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SCHOOL OF AERONAUTICS AND ASTRONAUTICS

West Lafayette, Indiana 47907

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Sincerely,

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Barbara Rumbaugh
Senior Project Administrator

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NASA/USRA Advanced Design Program
Aeronautics Division
Final Report 1988-89

Design of a Spanloader Cargo Aircraft

submitted by the

School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana

Professor Terrence A. Weisshaar
Principal Investigator

June 12, 1989

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Ronald Henderson
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Advisor

Introduction

With a growing demand for fast international freight service, the slow-moving cargo ships currently in use will soon find a substantial portion of their clients looking elsewhere. One candidate for filling this expected gap in the freight market is a span-loading aircraft (or "flying wing") capable of long-range operation with extremely large payloads. This report summarizes the design features of an aircraft capable of fulfilling a long haul, high capacity cargo mission.

During the academic year 1988-89 a total of eight groups worked on the design of this type of aircraft. The Request For Proposal was developed in cooperation between NASA/Langley Research Center and Purdue University. The principal architects of this proposal were Professor T.A. Weisshaar of Purdue and Dr. Vicki Johnson of NASA/Langley. Assistance was received from Mr. Jeffrey Layton (the NASA/USRA Teaching Assistant at Purdue) during his tenure at Langley during the summer of 1988.

During Mr. Layton's time at Langley he developed a data base for weight estimation of flying wings and spanloaders from reports and papers written on the subject. These included Northrop's early flying wings.

The spanloader seeks to gain advantage over conventional aircraft by eliminating the aircraft fuselage and thus reducing empty weight. The primary disadvantage of this configuration is that the cargo-containing wing tends to be thick, thus posing a challenge to the airfoil designer. It also suffers from stability and control problems not encountered by conventional aircraft. The result is an interesting, challenging exercise in unconventional design.

The report that follows is a student written synopsis of an effort judged to be the best of eight designs developed during the year 1988-89. Each of the eight design teams prepared a 100 page document detailing their design, the design process and recommendations for the future. The present report was prepared by a team of Purdue seniors consisting of Mssrs. Ronald Henderson, Timothy Ventimiglia, Jeffrey Focke, David McGruder and Scott Bravard. This report was presented at the NASA/USRA Student Design Conference during 1988-89.

The Request for Proposal provided to the class [1] and attached as an Appendix to this report is summarized as follows.

Range:	**6000 nautical miles**
Payload:	**300,000 lbs, plus 30 first class passengers**
Crew Size:	**6 (includes two flight crews)**

Cruise Mach Number:	0.7 minimum
Cargo Compartment Size:	Sufficient to handle 8 x 8 x 8 ft. standard cargo containers

The aircraft must meet all FAR requirements and be able to operate from international airports. The design will take advantage of technology available for production in the year 2000. The projected market for this aircraft is transportation of freight from Europe and the U.S.A. to countries in the Pacific Basin.

Design Overview

The result of this design study, encompassing 14 weeks of effort by a team of five students, was the **Bisonaire Buffalo,** shown in Figure 1. This aircraft is a spanloader with a payload capability of 300,000 lbs plus 30 first class passengers, well within the range of a useful spanloading aircraft. For structural efficiency, the cargo distribution within the wing is balanced by the aircraft lift distribution. This efficiency results in an aircraft operating empty weight of 457,300 lbs. and a maximum take-off weight of 1,131,500 lbs.

The propulsion unit consists of six turbofan engines to take advantage of turbojet speed and economy. Aerodynamic design takes advantage of thick supercritical airfoils, low-aspect ratio wings, and end plates (winglets) to combine performance and sufficient wing volume for the cargo. A detailed study of the stability of the aircraft for both normal operation and off design conditions was done to ensure proper handling qualities and adherence to FAR requirements.

Aerodynamics

The final design evolved from simple concepts, to which were gradually added more complex components; the final aircraft design is the result of compromises between the ideal design and restrictions imposed by operational reality. For example, since this aircraft carries its payload in the wing, relatively thick airfoils must be used to accommodate the volume requirements. This creates drag at transonic Mach numbers, placing a restriction on the cruise Mach number. Also, winglets were necessary to improve lift and to provide yaw-control.

To achieve an operational cruise Mach number of 0.75, while minimizing drag and providing the largest airfoil cross-section possible, new supercritical airfoil designs were developed using the PANDA airfoil design program[2]. PANDA uses an analytical method based on superposition of sources and vortices; once the pressures have been calculated, the boundary layer properties can be computed and the total drag estimated using the Squire-Young formula. These cross-sections, together with their predicted surface pressure distributions during cruise and respective placement on the wing, are shown in Figure 2.

The wing design effort was also aided by the use of a computer code developed for the MacIntosh computer. This code, LinAir, is a program capable of modeling multi-element, non-planar lifting surfaces[3]. This code allowed the proper selection of wing sweep and jig shape to improve the cruise configuration and allow for trim.

For design purposes, the aircraft was modelled using three wing sections (each with variable sweep and incidence to optimize local Mach number and thickness requirements) The effects of winglets, and a small horizontal surface mounted flush with the trailing edge of the main wing were also accounted for. Based on Reference 4, a winglet surface area of 15% of the wing semi-span was chosen. The total wing area is 15,180 square feet. The wing span is 278 ft., a span that is restricted by requirements that the plane fit on existing runways.

By varying flight parameters, such as angle of attack and Mach number, a detailed analysis of the wing performance was constructed. Figure 3 shows the predicted drag polar for this design. Figure 4 gives L/D values for various angles of attack at the cruise Mach number. Several projected high-technology applications were included in this design (see Table 1 below).

