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Application of Hybrid Laminar Flow Control to Global Range Military Transport Aircraft

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FOREWORD

The technical work herein was accomplished under Task 2 of Contract NAS1-18036 sponsored by NASA-Langley, Langley Research Center, Hampton, Virginia 23665-5225 and the Air Force Flight Dynamics Laboratory, WPAFB, Ohio. Task 2 go-ahead was initiated in September 1986. Mr. Richard D. Wagner, Manager, Laminar Flow Control Project Office, NASA-Langley, was the Task Manager, Mr. D. V. Maddalon was the Technical Representative of the Contracting Office, and Mr. Russ Osborn was the Technical Representative from the Air Force Wright Aeronautical Laboratories, AFWAL/FIMM, WPAFB, Ohio.

Mr. Roy H. Lange, Lockheed Program manager, LFC Projects, is responsible for the overall guidance and technical direction of the Laminar Flow Enabling Technology Development Contract, NAS1-18036 and also served as Task 2 Study Manager. The technical work for Task 2 was performed under the direction of the Preliminary Design Division (D/72-90) of the Lockheed Aeronautical Systems Company in Marietta, Georgia. The key technical people working during this reporting period include:

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1.0 SUMMARY

This report summarizes the results of a study conducted by Lockheed under NASA Contract NAS1-18036 to evaluate the application of hybrid laminar flow control (HLFC) to global range military transport aircraft.

By mutual agreement among NASA, the Air Force, and Lockheed the global mission of the aircraft in this study included the capability to transport 132,500 pounds of payload 6,500 nautical miles, land and deliver the payload and without refueling return 6,500 nautical miles to a friendly airbase. The design cruise Mach number for the mission is M = 0.77. Both turbulent flow and hybrid laminar flow control aircraft were sized to perform the global mission. A baseline turbulent flow aircraft was used as the reference aircraft for comparison with the HLFC aircraft concepts. The hybrid LFC concept restricts the active suction system to the region ahead of the front spar, i.e., 15 percent wing chord and the remainder of the airfoil is tailored aerodynamically to achieve the maximum extent of laminar flow, which is expected to extend to about 50 percent chord.

Originally intended as a six month study, the scope was expanded as initial results were obtained to include additional comparisons and sensitivity runs. This expansion in scope has provided for a better understanding of the results and for a more complete data base of aircraft design and performance parameters. Thus, the preliminary aircraft design study has generated a considerable amount of sizing data for both turbulent flow and hybrid LFC aircraft concepts.

Preliminary design system studies of the application of hybrid laminar flow control to military transports sized to perform global range mission characteristics show significant performance benefits obtained for the hybrid LFC aircraft as compared to counterpart turbulent flow aircraft. The study results at M = 0.77 show that the largest benefits of HLFC are obtained with a high wing with engines on the wing configuration. As compared to the turbulent flow baseline aircraft, the high wing HLFC aircraft shows 17 percent reduction in fuel burned, 19.2 percent increase in lift-to-drag ratio, an insignificant increase in operating weight, and 7.4 percent reduction in gross

weight. For this high wing configuration, the performance data are based on the assumption that there is no loss in laminar flow on the upper wing surface with engines mounted on the wings. It is felt that this is an optimistic assumption especially for the longer laminar runs for the HLFC conditions of this study and for the multi-engine configurations. The second best HLFC configuration is the low wing, fuselage mounted arrangement with no HLFC on the empennage. This configuration shows 13.7 percent reduction in fuel burned, 18.2 percent increase in lift-to-drag ratio, 5.4 percent increase in operating weight, and 4.2 percent reduction in gross weight as compared to the turbulent flow aircraft.

Sensitivity studies include the determination of the effects on performance of increase in cruise Mach number from 0.77 to 0.80, increase in initial cruise altitude to 36,000 feet, and elimination of HLFC on the lower wing surface. These changes generally resulted in degradation in performance as compared to the baseline aircraft characteristics. As expected, the reduction in aspect ratio from the baseline value of about 13 to a value of 10 reduced the benefits for fuel consumption and lift-to-drag ratio.

In view of the superior performance of the high wing with engines mounted on the wing HLFC configuration, it is recommended that further research and development be conducted to provide the necessary data base for validation of the effects of engine operation on laminar boundary layer transition for flight Reynolds numbers corresponding to large, long range transport aircraft. Operation at higher altitudes of 36,000 feet and above are more favorable to the attainment and preservation of laminar flow. The data in this study show a moderate increase in lift-to-drag ratio for operation at initial cruise altitude of 36,000 feet, but with an attendant large increase in engine thrust for the relatively high by pass ratio engines used in this study. It is recommended that additional studies be made of high altitude operations with lower by pass ratio engines.

All HLFC aircraft in this study have been sized without the use of leading-edge high lift devices on the wings. In view of the favorable effects of leading-edge high lift systems on the airfield performance and the shielding effects for HLFC operations, it is recommended that additional sizing studies be conducted on the two best HLFC configurations of this study with the addition of leading-edge high lift systems.

2.0 INTRODUCTION

Among the many concepts for aircraft drag reduction, laminar flow control, LFC, has indicated the greatest potential for skin friction drag reduction. A review of early progress since 1939 in analytical and experimental investigations of boundary layer transition and methods for achievement of laminar flow is contained in a paper by Braslow and Muraca (Reference 1).

Lockheed performed the initial feasibility study of advanced technology LFC aircraft beginning in October 1974 (References 2-5). The favorable results of this initial study provided the impetus to additional investigations of LFC, and NASA, in concert with industry, has been sponsoring LFC technology development activities for the past 12 years to achieve LFC technology readiness in the 1990's (References 6-9). Major Lockheed LFC development programs funded in 1980 under the NASA ACEE program include wing surface panel structural development (References 10, 11) and the design, fabrication, and flight test of leading-edge articles (Reference 12).

The Lockheed motivation in LFC activities has been directed to the eventual application to long-range or long-endurance military strategic aircraft systems. During the time period of the intensive system evaluation studies of commercial LFC transport studies under NASA contracts, Lockheed was continuing its preliminary design studies of military LFC airlift aircraft under Independent Research and Development projects.

Encouraged by the progress made in the development and validation of leading-edge cleaning, anti-icing, and suction systems so vital to the success of an LFC transport, Lockheed and Douglas developed flight test articles with NASA funding that were installed and tested on the NASA-Dryden Flight Research Facility JetStar aircraft. The Lockheed activity is reported in Reference 12. An early review of the total NASA program is given by Wagner and Fischer in Reference 9. A review of the above activities since 1974 is given in an AIAA paper by Lange (Reference 13).

