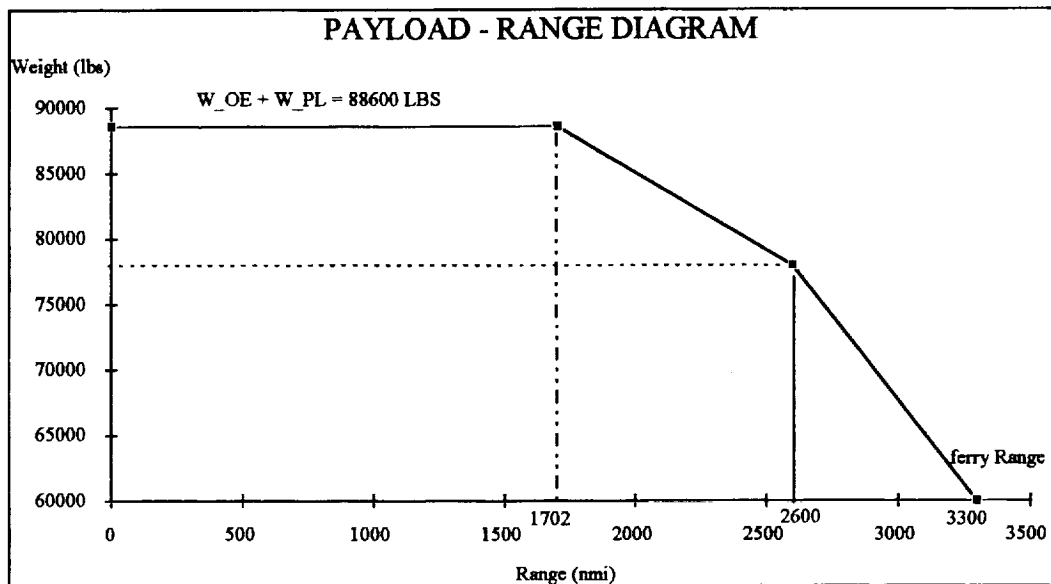


Figure 30. Payload - Range Diagram.

## CENTER OF GRAVITY TRAVEL

The AC-120 was designed such that payload shifts would result in small aircraft center of gravity shifts. This was done by designing the aircraft cabin, cargo compartment, and fuel tanks symmetrically distributed around the empty aircraft center of gravity.

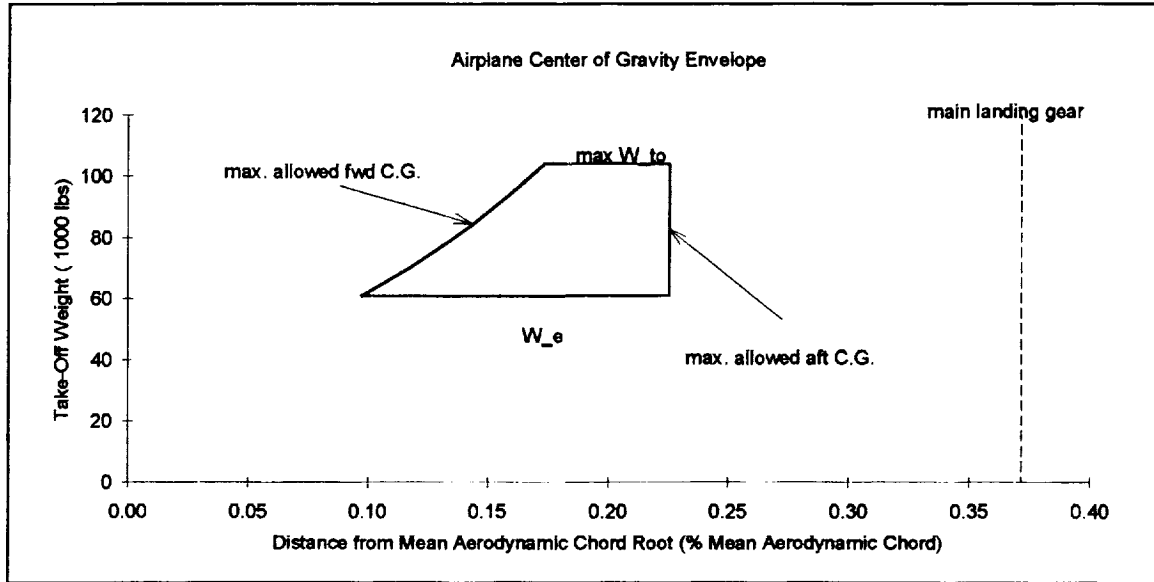
For having a passenger cabin symmetrically distributed around the empty center of gravity, any evenly distributed passenger loading will not change the center of gravity position. If an uneven distribution of passengers is encountered, this imbalance will result on a small center of gravity shift. The fuel tanks were also evenly distributed around the longitudinal center of gravity of the aircraft. As a result any percentage of maximum fuel possible could be carried by the aircraft while not changing the center of gravity location; so there will be no in-flight center of gravity shift due to fuel burn.

The cargo compartment was also evenly distributed around the center of gravity, allowing for a large change in cargo center of gravity location without affecting the loaded aircraft center of gravity. For a fully loaded aircraft, with the 4,000 lbs payload, the cargo center of gravity position will be allowed to vary by 9.2 ft (78.3% of the mean aerodynamic chord) while still keeping the aircraft within its center of gravity limits. The reduced center of gravity travel kept the AC-120 control surfaces small, which in turn reduced the parasite drag, and aircraft empty weight. A secondary benefit of the reduced center of gravity travel was the lower induced drag due to trimming the aircraft in flight.

The center of gravity envelope for the AC-120 is shown of Figure 31. The aft limit of the envelope is required for landing and is a function of the main landing gear location. In order to define the aft limit, the neutral touch down point was located. At a neutral touch down, the aircraft center of gravity would be located vertically above the tires when the tires touch the runway pavement. This would create a condition where there would be no tendency of the aircraft to lower the nose, requiring excellent pilot skills in order to perform a smooth landing. For this reason, a factor was included in the calculation of where to place the aft center of gravity



limit. If the center of gravity of the aircraft was to be placed at the aft limit, the aircraft would have enough nose-down moment making the landing easier for the pilot.



**Figure 31 - Center of Gravity Envelope.**

The forward limit of the envelope was fixed by the ability of the aircraft to lift the nose, which would be done by the canard and tail surfaces. For having canard with flaps and a moveable horizontal tail, the ability to rotate the aircraft did not present a problem during the design. At the forward center of gravity limit, the industry standard of enough tail power to create a  $4.5^\circ/s$  pitch rate during a full flap take-off was easily achieved.