Table 1 Aerodynamic Features and Benefits

Feature	**Benefit**
Low Wing Loading	**• Improved Take-off/Landing**
Supercritical Airfoils	**• Thicker cross-sections** **• Lower Drag** **• Higher cruise Mach Number**
Winglets	**• Improved L/D (3.4% - 6.2%)**
Swept Wings	**• Delayed drag rise**
Laminar Flow Control	**• Decreased drag (up to 80%)**
Vortex Management	**• 50% (targeted) decrease in landing /take-off separation**

Structures

The flying-wing design provides several challenging structural problems, while at the same time offering such sought-after advantages as cargo arrangement that balances the lift distribution. The primary benefit of the design is a significant reduction in overall structural weight.

The initial design efforts focussed on an all-flying-wing structure. However, such designs were aerodynamically unstable. This problem was solved by adding a small fuselage section. Figure 5 shows a top view of the final design. This arrangement allowed the movement of passengers, cargo, and fuel forward to produce a statically stable aircraft.

The aerodynamic center was calculated using methods from Roskam [5]. Using this data, together with center of gravity data, the static margin computed for all flight segments The aircraft was stable with a minimum stability margin of 5.44% during landing. The weight breakdown used in all calculations was obtained from the flight optimization program FLOPS [6], modified for use at Purdue on the Engineering Computer Network.

The wing loading at maximum gross weight is 74.54 lbs. Design analysis included the determination of shear and bending moments for a wing constructed of T300/5208 graphite/epoxy composite skin material[7].

For the aircraft to be commercially feasible, it must use available, standardized cargo containers now in use by Federal Express. Using two different size containers, the AYY and the M3 [8,9] and a payload density of 9.2 lbs/ft^3, this design can carry a payload of 327,500 lbs. Construction of the flight deck and landing gear was modeled after the Boeing 757 [10]. This creates an aircraft which fulfills both the RFP and FAR requirements.

Propulsion

The propulsion system provides controlled thrust as well as power for the accessory equipment. It can be broken down into four subsystems: the engine, lubrication subsystem, engine controls and accessory drives. This design uses six turbojet engines. This number was chosen by carefully considering reliability, maintainability and weight. Engines were sized using fuel data and operational characteristics for a hypothetical engine provided by NASA/Langley Research Center.

A major consideration in engine sizing is the amount of thrust necessary at take-off and at cruise. Figure 6 shows the results of a constraint analysis considering required thrust-to-weight versus wing loading for the aircraft design. Based on this analysis, a sea-level value of engine thrust-to-weight ratio of 0.23 was chosen. To produce this amount of thrust, six engines will be needed, each producing 45,000 lbs of thrust. Prohibitive size ruled out fewer engines, while the use of more than six engines would result in excessive maintenance cost.

As mentioned previously, NASA /Langley provided the engine deck used to size the engines and to provide performance estimates. An engine deck gives net thrust and fuel flow for selected Mach numbers and altitudes. Using this engine deck, a scaling program was developed and was used to adjust the engine to meet the required thrust level. The scaled-up engine will have a total length of 19.1 feet and a maximum diameter of 11.8 feet, with a total engine weight of 14,280 lbs. The breakdown the engine component weights is given in Figure 7.

Performance

Performance analysis will define an aircraft's capabilities and limitations for specific tasks that it must accomplish.

This discipline takes a set of physical characteristics for an aircraft and determines various parameters, such as how high, how far, how fast, and how well the aircraft accomplishes its mission.

The Request for Proposal required this aircraft to fly a 6000 n.m. flight in 16 hours or less. Given the requirements for payload and range, a climbing cruise profile was utilized to maximize the range for a minimum amount of fuel. This cruise schedule is permissible since the aircraft will be operating primarily over the Pacific Ocean.

This aircraft is designed to cruise at a Mach number of 0.75. Cruising at a higher Mach number leads to transonic flow conditions over the wing and an associated drag rise. Cruise at a lower Mach number reduces engine efficiency and increases trip time. The aircraft has a maximum service ceiling of 46,000 ft. By using a cruise-climb schedule between 35,000 ft and 39,200 ft, the aircraft has a range of 6,184 n.m. fully loaded and completes its mission in less than 15 hours [6].

Calculations from FLOPS [6] show that, fully loaded, this aircraft can lift off in 7,215 ft and land in 9567 ft. The stall speed is 115 knots with an approach speed of 150 kts, which complies with FAR 25.119 [10]. Also, the one engine inoperative characteristics (OEI) meet FAR 25.111 and 25.121 requirements [11].

Figure 8 shows the fuel requirements for each segment of the mission. With a total fuel capacity of 56,600 gallons, a diversion to an alternate airport still leaves the aircraft with 2,600 gallons in reserve. Figure 9 shows altitude versus Mach number for the most efficient flight, as determined using the FLOPS code mentioned previously.

Stability and Control

Leonardo da Vinci wrote, "A bird is an instrument working according to mathematical law . . . it is within the capability of man to reproduce its movements." However, a bird has the advantage of greater flexibility over an aircraft and this gives rise to movable control surfaces. In fact, the feathering structure on some birds' wings was the inspiration for some multi-element airfoil designs [12].

Both stability and control have been demonstrated in flight tests to be difficult, though obtainable, with a spanloader configuration [13]. A pure flying wing is desired as the aerodynamically optimum vehicle, but a trade-off is encountered between efficiency and static stability. In this aircraft, some of that aerodynamic efficiency had to be sacrificed to include a small fuselage section and tail surfaces, resulting in a spanloader as opposed to a true "flying wing."