Current activities in the NASA/Lockheed Laminar Flow Enabling Technology Development Contract No. NAS1-18036 include the Task 1 development of a slotted surface structural concept using advanced aluminum materials (Reference 14) and the Task 2 preliminary conceptual design study of global range military HLFC transports reported herein.

This report summarizes the results obtained in the Task 2 preliminary conceptual design studies of the benefits derived from the use of hybrid laminar flow control (HLFC) for military transports designed to achieve payload/range requirements of global range aircraft. The Air Force Project Forecast II effort has identified system PS-03 Multrirole Global Range Aircraft as a subsonic element in global force projection. It is anticipated that this global range aircraft must have exceptional aerodynamic and propulsive efficiency to achieve the mission characteristics. Previous Lockheed preliminary design studies have shown significant increase in aerodynamic efficiency by the application of LFC to military transport aircraft. These results were obtained in an Air Force contract study of Technology Alternatives for Airlift Deployment (TAFAD) (Reference 15). Section 4.0 of the report contains background information on the study objectives, study plan, assumptions basic to all study tasks, and the technology level appropriate for the study. Section 5.0 describes the mission characteristics and the baseline configuration studies of turbulent flow and hybrid LFC aircraft sized to perform the mission requirements of the study. Section 6.0 contains the results of sensitivity studies of several aircraft performance parameters for both hybrid LFC and turbulent flow aircraft. In Sections 5.0 and 6.0 comparisons are made between the turbulent flow and hybrid LFC configurations in order to determine the benefits attributable to hybrid LFC. An overall assessment of hybrid LFC benefits is contained in Section 7.0, along with a preference for the best hybrid LFC configuration. Conclusions and recommendations are provided in Section 8.0.

3.0 SYMBOLS AND ABBREVIATIONS

Symbols

b	wing span, ft
c	local wing chord, ft
C_L	lift coefficient
Cp	pressure coefficient
M	Mach number
R_N	Reynolds number
S	wing area, ft^2
t	thickness, ft
t/c	wing thickness-to-chord ratio
U	potential flow velocity, ft/s
V_S	area suction velocity, ft/s
W	slot width, in.
X	streamwise coordinate, ft
x/c	chordwise location
α	angle of attack, deg
η	cruise power ratio, wing semispan location
ρ	density, lb/ft^3

Subscripts

∞	free stream
s	slot
w	at surface
z	sucked height of boundary layer

Abbreviations

AR	aspect ratio
CFL	critical field length, ft
HLFC	hybrid laminar flow control
HP	high pressure
H.P.	horsepower
IGV	inlet guide vane
L/D	lift-to-drag ratio
LP	low pressure
MAC	mean aerodynamic chord, ft
O/B	overboard vent
RPM	revolutions per minute
SFC	specific fuel consumption, $\frac{lb/hr}{lb}$
SL	sea level
STD	standard day
TOGW	takeoff gross weight, lb

4.0 STUDY APPROACH

This section outlines the basic assumptions and criteria which are fundamental to all aspects of the study. Included is a definition of study objectives, the overall plan employed to achieve study objectives, design criteria, and the assumed technology level.

4.1 STUDY OBJECTIVES

The objective of this task is to determine by means of preliminary design studies the benefits derived from the use of hybrid laminar flow control for military transports designed to achieve the payload/range requirements of the global range aircraft.

The Air Force Project Forecast II effort has identified system PS-03 Multirole Global Range Aircraft as a subsonic element in its global force projection. Although the system characteristics have not been finalized, it is anticipated that this aircraft will have the capability to carry large payloads for a distance of 10,000 nautical miles unrefueled at high subsonic cruise speeds. The aircraft will land and deliver the payload without support at the destination airfield and fly back either to its base in the continental U.S. or to a friendly airbase unrefueled. The aircraft must have exceptional aerodynamic and propulsive efficiency to achieve these mission characteristics.

Previous Air Force/LASC-Georgia preliminary design studies of 1995 IOC military transports have shown high performance and economic efficiency with capabilities of Mach 0.80 cruise speed, 212,000 pounds payload, and 3500 nautical miles range (Reference 15). The addition of laminar flow control on an alternate configuration provided a range increase to 5800 nautical miles for the same payload and cruise Mach number and a 26 percent higher take off gross weight. The laminar flow control concept utilized active suction slots on the wing and empennage to 70 percent of the chord.

In order to provide for a near-term application of laminar flow control, a more simplified concept referred to as hybrid laminar flow control, HLFC, has been used for the current study. The HLFC concept, shown in Figure 1 has the active suction system restricted to the region ahead of the front spar of the wing. Aft of the active suction region the airfoil shape is tailored to achieve the maximum extent of laminar flow, and this is expected to extend to 50 percent or more of the wing chord as indicated by HLFC studies by Boeing reported in Reference 16. The HLFC concept avoids a number of concerns by the industry and the airlines, in particular, suction surfaces and ducting are not required in the main wing box areas which also contain the fuel for the aircraft. Thus the weight and complexity of the suction systems is greatly reduced and the possible hazards with the fuel are eliminated. The suction in the leading-edge region can control the cross flow disturbances for swept wings and the airfoil tailoring over the wing box can stabilize two-dimensional disturbances.

4.2 STUDY PLAN

The preliminary design study consists of five elements as shown in Figure 2. These elements consist of (1) Basic Data and Assumptions, (2) Mission Characteristics, (3) Configuration Development, (4) Configuration Selection, and (5) Analysis of Laminar Flow Benefits. These elements are briefly described in the sections that follow.