### SPEED AND RANGE COMPARISON

The AC-120 was compared to existing turboprop and jet powered aircraft on speed and range characteristics. Both the AC-120's range of 1,550 nmi and speed of 410 knots were higher than most of the propeller power aircraft (Figure 32), but lower than most of the jet powered aircraft. The higher speed was possible by the used of six bladed swept propellers. The range was a factor of the decision to design a medium range aircraft.

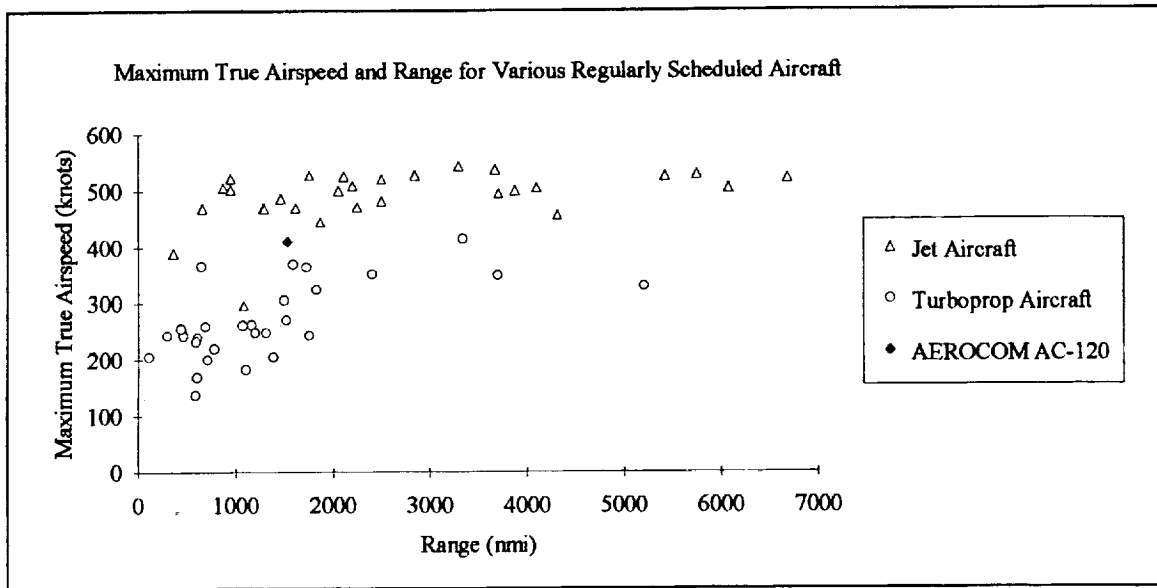


Figure 32. Comparison of Speed and Range of Various Aircraft.

### PAYLOAD COMPARISON

Various airplanes were compared against the AEROCOM AC-120 on a basis of what percentage of the maximum take-off weight was composed by the payload. This study was done in order to compare the profitability of the aircrafts (Figure 33). Knowing that fuel consumption is directly related to weight, it was of great interest to design an aircraft where the payload weight / $w_{t\text{omax}}$  ratio was the largest possible

As Figure 33 shows, the AC-120 payload range is competitive with other aircrafts in it's category. As a comparison the BOEING 737-400 has a payload/ $w_{t\text{omax}}$  of 25%, while the AC-120 has a payload/ $w_{t\text{omax}}$  of 28%. This results in a higher profit margin for the AC-120.

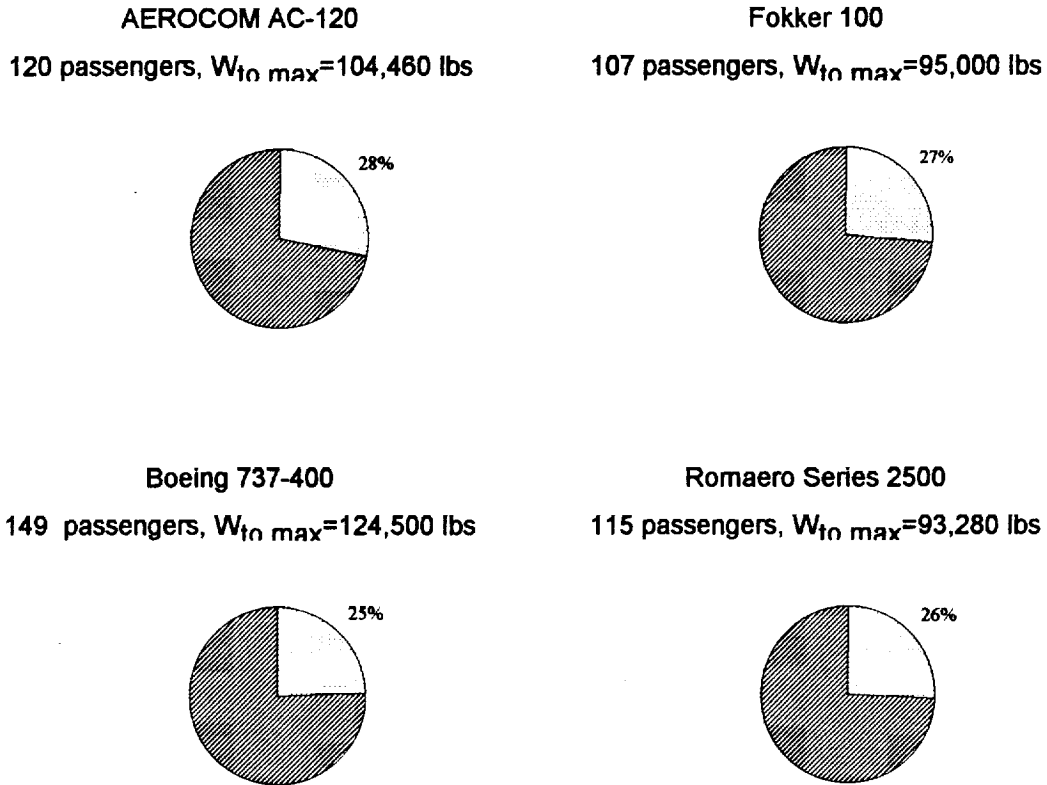


Figure 33. Payload Comparison.

## STABILITY AND CONTROL

### STABILITY DERIVATIVES

Stability derivatives for the AC-120 were calculated using the computer program, Advanced Aircraft Analysis. The derivatives were calculated for two different flight conditions: cruise and approach which and are presented in Table 18.