Two fundamental problems were encountered during the design of stabilizing surfaces for this aircraft. The first of these, mentioned previously, was positioning the center of gravity relative to the aerodynamic center so as to produce a positive static margin. The combined effect of adding a fuselage and horizontal tail resulted in a static margin ranging from 6% - 15% for the entire mission. The second problem was the size and position of the vertical tail surface.

To examine static stability of the aircraft, two computer codes were available: LOPROG (longitudinal) and LAPROG (lateral-directional) [14]. Using results from LAPROG, vertical winglets were designed to act as rudders with sufficient control deflection to provide lateral stability.

Control surfaces were sized based on studies of other aircraft of similar gross weight [15]. A plan view of these surfaces is presented in Figure 10. The greatest area of concern for the design and placement of the control surfaces occurs during landing. The final design is stable and controllable about all three axes during all phases of the mission.

Economics

It is estimated that a fleet of 100 aircraft would cost $95 million per aircraft. From the manufacturer's point of view, there are two basic goals of a cost analysis. One is to estimate the development cost of the project. Another is to estimate probable operating costs, for this is one factor upon which the potential buyer will base his purchase decision. It is this analysis which will probably determine whether or not the preliminary design becomes a full-blown project.

In 1982, the Office of Technology Assessment estimated the development costs of a major new aircraft at $6 billion [16]. For example, the Boeing 767 is estimated to have cost somewhere between $2 - $10 billion dollars to develop [17]. It follows from this that market conditions at the time of the sale will determine the selling price of an airplane. This often requires selling below cost, or making promises which, in the long run, cannot be kept [17].

While presumably not as interesting to the manufacturer as development costs, operating costs are easier, to estimate. If the manufacturer can promise a more financially efficient product than his competitor, he will have a better chance at making the sale. A breakdown of operating costs for this aircraft is shown in Figure 11.

Figure 12 shows the price for tickets and cargo which must be charged by the operator to make a profit. To calculate these costs, the following assumptions were made:

(1) Fuel costs over a period from July, 1987 to June, 1988 were averaged to obtain a fuel cost of $ 0.62 per gallon[18],

(2) the load factor (ratio of passengers to seats available) was set at 70%,

(3) Cargo hold was fully loaded at 300,000 lbs, and

(4) the profit margin was set at 10%.

These prices are very competitive: a one-way ticket from Los Angeles to Tokyo, (November, 1988) cost $760, and overseas shipping rates are consistently greater than $1 per pound.

Conclusion

An initial design study of a spanloading air freighter has been completed. The analysis of this design shows that an aircraft of this type is feasible, both to build and operate. Utilizing existing technology and technology anticipated to be available in the near future, the aircraft can be manufactured, flown, and should make money for its operators.

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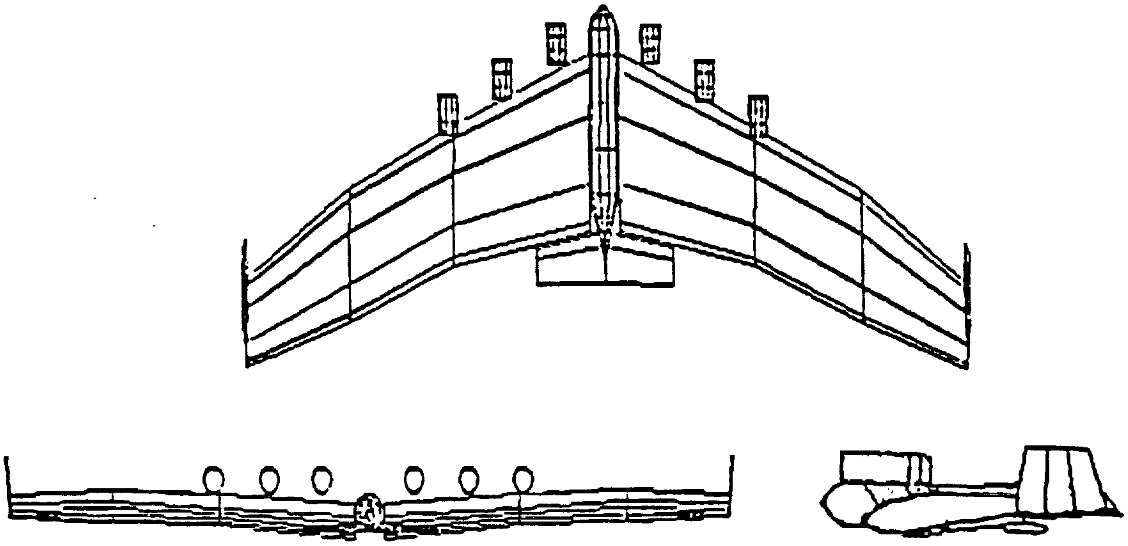