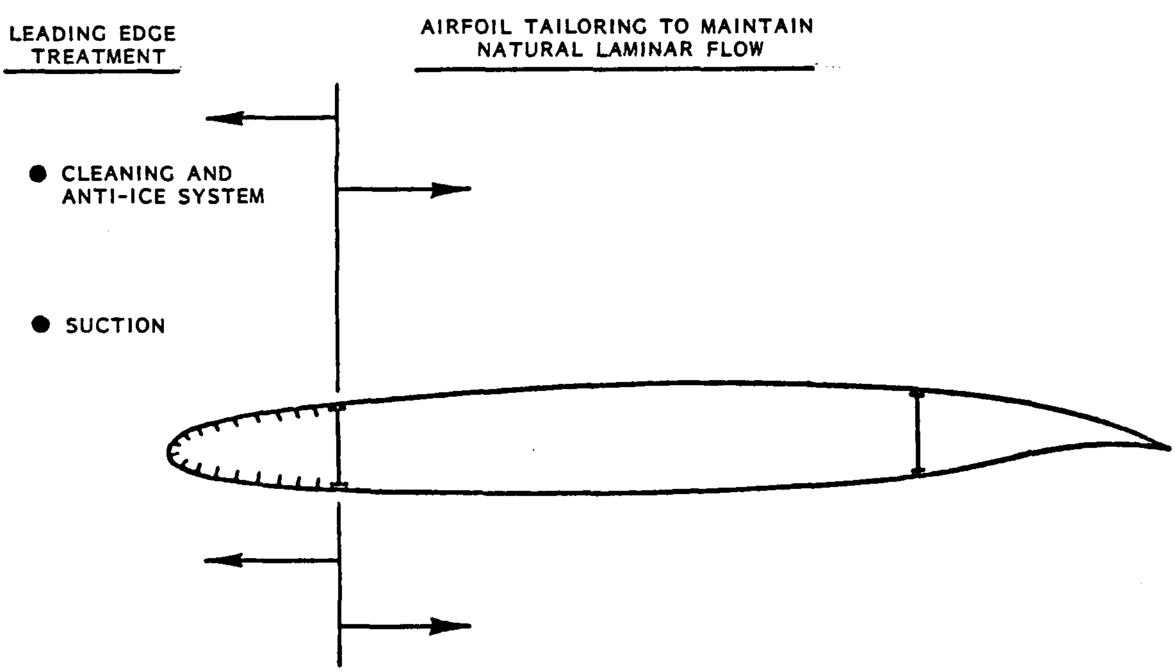

Figure 1. Hybrid Laminar Flow Control Concept

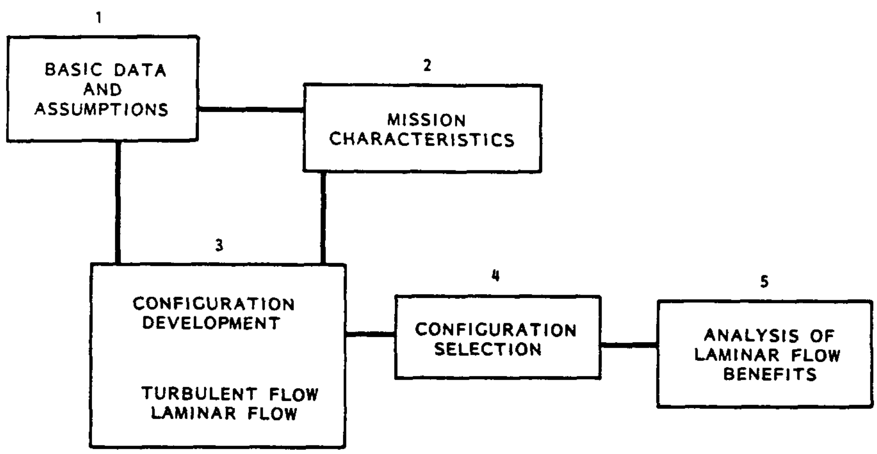

Figure 2. Study Plan

Element 1

In the basic data and assumption area and from considerations of the scope for this study, the approach taken was to utilize the technology data base in the Lockheed Generalized Aircraft Sizing and Performance (GASP) computer program that was used in the Air Force Technology Alternatives for Airlift Deployment (TAFAD) study mentioned previously (Reference 15). Modification has been made to the data base to account for the change to the hybrid laminar flow control concept and an update of the technology data base incorporated. For this study a technology readiness date of 1994 is assumed along with an initial operational capability IOC, date of 2000.

Element 2

Mission characteristics such as payload, range cruise Mach number, airfield performance, other systems operational concepts were established in this study element as they apply to the Multrirole Global Range Aircraft. As noted previously, the mission characteristics for System PS-03 have not been finalized; but as subsonic part of the Air Force Global Force Projection, this aircraft is to provide conventional massive response and tactical presence. In the TAFAD study an in-depth mission analysis of the Congressionally Mandated Mobility Study established an optimum payload of 212,000 pounds for rapid deployment. In the Configuration Integration for Large Multipurpose

Aircraft study (Reference 17) the payloads varied from small 50,000 pounds for AWACS to medium 130,000-150,000 pounds for ICBM launcher and cruise missile carrier and around 200,000 pounds for the aircraft carrier. A space vehicle launcher payload is about 275,000 pounds. Utilizing these results and other information, a set of mission characteristics was mutually agreed upon among NASA, the Air Force and Lockheed. These mission characteristics summarized in Figure 3A include a payload of 132,500 pounds, a cruise speed of M=0.77, and a range capability to fly out 6,500 nautical miles with full payload, land and offload payload and fly back 6,500 nautical miles unrefueled. The typical mission profile is provided in Figure 3B. All aircraft configurations in this study were sized to perform these mission characteristics. It should be noted on the general arrangement drawings shown later, the listed aircraft parameters include an asterisk after "Range 6500 NM." The asterisk directs the reader to the mission characteristics of Figure 3 because the total cruise distance for the mission is not a range or radius distance. Deviations from these mission characteristics were made in the sensitivity studies described in Section 6.0. For this long range mission, fuel reserves include 5 percent of cruise fuel plus one half hour.