**Table 18. Flight Conditions.**

Phase	Approach	Cruise
Configuration	Flap down	Full Stored
Altitude	Sea Level	33,000 ft
Mach		0.68
Aircraft Weight (lbs)	89,200	95,950
Static Margin (%MAC)	0	0

The calculated longitudinal and lateral/directional derivatives are listed in Tables 19 and 20, and these stability derivatives played important roles in sizing control surfaces and choosing the control systems for the AC-120.

These derivatives were useful in predicting the behaviors of the airplane without actually testing a scale model of the aircraft, therefore the results should be considered a preliminary prediction. To increase accuracy and develop a detailed discussion of stability, it would be necessary to perform wind tunnel testing or a flight testing program.

**Table 19. Longitudinal Derivatives.**

	Approach	Cruise
$C_{m_u}$	0.09	0.28
$C_{m_\alpha}$	-1.05	-0.95
$C_{m_{\alpha.\dot{\alpha}}}$	-11.1	-16.2
$C_{m_q}$	-42.5	-48.1
$C_{l_{\dot{u}}}$	0.16	1.1
$C_{L\alpha}$	5.62	6.7
$C_{L_{\alpha.\dot{\alpha}}}$	2.17	2.9
$C_{D\delta F}$	0.00	0.00
$C_{l_{\delta F}}$	0.12	0.10
$C_{L\alpha}$	6.34	7.4
$C_{D_\alpha}$	0.59	0.70

**Table 20. Lateral - Directional Derivatives.**

	Approach	Cruise
$C_{l\beta}$	-0.06	-0.11
$C_{l\beta.\text{dot}}$	0.00	0.01
$C_{l\rho}$	-0.69	-0.69
$C_{l\kappa}$	0.42	0.56
$C_{l\delta A}$	0.12	0.15
$C_{l\delta S}$	0.00	0.01
$C_{n\beta}$	0.07	0.23
$C_{n\beta.\text{dot}}$	0.00	0.00
$C_{np}$	-0.18	-0.18
$C_{nr}$	-0.49	-0.68
$C_{n\delta A}$	-0.02	-0.02
$C_{n\delta R}$	-0.10	-0.11
$C_{n\delta S}$	0.006	0.01
$C_{y\beta}$	-0.88	-1.10
$C_{y\beta.\text{dot}}$	0.00	0.00
$C_{yp}$	-0.88	-0.33
$C_{yr}$	0.73	1.02
$C_{y\delta A}$	0.00	0.00
$C_{y\delta R}$	0.16	0.17

## COST ANALYSIS

The AC-120 is a commercial transport designed to compete against existing aircraft such as the Boeing 737, Fokker 100, Bae 146, DC9, and MD 90. The unit cost for the AC-120 was calculated (Roskam Part VIII) to be 24.5 million in 1993 US. Dollars (USD) and the cost is estimated to be 26.1 million (USD) in the year 2000 when the AC-120 is expected to enter service. The average price for an aircraft of this size currently ranges from 22 to 30 million dollars, therefore the price of 24.5 Million for the AC-120 makes it very competitive.

When the price is compared in relation to take-off weight, the AC-120 demonstrates its competitiveness in aircraft price against other aircraft in its class (Figure 34).

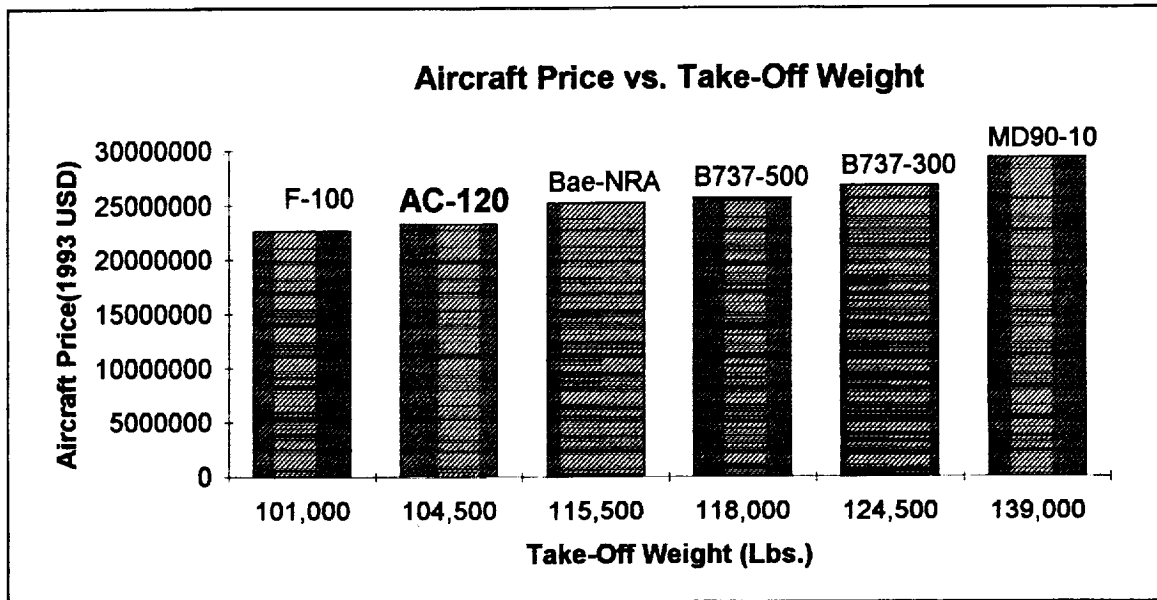
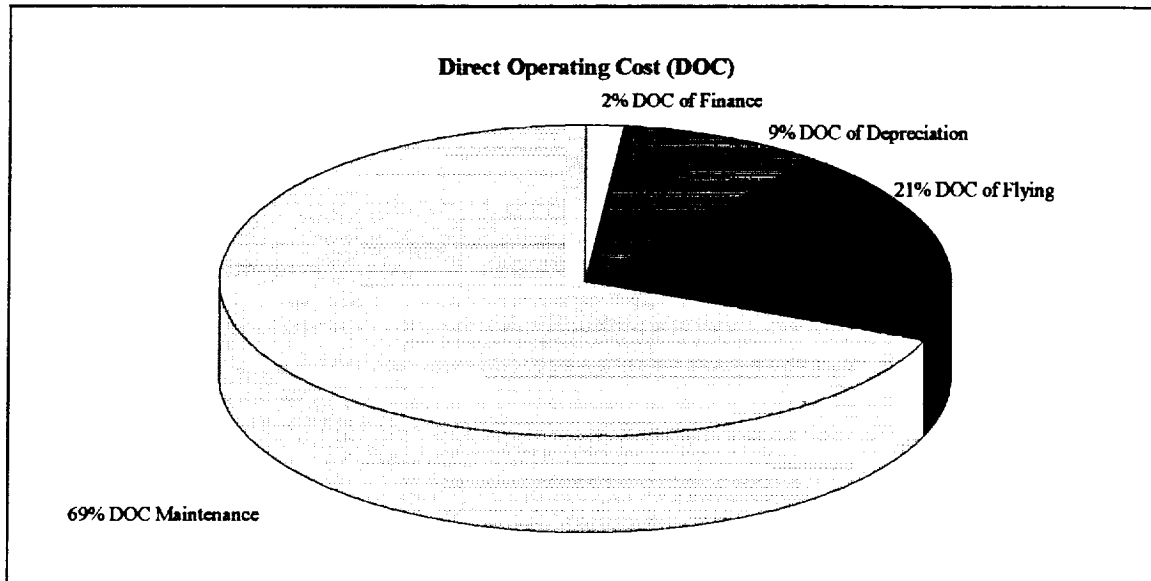


Figure 34. Aircraft Price in Relation to Take-off Weight.