Figure 1 - The Bisonairre Buffalo Spanloader Transport

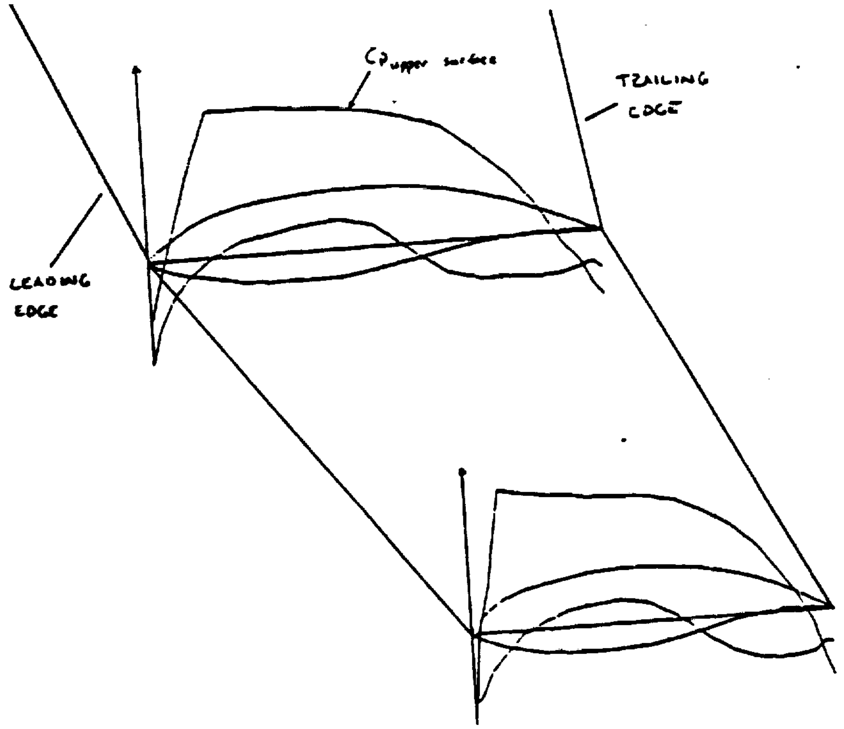


Figure 2 - Airfoil cross-sections with calculated pressure distributions

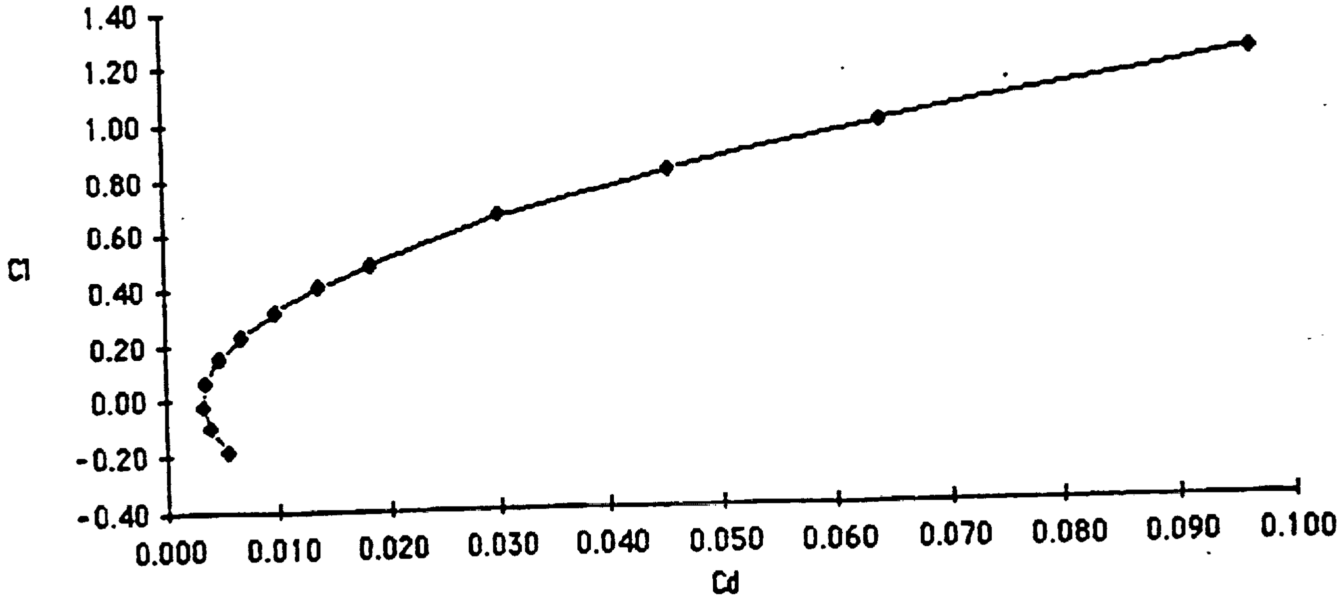


Figure 3 - Drag polar for the Buffalo

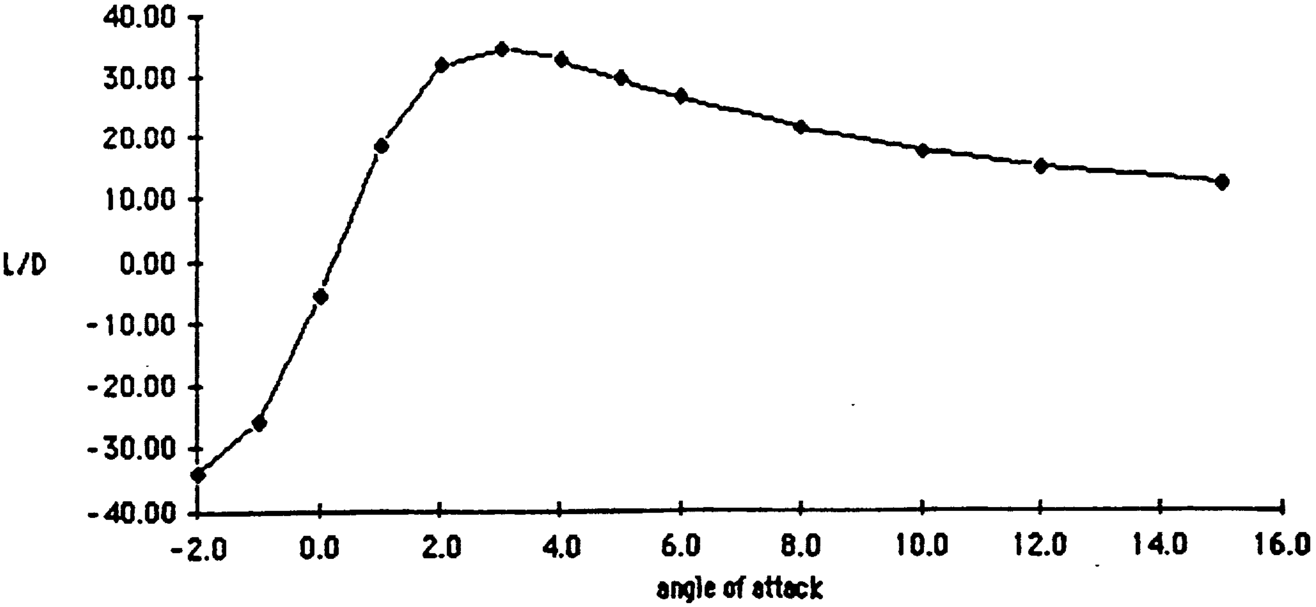


Figure 4 - L/D vs. aircraft angle of attack

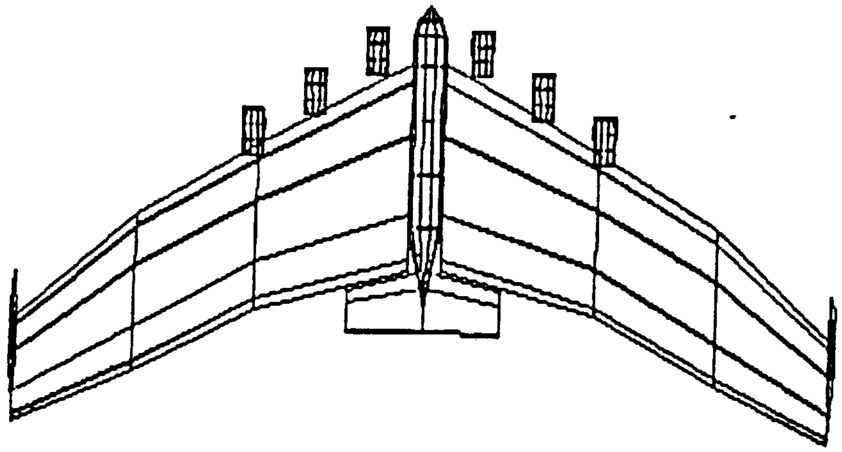