Element 3

Configuration development using preliminary design studies were made of turbulent flow and hybrid laminar flow control aircraft to satisfy the mission characteristics established in Element 2. The Lockheed Generalized Aircraft Sizing and Performance (GASP) computer program used to size and define the

- PAYLOAD = 132,500 LB @ 2.5G
- CRUISE SPEED = 0.77 MACH
- INITIAL CRUISE ALTITUDE = FALLOUT VALUE
- AIRFIELD (CFL) = 10,000 FT @ S.L. STD, DAY
- FLYOUT 6,500 NM WITH FULL PAYLOAD, LAND AND RETURN 6,500 NM WITH ZERO PAYLOAD UNREFUELED
- FIELD LENGTH @ MIDPOINT $\leq$ 8,000 FT @ S.L. STD, DAY

Figure 3A. Mission Characteristics

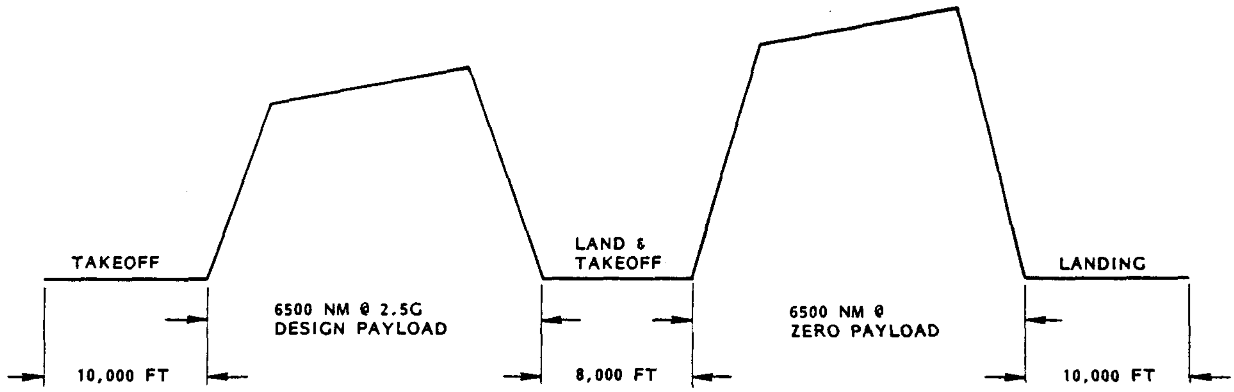

Figure 3B. Mission Profile

aircraft is described in Appendix A. The aircraft configurations were limited to conventional arrangements in this study. The output of this preliminary design Element 3 activity has provided the data listed in the following for each configuration:

- General arrangement drawing
- Weight statement including propulsion systems
- Geometric characteristics
- HLFC peculiar structures and cleaning (anti-icing fluid weights)
- Payload-range curve (some for all aircraft)
- Inboard profile and cross section

In addition, some sensitivity studies were performed in the development of the baseline turbulent flow and hybrid LFC configurations as described in Section 5.0.

Elements 4 and 5

The best turbulent flow and hybrid LFC configurations were selected in these elements of the study plan based on the results of Element 3 and additional sensitivity and configuration studies performed in Element 4 as a result of a meeting of NASA and Air Force technical personnel at the Lockheed Aeronautical Systems Company in Marietta, Georgia, on March 5, 1987. These additional studies extended the overall scope of the study for both turbulent flow and hybrid LFC configurations and are described in Section 6.0. The benefits in performance of hybrid LFC aircraft as compared with turbulent flow aircraft were determined from a direct comparison of the best aircraft in each case.

4.3 REFERENCE TECHNOLOGY LEVEL

As a preliminary to the parametric configuration analyses and subsequent configuration activities leading to the definition of selected aircraft, the level of technology likely to be available for application in the early 1990 period was established. This section summarizes the reference technology level assumed for all configuration development activities.

4.3.1 Aerodynamics

4.3.1.1 Aerodynamics Criteria

The most complete set of criteria for the development of external aerodynamic configurations compatible with LFC systems requirements was developed as a part of the X-21 program and is described in Reference 5. The criteria of this document were updated to include results of pertinent recent investigations. This updating included a critical review of LFC suction requirements and dual use of active trailing-edge control flaps for gust alleviation and minimization of LFC suction flow rates in varying operational conditions. Acoustic effects on suction requirements were addressed by inclusion of an excess suction system capacity similar to the approach used for the X-21. As a result of improvements in aerodynamics design and analysis methods, aerodynamics criteria used in previous studies, as depicted in Figure 3 of Reference 4, were updated appropriately for this study.

4.3.1.2 Airfoil Technology

The aircraft configurations developed in this study incorporate advanced technology supercritical airfoil sections characterized by an extensive region of supercritical flow terminated by a moderate-strength shock located fairly far aft. Typical wing section design curves, which define the technology level of the airfoil type, are shown in Figure 4. Some variation in airfoil thickness and form were examined to maximize internal volume for fuel and ducting and improve leading-edge boundary layer characteristics.

Advanced technology secondary active trailing-edge flaps of the type shown in Figure 5 were adopted as a means of automatically maintaining desired pressure gradients, controlling shock position, and minimizing LFC suction requirements over a moderate range of operating conditions.