The AC-120 is the second lowest priced aircraft when comparison to the current flying aircraft in the same class. The lowest price is \$600,000 USD lower than the AC-120's price but when compared to the MD-90, whose price is estimated to be 29.3 million dollars, the AC-120 is 6 million dollars less expensive.

Currently the AC-120 operates at a cost of 6 cents per passenger mile (USD) for a 1500 nautical mile mission and the cost rises to 7 cents per passenger mile for a 800 nm. mission. Figure 35 shows a percentage breakdown of the total direct operating cost of the AC-120.



**Figure 35. Direct Operating Cost (DOC).**



## CONCLUSION

AEROCOM's inquiry into the possibilities of designing a competitive replacement for the 100 to 150 passenger short haul transports in use today resulted in an aircraft capable of producing significant improvements in both operational and acquisition costs. However, the aircraft that resulted cannot be considered to be a "perfect" solution because of the compromises necessary to produce these results.

The aircraft found to be most effective at producing these results was a swept-blade turboprop aircraft in a three lifting surface layout. The introduction of swept bladed propeller technology has made it possible to consider turboprop transports with only marginal speed and altitude losses as compared with conventional short haul jet transports. Additionally, no aircraft in the airline market has yet taken advantage of the induced trim drag benefits of the three lifting surface configuration.

Nonetheless, valid questions must be raised about a slower and lower flying turboprop's ability to compete with faster, higher flying, and possibly more glamorous jets. AEROCOM studies indicate that there is a significant probability these risks can be met and that the benefits to be reaped therein, merit further investigation of this type of aircraft.

## **APPENDICES**

## **FIRST CONCEPT**

AEROCOM's first configuration was a very radical aircraft, as is apparent from Figure 36. The unusual components to this aircraft resulted from a zealous attempt at reducing drag. The initiative towards reducing drag was centered around the concepts of natural laminar flow, structural communality, and reduction in wetted surface area.

AEROCOM initially believed there were great benefits to be reaped from making use of natural laminar flow airfoils on all lifting surfaces. NLF airfoils require clean undisturbed air in order to work effectively. This dictated placement of the engines in the rear. It was also a contributing factor in the decision to use a mid-wing, since the mid-wing arrangement would place the wing out of the dirty air from the canard. Unfortunately, it was later learned that an aircraft of this size has a main wing section Reynold's number that is too high for natural laminar flow to occur.

Structural communality was believed to be a method by which the first configuration for the AC-120 could achieve a substantial reduction in structural weight. Structural communality refers to a reduction in weight created by using a common structure to carry loads generated by a variety of sources. When a central location is used to support many different loads, significant reductions in structural weight can often be achieved. The main location for structural communality in configuration number one is directly aft of the rear pressure bulkhead. This location handles the loads of the main gear, the vertical stabilizer, the engine nacelles, the main wing, and the rear pressure bulkhead. Another location of structural communality is at the junction of the canards within the fuselage, which supports the loads of the canard and landing gear.

Unfortunately, the aircraft's swept forward wings negated all of the weight savings achieved by structural communality. If an aircraft wing is modeled as a beam rigidly attached to a wall at a certain sweep angle, it can be shown that the variance in torsional loads experienced with changes in sweep is inversely proportional to the tangent of the sweep angle (Area and Aspect Ratio held constant). This means that the wing proposed for the first configuration would

experience almost 2.5 times the torsional load of a straight wing. Additionally, it should be pointed out that this rough estimate does not even begin to take into account the aeroelastic problems associated with a swept-forward wing. For these reasons, the wing initially chosen for the AC-120 was not an effective solution.

Another method by which the first configuration was to achieve an improvement in drag was to reduce the wetted area of the control surfaces. This was to be accomplished by using a three lifting surface configuration, and by having the aircraft CG, the wing-fuselage aerodynamic center, and the aircraft aerodynamic center at the same place. As outlined earlier in the report, this combination results in an aircraft that is perfectly trimmed, and carries no loads on its control surfaces other than that needed to balance the wing's pitching moment. Since these forces are not large, it was thought that the control surfaces could be very small. Unfortunately, this line of reasoning fails to consider several important points. First, the aircraft will not always be loaded at the same location. Second, the cruise condition of the aircraft is not the only condition pertinent to the sizing of the control surfaces.

This proved to be a major oversight. With the entire passenger cabin ahead of the wing, the CG shift for the aircraft proved to be 10 ft., an intolerable number for nose rotation during landing. An enormous tail would be required because the horizontal stabilizer would have to lift at least the moment generated by the ten foot arm between the gear and the CG. Several schemes were considered in an attempt to fix this problem, including elaborate fuel pumping systems, but ultimately it was decided that this type of fix was akin to patching holes in a sunken ship.

Since the problems encountered with CG shift, and weight were clearly unrepairable, AEROCOM chose to abandon this concept. In the second configuration, see appendix Second Concept, the CG shift problem was addressed, but further difficulties were encountered, ultimately leading to its rejection, as well.

Fuselage Length	=	109 ft.
Cabin Length	=	53 ft.
Fuselage Diameter	=	12.5 ft.
Overall Length	=	122 ft.
Wing Span	=	96 ft.
Root Chord	=	10.5 ft.
Tip Chord	=	6.3 ft.
Horizontal Tail Width	=	31 ft.
Canard Span	=	30 ft.