Figure 5 - Planform view of design

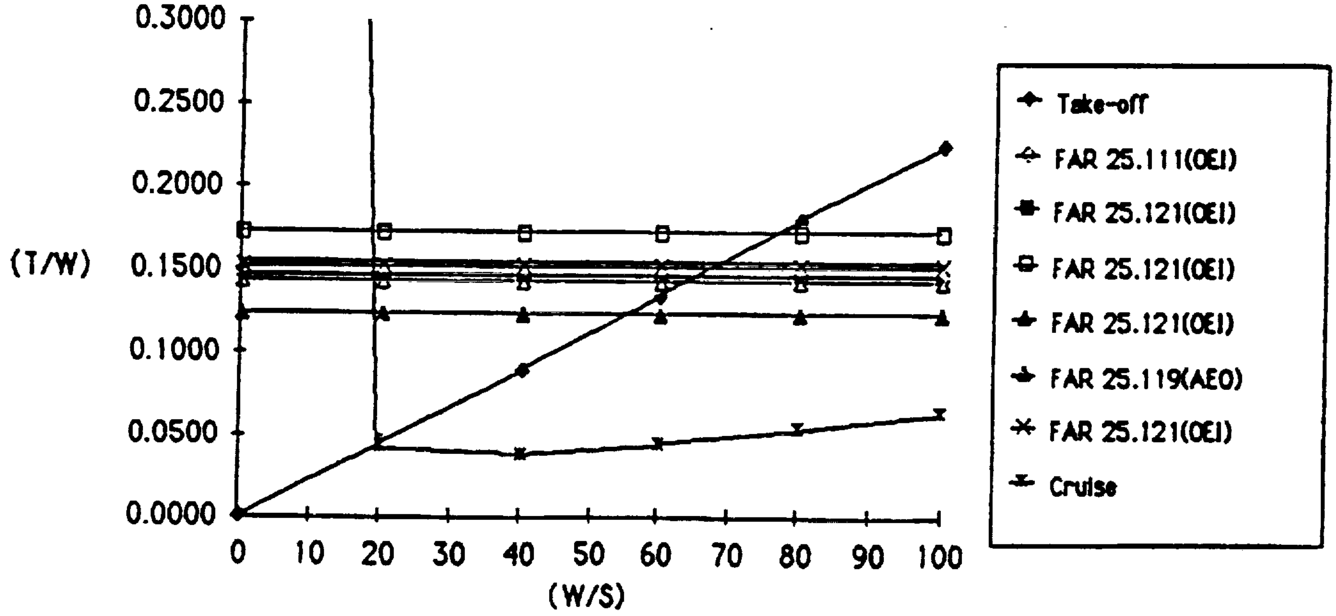


Figure 6 - Constraint analysis for aircraft

Engine Weights Summary

Engine Weight	9232.37 lbs
Nacelle Weight	1963.80 lbs
Thrust Reverser Weight	1759.92 lbs
Total Misc Propulsion Weight	563.56 lbs
Total Prop. Plumbing Weight	757.82 lbs
Total Engine Weight	**14277.47 lbs**