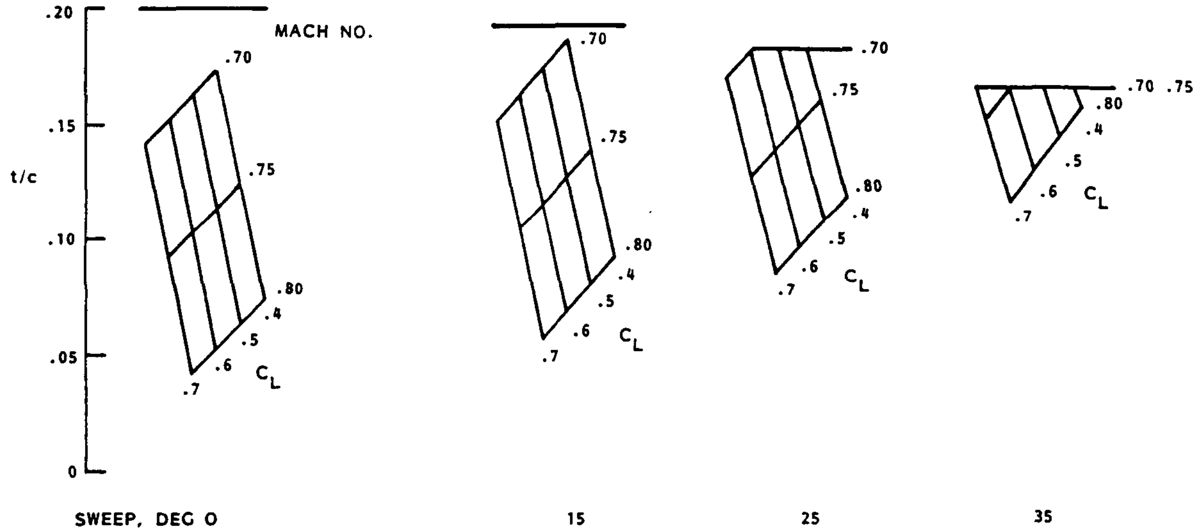

Figure 4. Wing Section Design Curves

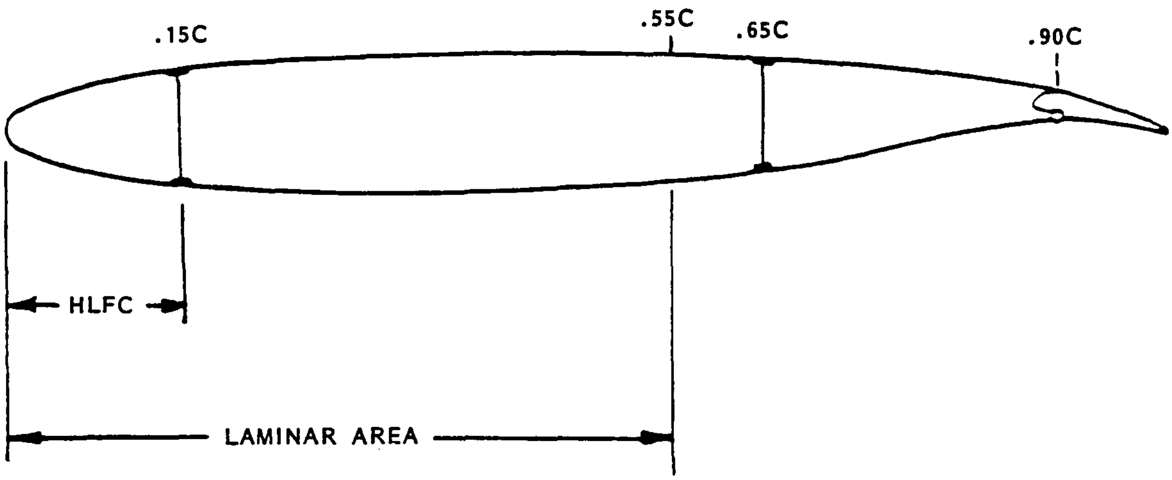

Figure 5. Example of Secondary Active Trailing Edge Flaps

4.3.1.3 High-Lift Device Technology

Design and analysis studies performed were compatible with a current-technology mechanical flap system which provides the required airport performance with the smallest penalty to direct operating cost. Single- and multiple-slotted flaps were assessed in the study from the standpoint of chordwise and spanwise extent, lift and drag effectiveness, relative weight penalty, and high-lift compatibility with airfoil section shapes desirable for LFC. For this study no leading edge devices are used in order to allow for HLFC on both upper and lower surfaces.

4.3.2 Flight Controls

The flight control system included in the sizing program incorporates the elements of active control technology (ACT) which promise significant improvements in the efficiency of large transport aircraft.

The ACT system encompasses the following modes of control:

- Relaxed Static Stability
- Stability Augmentation System
- Maneuver Load Control
- Gust Load Alleviation
- Flutter Mode Control
- Ride Control

The major improvement offered by the above systems are: minimization of airframe weight, incorporation of automatic trouble-shooting, and improved ride characteristics. These systems were employed in previous Lockheed LFC aircraft studies and are described in more detail in Ref. 5.

The four channel fly-by-wire (FBW) system is controlled on each channel by an on-board digital computer. A digital system is mandated by the extensive complex signal processing, the flexibility required to accommodate the multi-mode control logic laws, and the redundancy required by an FBW system.

Geared elevators driven by the stabilizer, a double hinged rudder, and outboard ailerons provide low speed control. Ground-operable-only spoilers are provided for deployment during ground rollout or rejected takeoff. All controls and instrumentation required for the operation of the airplane in the air and on the ground are located in the flight station. The on-board computers provide feedback for two hydro-mechanical units which provide the pilots with artificial feel in all three control axes.

4.3.3 Propulsion Systems

The Pratt & Whitney Aircraft STF-686 study engine was chosen as the primary propulsion unit for the baseline aircraft. This engine is a twin-spool, separate flow turbofan engine with 19,350 pounds of takeoff thrust. The preliminary weight of the engine is 3800 lb. The high pressure spool is a scaled version of the STS-686 high pressure spool, made up of an 11 stage high pressure compressor, a low emissions combustor, and a two stage high pressure turbine. The low pressure spool consists of a single stage shroudless fan, a three stage low pressure compressor and a five stage low pressure turbine. An active clearance control system is incorporated which controls the clearances of several components in order to minimize the fuel consumption at cruise. This system is activated at all operating conditions at altitudes above 15,000 feet. The engine has a design fan pressure ratio of 1.66, a bypass ratio of 6.97, and an overall compression system pressure ratio of 37.2.

The performance and weight improvement schedules for the STF-686 are shown in Figures 6 and 7. Figure 6 shows the projected performance improvement for the engine through the year 2005, using the PW2037 engine as a baseline, by which time SFC will have decreased 13.5 percent. Figure 7 shows the projected weight improvement for the engine in the same time frame and using the same baseline, a 13 percent reduction in weight by the year 2005. It is noted that both characteristics assume that aggressive component and engine technology programs will be maintained during this time span.

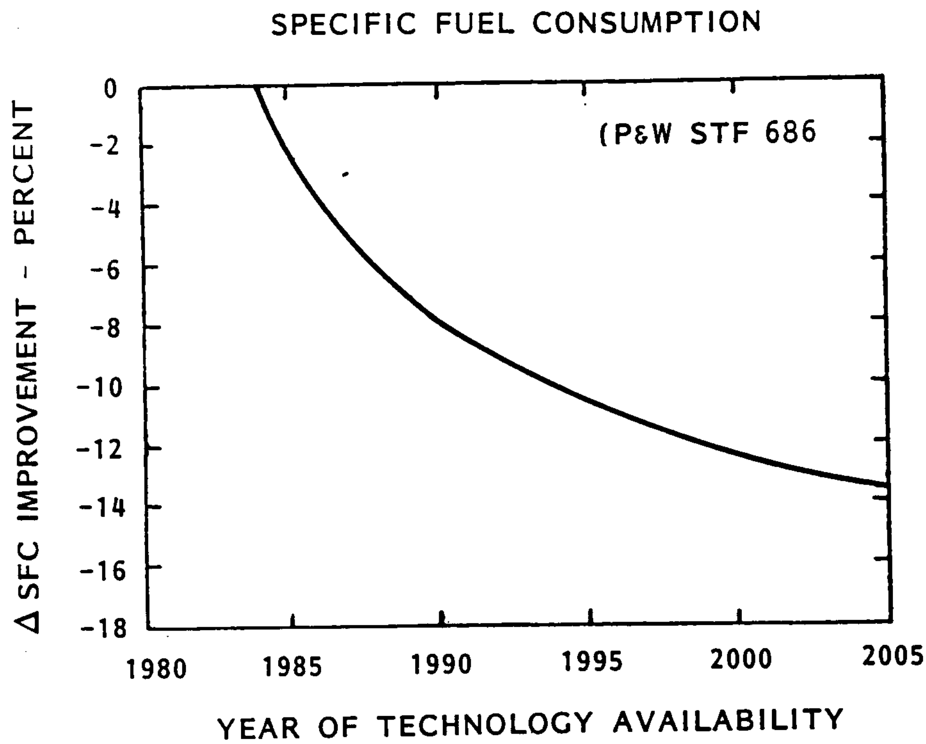

Figure 6. Specific Fuel Consumption (P&W STF686)