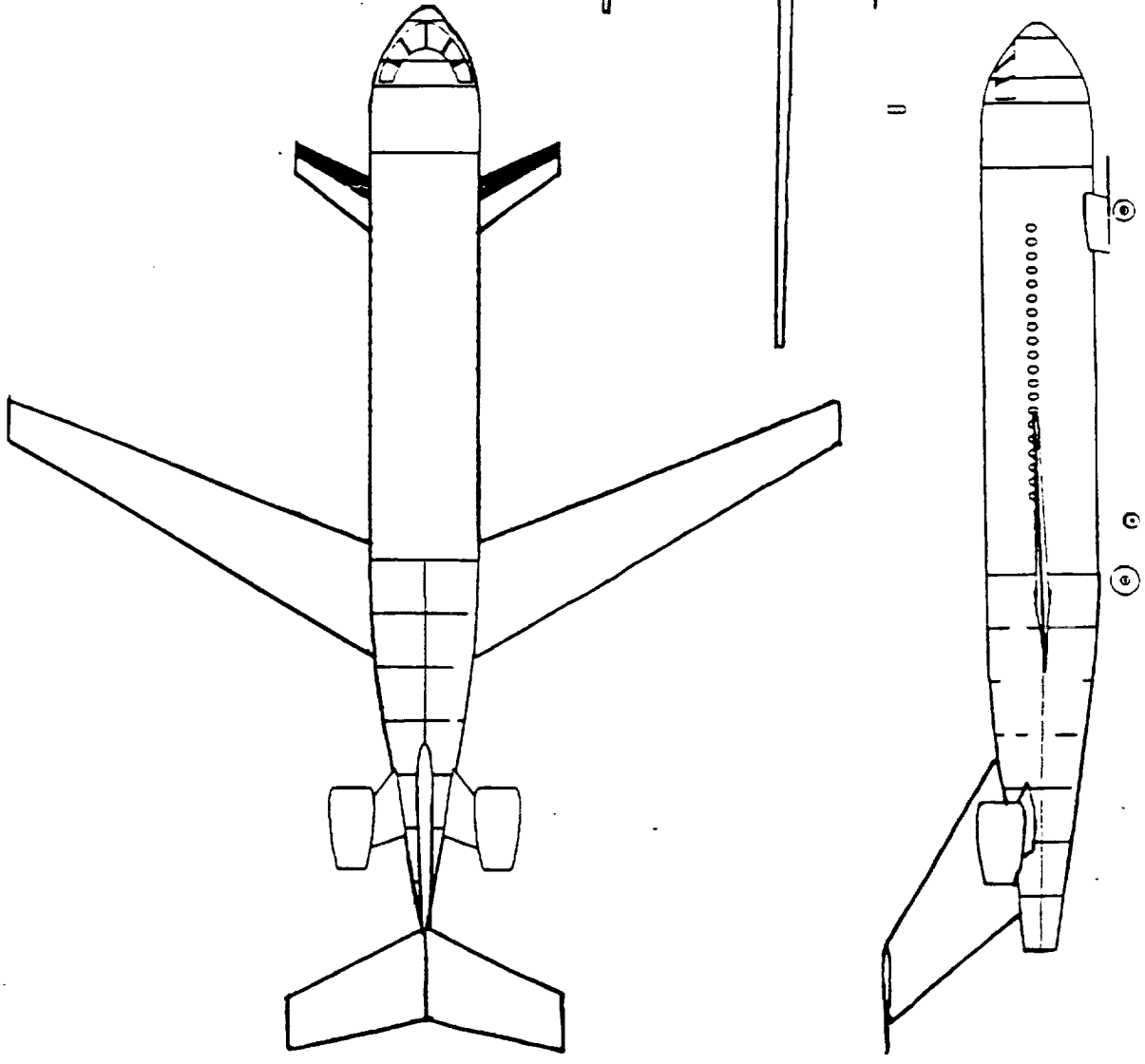


Figure 36. First Aircraft Concept.

## SECOND CONCEPT

After rejecting the first AC-120 configuration, AEROCOM chose to modify that configuration to the extent that only a few features of the original aircraft were retained. The primary difference between the first and second aircraft is the wing location and the powerplant (Figure 37). The change in powerplant was retained in the final aircraft, and is covered in the main report.

The primary motive for moving the wing forward was to create an aircraft that would be immune to precisely the CG difficulties encountered with the first aircraft. Thus, the second concept has a rear swept wing with the passenger cabin and baggage compartment symmetrically distributed about the wing box. The mid-wing was retained in order to reduce interference drag, and because the natural laminar flow airfoils still in favor at this point in the process require clean undisturbed flow. If the aircraft had a low wing, the canard would have disrupted the laminar flow over the wing. A high wing, the alternative to a mid-wing, was considered, but it was considered undesirable because of the associated penalties in induced drag and weight.

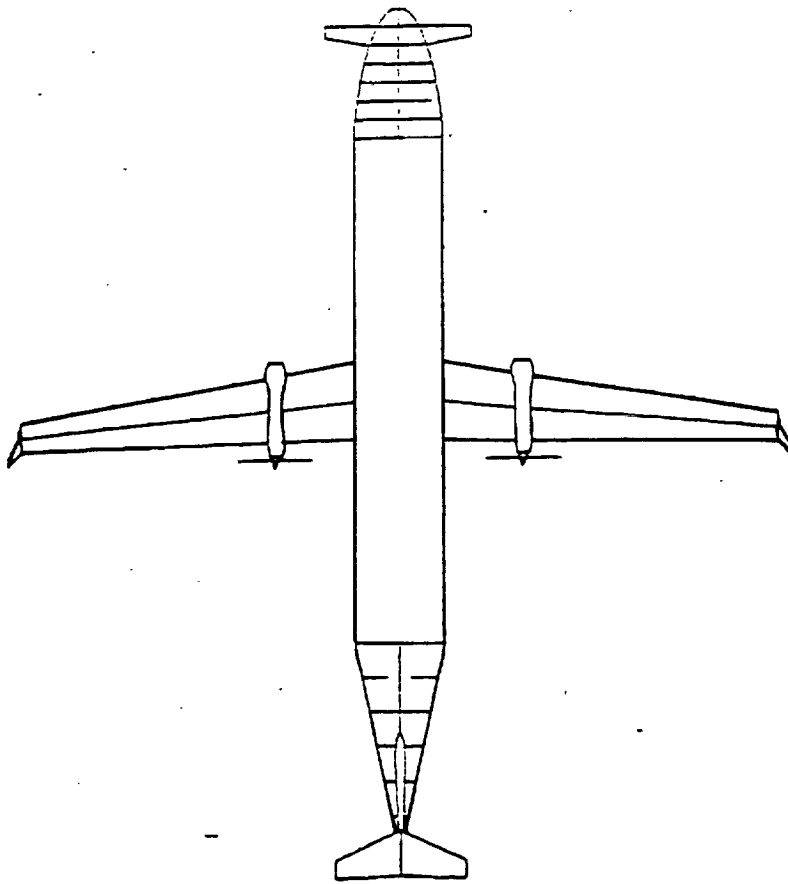
Mid-wings, however, have their own set of problems. An airplane wing is usually located either at the top or bottom of the fuselage in order to avoid interfering with the passenger cabin. Both of these configurations have the advantage that a relatively un-problematic straight carry-through wing can be designed. In contrast, a mid-wing airplane presents a challenge in the design of a wing box because the wing-spar loads must somehow be carried around the passenger compartment without large increases in weight or adverse affects on passenger comfort.