Figure 7 - Engine component weights

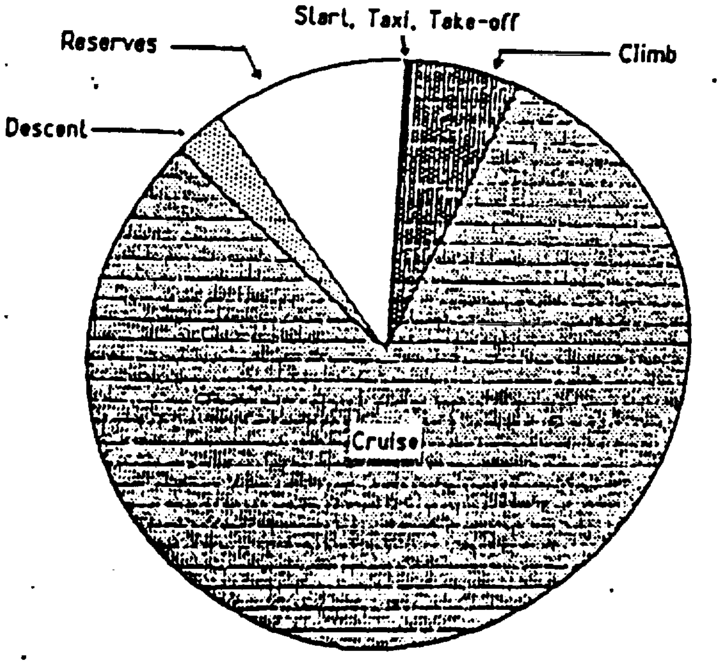


Figure 8 - Fuel requirements to complete mission

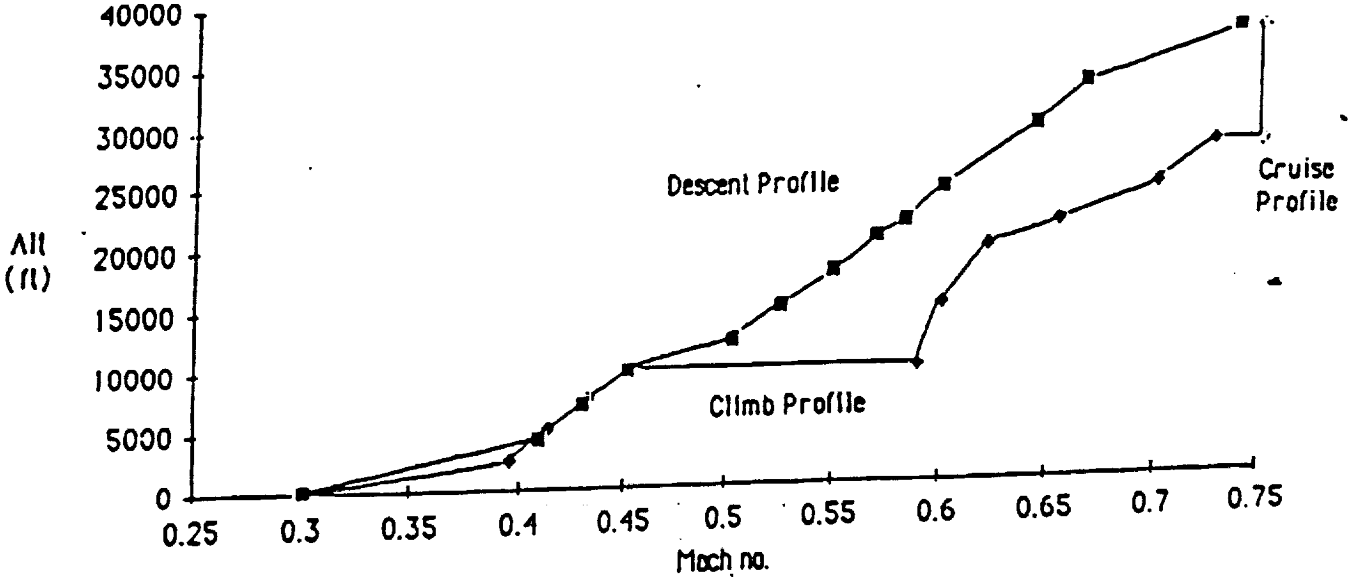


Figure 9 - Altitude-Mach number schedule for efficient flight

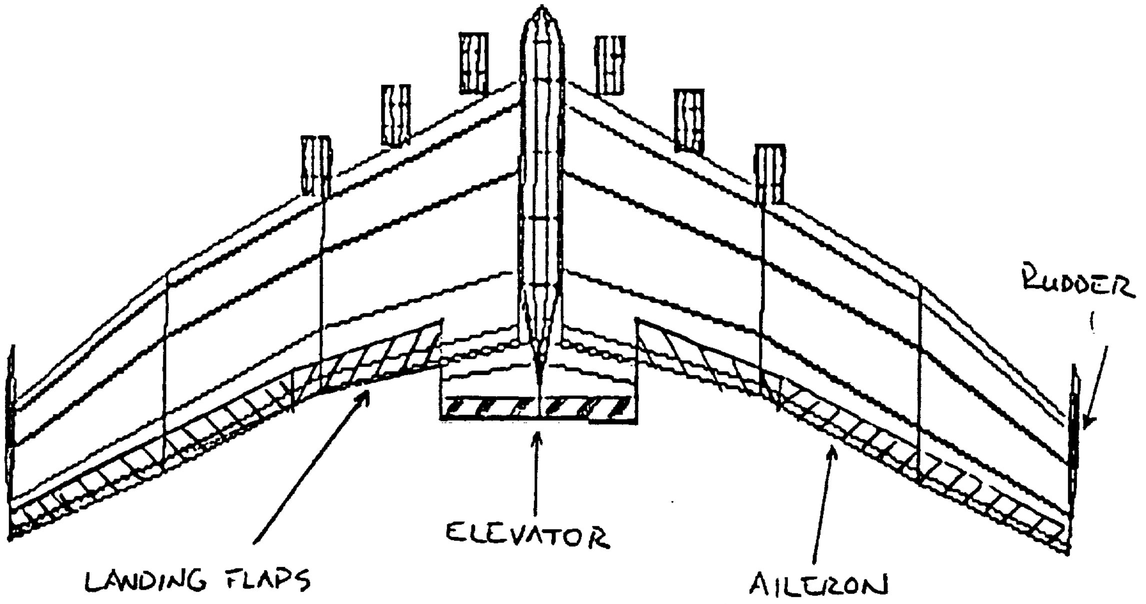


Figure 10 - Planview of control surface layout

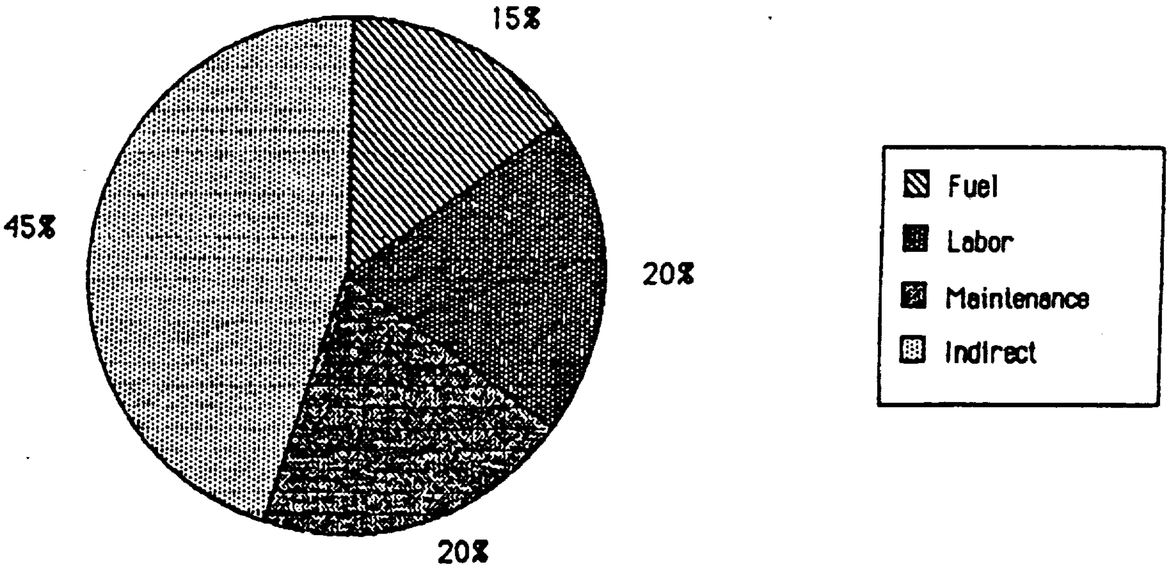


Figure 11 - Operational costs

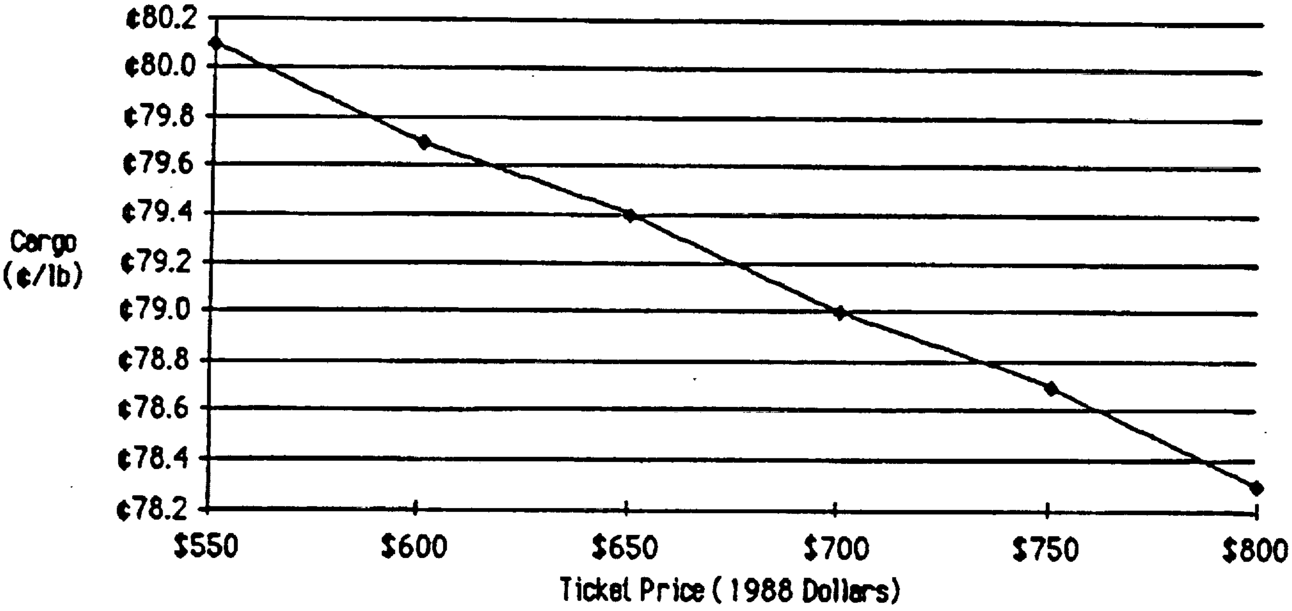


Figure 12 - Ticket and cargo prices

AAE 451 - Aeronautical Design - Weisshaar

REQUEST FOR PROPOSAL
DESIGN FOR A SPANLOADER AIR FREIGHTER

Expanding international freight markets suggest the possible use of an efficient large payload aircraft for overnight freight such as Federal Express. The objective is to reduce the cost of next day or two day mail and freight service from Europe and the USA to countries such as Australia, Japan, Taiwan, China, Singapore, and South Korea.