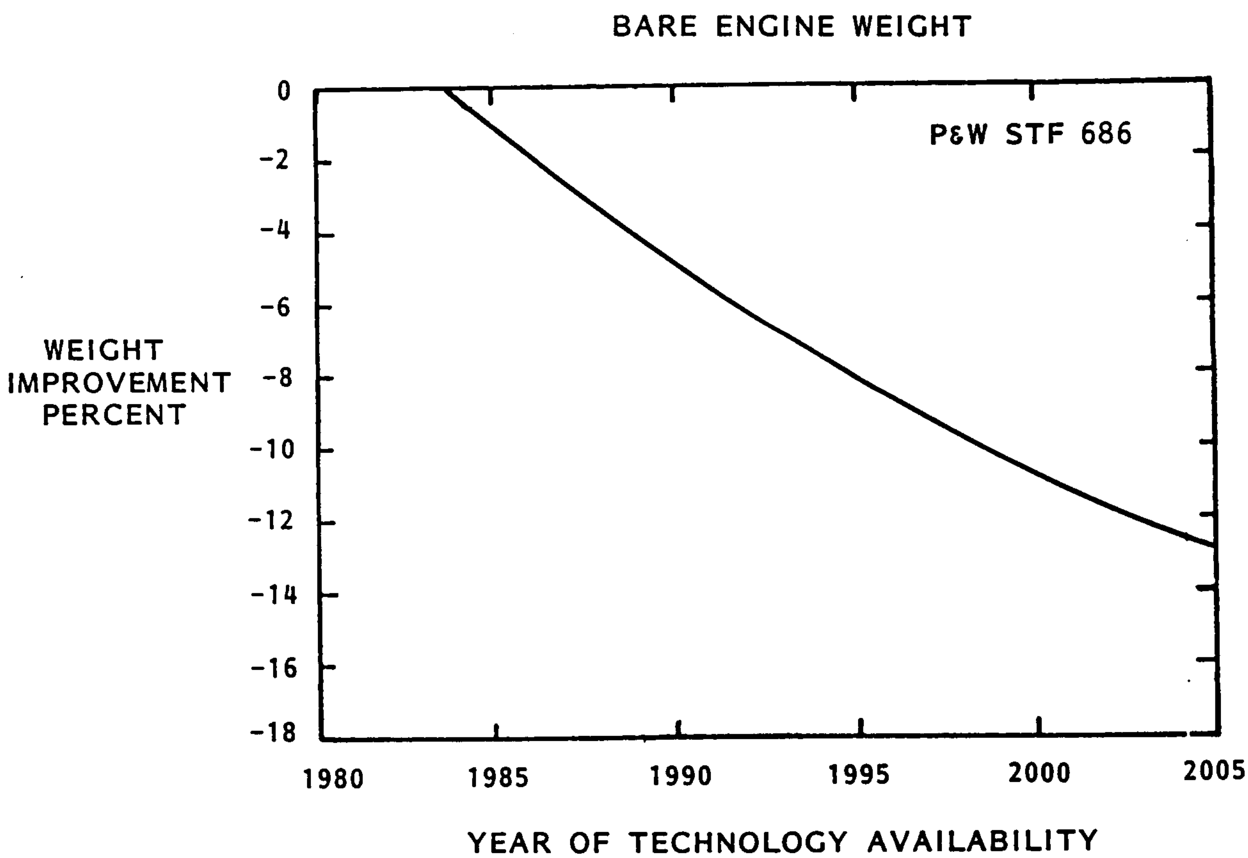

Figure 7. Bare Engine Weight (P&W STF686)

4.3.4 Structures and Materials

The aircraft structure contains conventional materials and graphite/peek composite materials to represent a materials technology level of approximately 1994. The percent utilization of the advanced composite material is illustrated in Figure 8. Graphite/peek composite is composed of graphite fibers in a thermoplastic resin and it offers the potential of high strength and stiffness along with resistance to delamination and embrittlement.

Figure 9 presents the weight reduction percentages that have been determined from detailed analytical trade studies. These weight reduction values are included in the weight estimation methods within the vehicle design synthesis process. This synthesis process is performed by MODGASP where further weight decreases will occur in fuel and operating weight because of the advanced material weight reductions.

The weight estimating methods used for aircraft sizing within GASP are those for conventional transports plus allowances for LFC peculiar design variables and consideration of advanced technology.