Several wing boxes were considered, the most promising of which is shown in Figure 38. This wing box consists of two bulkheads 35 inches apart located at the middle of the aircraft. This design was considered to have great potential because it utilizes the entire diameter of the fuselage to carry across the bending loads of the wing. Since the ability of a beam to carry bending loads is proportional to the square of the beam's height normal to the bending axis, it was hoped that by utilizing the entire fuselage cross-section, a very thin light wing box could be

created. With such a thin structure it was very important to obtain accurate results for the loads within the bulkheads in order to determine their ability to resist buckling, and to determine how effectively the bending loads were distributed within the bulkhead.

The bulkhead was first analyzed using Roark's Method of Stress and Strain (Roark, 1989). The curved reinforcements located on the underside of the carry-through section were sized to the expected pattern of shear flow using this method. As previously mentioned, a central key to this design was that the stresses would be fairly evenly distributed around the bulkhead. In order to obtain a more accurate analysis of this design, a finite element analysis program, COSMOS/M, was used to run a stress analysis of the wing box. From a reference point outside of the airplane, the bulkhead seemed to perform well, because, as seen in Figure 39, which depicts aircraft stress in the take-off condition, the stresses were distributed along the fuselage. Upon examining the conditions present in the interior of the wing box, however, the finite element program showed that the design did not perform as expected because the shear was not distributed within the bulkhead as was desired. Figure 40 illustrates how the aircraft's bulkhead performed under a 1 g loading. The figure clearly depicts a very high stress concentration where the wing joins with the bulkhead. The rest of the bulkhead, as a rule, was not under any considerable stress. When the load was increased to 2 g's, as depicted in Figure 41, the stresses were still not distributed about the wing box. Since stress concentrations are the bane of composite materials, this result was unacceptable.

Since the structural difficulties associated with a mid-wing box were not dealt with satisfactorily, a decision was made to abandon the second conceptual representation of the AC-120. In the interim between this design and the final AC-120 configuration, a thorough reconsideration of all AEROCOM design philosophies was conducted, resulting in a much more practical aircraft.



Fuselage Length	=	115 ft.
Cabin Length	=	66.8 ft.
Fuselage Diameter	=	12.5 ft.
Wing Span	=	99 ft.
Aspect Ratio	=	13
Root Chord	=	10.8 ft.
Tip Chord	=	4 ft.
Canard Span	=	17.1 ft.
Horizontal Tail	=	17 ft

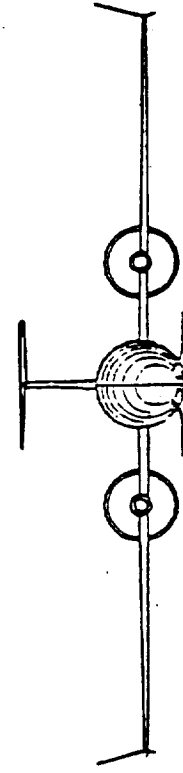
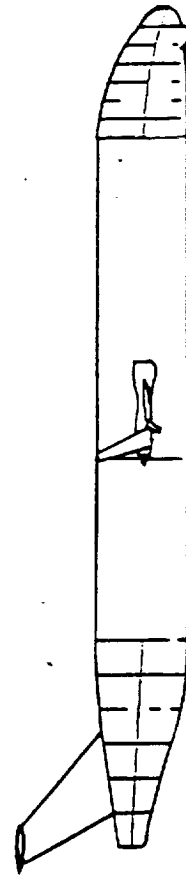


Figure 37. Second Aircraft Concept.