A typical trip might begin with packages arriving at an airport destined for a country in the Pacific Basin. A container on the back of a truck would come off of the truck bed and be loaded into the aircraft. This is similar to the containerized sea-going cargo ships in use today.

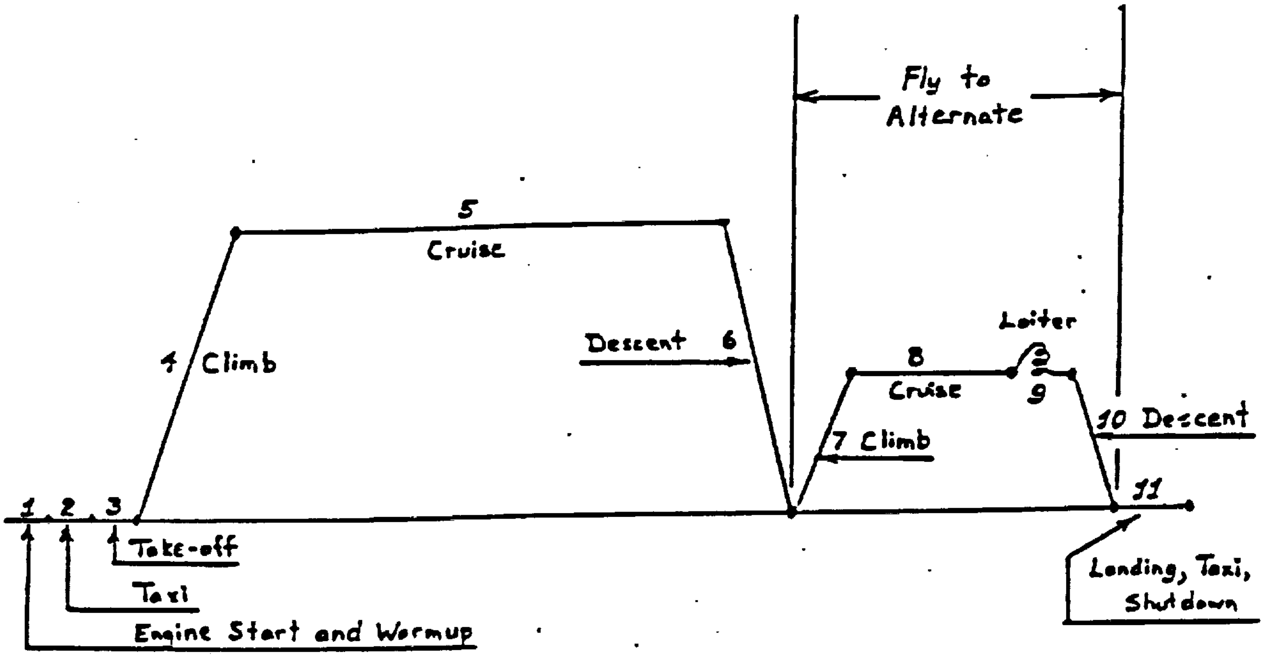
The aircraft would then take off on a 16 hour, 6000 n.m. flight to its destination. During the flight, the packages are sorted and redistributed among the containers. After landing, the containers again would be loaded onto trucks and then delivered to their final destination at a cost only slightly greater than that for an overnight package in the Continental U.S. It is proposed that the design have the following characteristics:

Range:	6000 n.m.
Payload:	300,000 lbs. plus 30 first class passengers and baggage.
Cargo-Compartment Dimensions:	Sufficient to handle 8 ft x 8 ft cargo containers of assorted lengths (8 x 8 x 20 is a typical cargo length).
Cargo-Compartment Pressurization:	8.2 lbs/in^2
Payload Density:	10 lbs/ft^3
Cruise Mach Number:	M=0.7 minimum
Operate from conventional airports	(balanced take-off field length less than 12,500 ft).
Maximum Width of Landing Gear:	80 feet
Crew Size:	6 (includes two flight crews).

Meet FAR 25 requirements

First flight in the year 2000.

Attachment: Mission Profile



1. Engine Start and Warmup.
2. 10-minute Taxi-Out Time.
3. 1-minute Takeoff Time.
4. Climb to cruising altitude with range credit.
5. Cruise for 6000 n.m.
6. Descend to airport with range credit.

7-10. Fly-to-Alternate airport after missed approach at primary airport (1 minute at full power) followed by an acceleration to climb velocity.

- (a) Climb to 5,000 ft. (segment 7). (with range credit)
- (b) Cruise for 200 n.m. to the alternate airport (segment 8).
- (c) Loiter for 30 minutes at 5,000 ft. (segment 9).
- (d) Descend to the airport with range credit (segment 10).

11. Landing and shutdown.
12. Add 5% to the trip fuel used in segments 1-6 (fuel reserves).