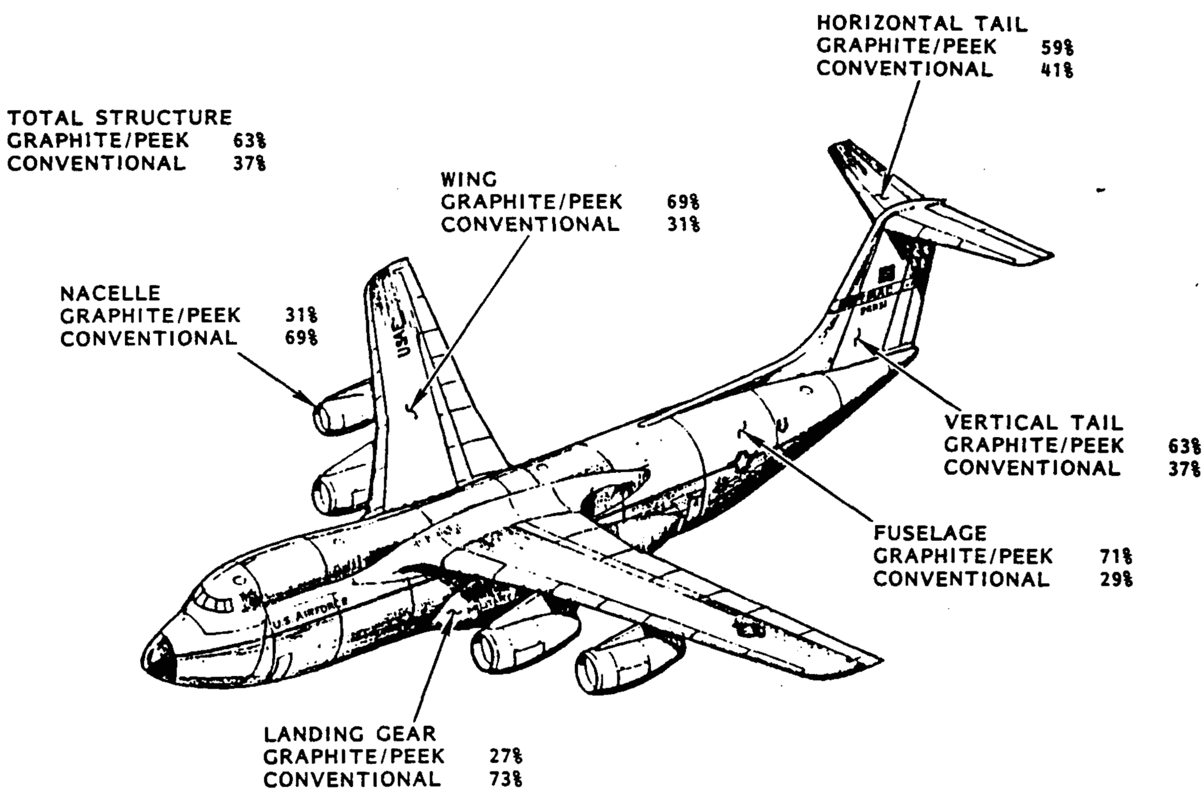

Figure 8. Advanced Material Technology for Hybrid LFC Study

STRUCTURAL COMPONENT	% GRAPHITE PEEK	% CONVENTIONAL MATERIAL	% WEIGHT REDUCTION
WING	69	31	29.5
HOZ TAIL	59	41	22.4
VERT TAIL	63	37	20.4
FUSELAGE	71	29	19.1
LANDING GEAR	27	73	11.4
NACELLE	31	69	21.0

Figure 9. Advanced Material Utilization

The methods for conventional transports have been developed and improved through past design studies. In these studies the sensitivity of the various design parameters have been derived from existing transport design data with extrapolations derived from various analytical studies. One of these design parameters is wing aspect ratio. Wing weight increases as aspect ratio increases while drag decreases. The mission requirements of the vehicle, therefore, influence the size of the optimum aspect ratio. Of course, other factors must be considered in the final selection of wing aspect ratio. Some of these considerations are flutter requirements, wing loading and CLMAX, runway width, fuel capacity, producibility, etc. The present wing weight estimation relationship for transport aircraft is the result of aspect ratio studies conducted during 1984 and it provides higher aspect ratio design synthesis than earlier methods.

The weight estimating methods for LFC peculiar design variables were derived during the Air Force/Lockheed studies (Reference 15, 1982 to 1985). These methods were revised to account for the hybrid LFC concept where LFC is applied to only the wing leading edge. The resulting weight increments are displayed separately in the various weight summaries for ready identification.

Advanced technology weight allowances are programmed in the weight estimation routines in the form of input factors for application to conventional transport weight relationships. The input factors are derived for each study program based upon the advanced design concepts under consideration for the particular vehicle. As previously described, graphite peek composite material is used in this study for basic and secondary structure in the wing, fuselage, tail, landing gear, and nacelle.

Figure 10 illustrates the Group Weight Summary for the Hybrid LFC configuration as produced by the GASP weight logic. On this table, the weight increments for LFC are identified within the Structure, Propulsion, and Fixed Equipment categories. This means that the normal weight categories are estimated from design parameters using conventional transport variations, and then the aircraft weight is modified by the LFC weight increments. The design parameters, however, are influenced by the LFC performance qualities so that LFC benefits must be evaluated from overall aircraft configuration parameters and not from the LFC weight increments alone. The LFC weight increments are derived from aircraft design parameters such as laminarized area, suction coefficients, pressure coefficients, source of air pressure (LFC engines), span of air discharge, and from the surface cleaning provisions and requirements. The fuel requirement of 2578 pounds for the suction pumps is also listed in Section 4.3.5.3 on the suction pump characteristics. The aircraft benefits are derived from lower fuel requirements, due to drag reductions, and its scaling effects on the various weight items are derived from the reduced geometry and gross weight conditions. This type of analysis is handled within GASP through iteration of the aircraft weight quantities as compared with the quantities required for mission performance.

4.3.5 HLFC Systems

4.3.5.1 Surface Design

The suction slot design must provide slots having flow characteristics that are predictable, stable, uniform along the length of the slot, and free from surface flow disturbances. Criteria and limits for slot design were developed to meet these requirements during the X-21 program in the early 1960's by NORAIR and are summarized in Reference 5. Unfortunately, supporting data are not well documented in the literature. When these criteria and limits are applied to the design of slots for the current airfoil requirements, mutually exclusive conflicts exist between the criteria. A strict application of the criteria and limits to define the surface slot configuration results in slot widths and spacings in the leading-edge region that are impractical, if not impossible, to manufacture on a production airplane. For these reasons, it is necessary to accept some compromises in these criteria

ITEM	WEIGHT (POUNDS)		
STRUCTURE			139,985
WING		68,888	
TAIL GROUP (EMPENNAGE)		6,450	
BODY GROUP (FUSELAGE)		42,999	
ALIGHTING GEAR GROUP		16,815	
NACELLE/PYLON		4,099	
SPECIAL ITEMS		734	
LFC WT. INCREMENT - WING	563		
LFC WT. INCREMENT - TAIL	171		
PROPULSION			34,057
PROPULSION GROUP		32,287	
ENGINES	20,282		
FUEL SYSTEM	6,598		
THRUST REVERSERS	3,407		
MISCELLANEOUS	2,000		
SPECIAL ITEMS		1,770	
LFC WT. INCREMENT - LFC ENGINES	536		
LFC WT. INCREMENT - DUCTING, ETC.	1,234		