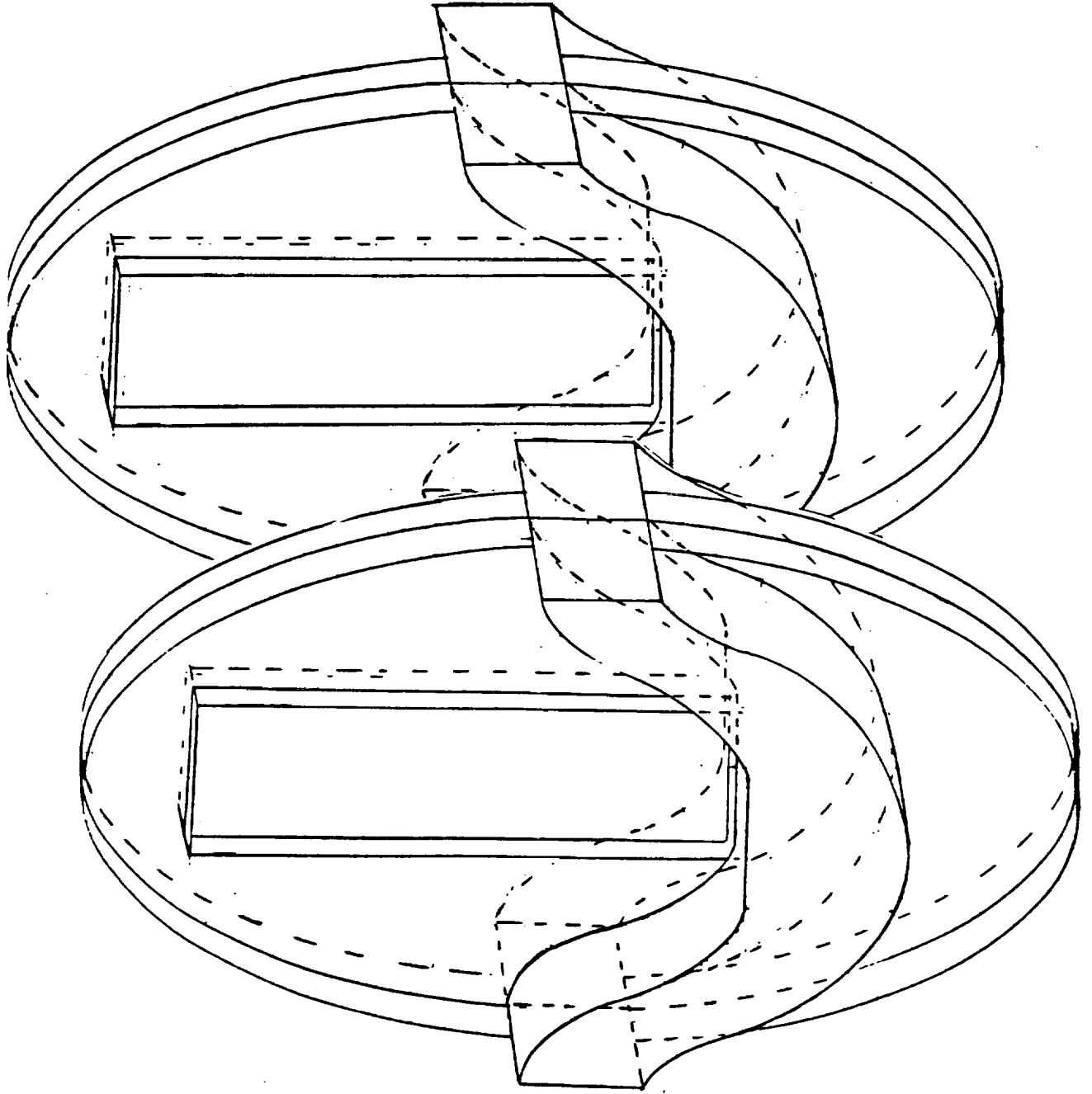


Figure 38. Second Aircraft Wing Box Desing.

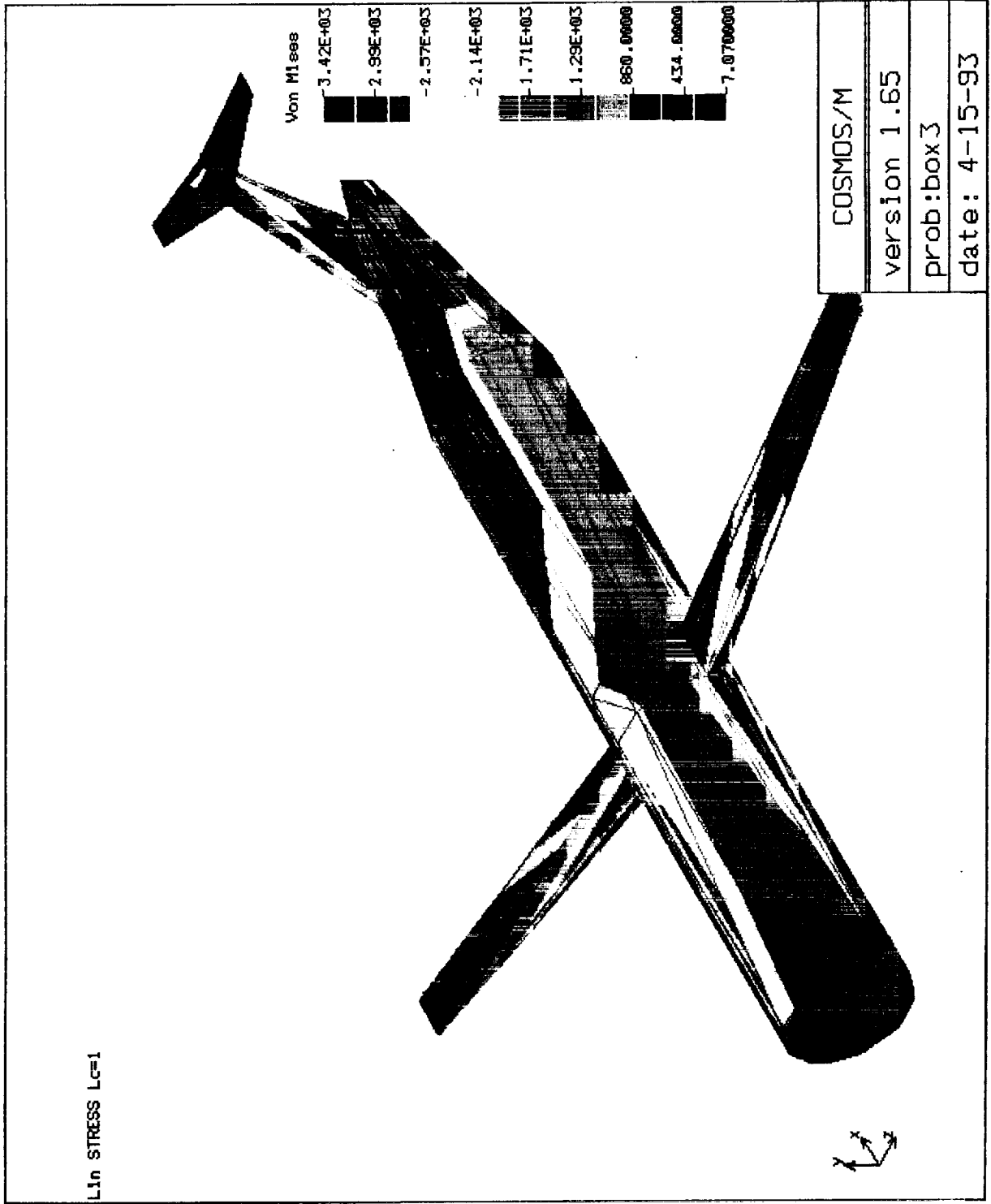


Figure 39. Stresses on the Second Concept Under Take-off Loading

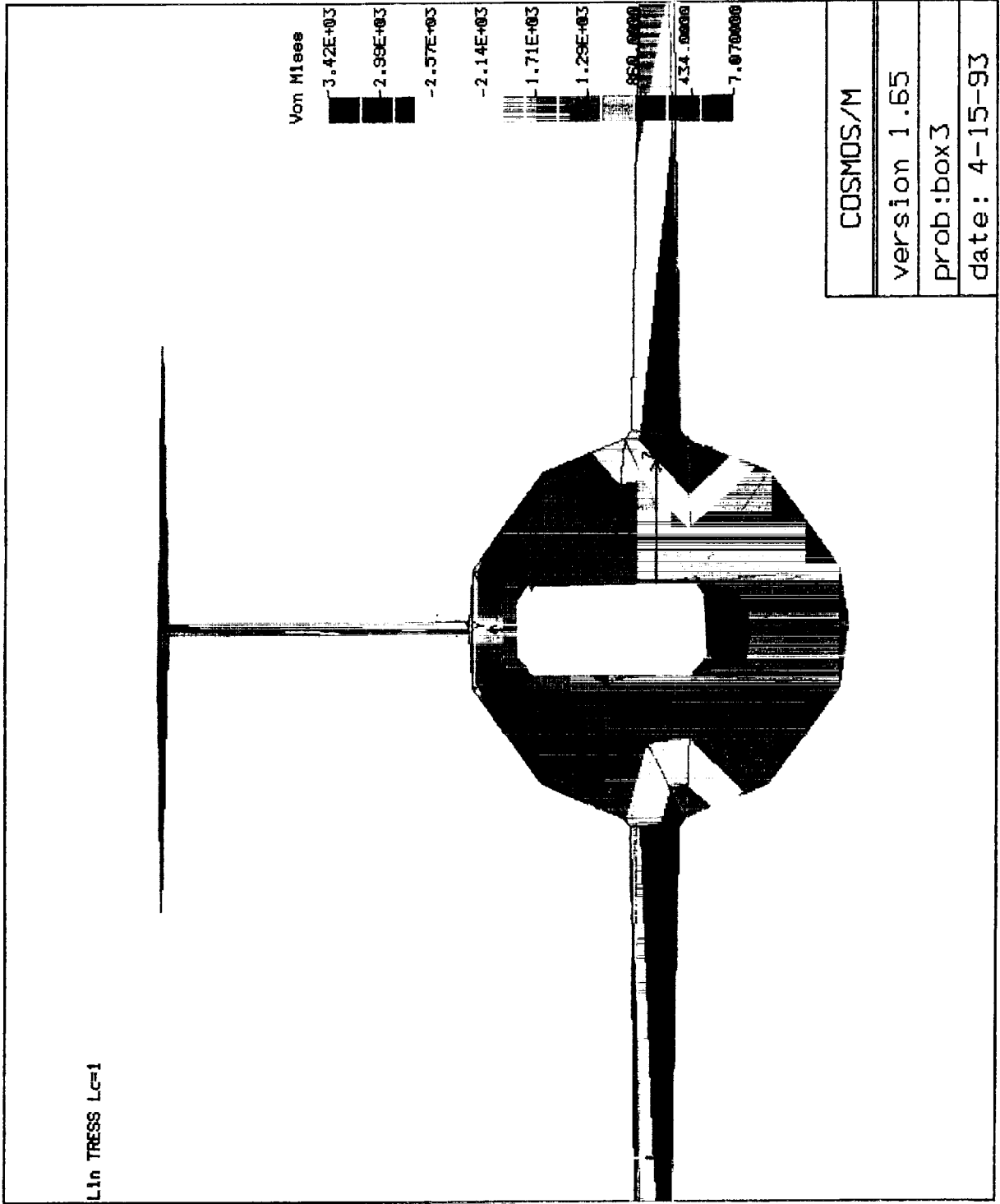


Figure 40. Stresses on the Wing Box Under a 1 g Loading.

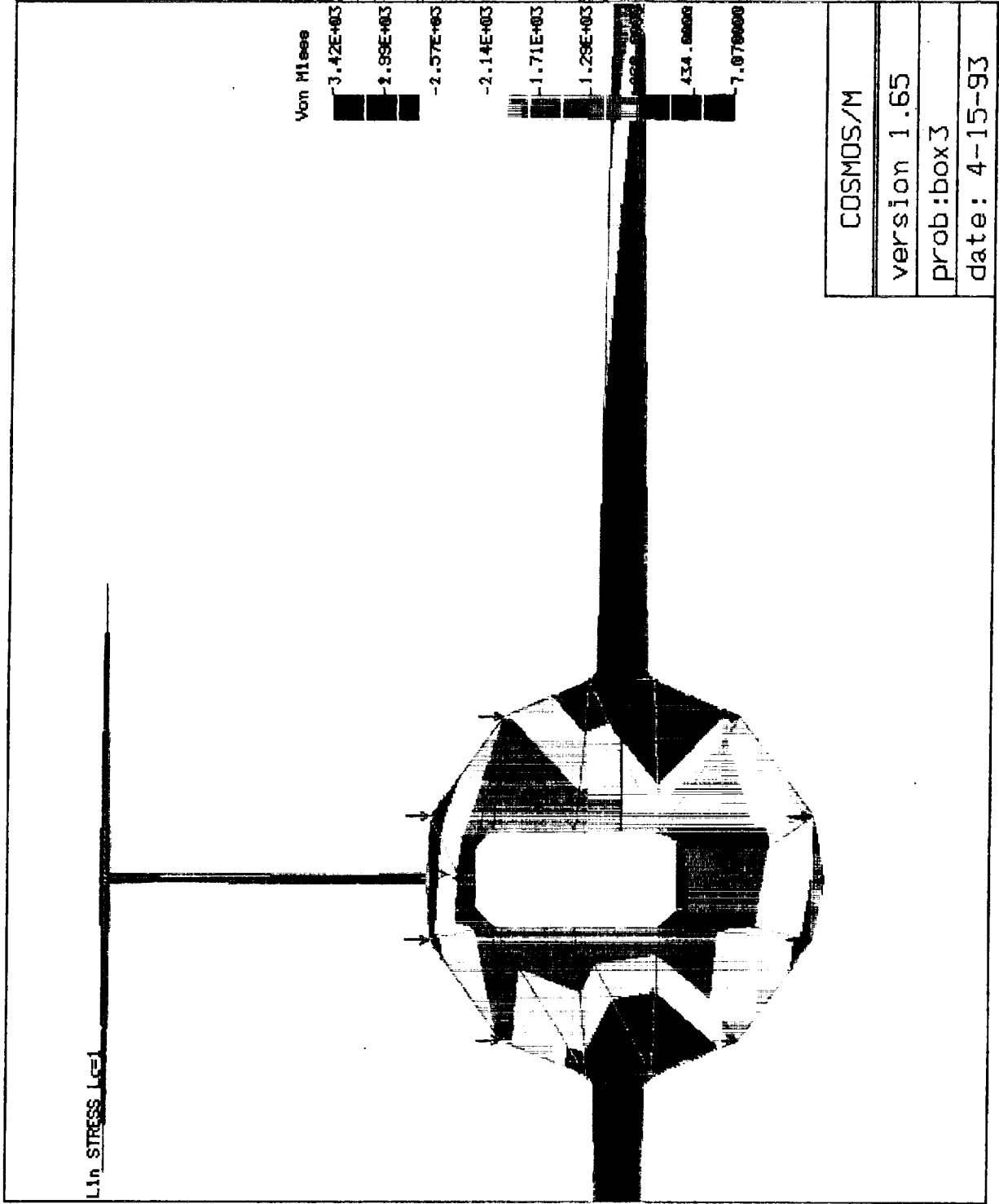


Figure 41. Stresses on the Wing Box Under a 2 g Loading.

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