Figure 10A. Hybrid LFC Design

ITEM	WEIGHT (POUNDS)		
SYSTEMS AND EQUIPMENT			23,598
SURFACE CONTROLS GROUP		4,280	
AUXILIARY POWER PLANT GROUP		842	
INSTRUMENTS & NAV. EQ. GROUP		912	
HYDRAULICS AND PNEU. GROUP		1,995	
ELECTRICAL GROUP		3,423	
ELECTRONICS GROUP (AVIONICS)		2,381	
FURNISHING & EQUIPMENT GROUP		5,850	
AIR COND. & ANTI-ICE GROUP		2,956	
AUXILIARY GEAR GROUP		-	
SPECIAL ITEMS		959	
LFC WT. INCR. - CLEAN SYS.	959		
WEIGHT EMPTY			197,640
OPERATING EQUIPMENT		5,006	
OPERATING WEIGHT			202,646
CARGO		132,500	
ZERO FUEL WEIGHT			335,146
MISSION FUEL		252,216	
LFC - L.E. CLEAN & ANTI-ICING FLUID		4,258	
GROSS WEIGHT			591,620

Figure 10B. Hybrid LFC Design

and limits. However, the lack of sufficient supporting data precludes a sound and confident judgement of these compromises.

For the design criteria discussed in Section 6.3.2.1 of Reference 5 and using Figure 11 in Reference 5, preliminary slot locations for the suction system were achieved. These slot locations are shown in Figure 11 for wing station Y/b=0.832. The chordwise design region for both the upper and lower wing surfaces start at the first slot aft of the leading-edge cleaning/de-icing system region located around X/C=.01. Since this is an HLFC configuration, active suction ends at the front spar (X/C=.15); natural laminar flow is utilized aft of the front spar. Since this is only a preliminary configuration, more analysis will be required for a final design. In the final design, more slots may have to be added at the inboard wing stations, but these slots will not extend across the entire wing.

The partial airfoil section shown in Figure 11 shows the airfoil as a function of X/C. The suction slots are represented by marks internal to the airfoil outline. The slot width and slot spacing were finalized using the design criteria in Section 6.3.2.1 of Reference 5. For manufacturing reasons,

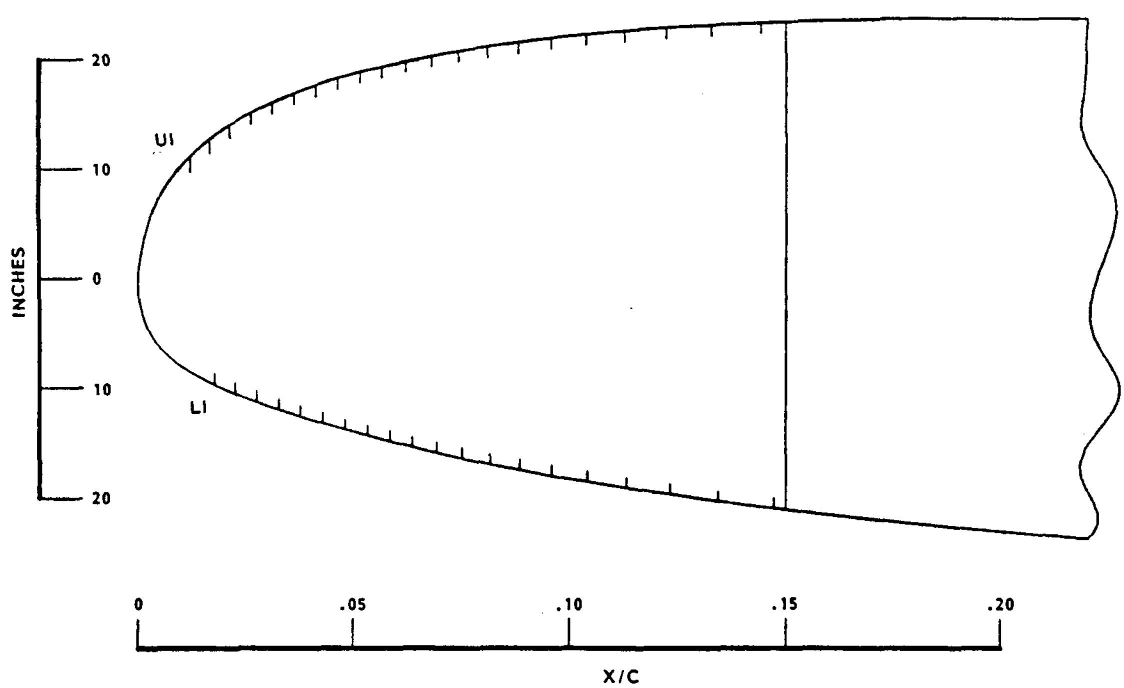

Figure 11. Wing Leading Edge Slot Locations

the distance between slots was kept to a minimum of 0.65 inch. Table 1 shows the geometry and performance of the upper surface of the wing at wing station Y/b=0.488. These calculations were made for the 0.77 Mach number cruise condition at 37,000 feet. The column headings correspond to a slot number (1 being farthest forward), chordwise (X/C) location, slot width (W) in inches, slot spacing (CN) in inches, slot Reynolds number (RW), the ratio of slot width to boundary layer sucked height (W/Z), the ratio of sucked-height velocity to boundary-layer edge velocity (UZ/UE), slot geometry and flow parameter (BETA), and slot pressure loss coefficient (CPS). Similar data were generated for all of the variations in spanwise location and cruise flight variations. The lower surface geometry and performance are similarly illustrated on Figure 10 and listed for the design cruise conditions on Table 2. As is shown, the performance parameters are all within the limits described in Reference 5 for optimum performance.

4.3.5.2 Suction Ducting System

The suction ducting system is composed of a combination of ducts, lines, and valves to meter, collect, and transport the suction flow from each surface slot to the suction pump. This system will provide a suction distribution compatible with boundary layer laminarization over a range of operating conditions representing cruise, climb and descent with emphasis on cruise.

TABLE 1. UPPER SURFACE DESIGN DATA

ALTITUDE = 37,000 FT   MACH = 0.77   CHORD = 16.159 FT

SLOT	X/C	W	CN	W/Z	Uz/Ue	RW	BETA	CPS
U1	0.5590E-02	0.3000E-02	0.3000E+01	0.8062E+00	0.8067E+00	0.1660E+03	0.8030E-01	0.9230E+00
U2	0.8160E-02	0.3000E-02	0.6543E+00	0.1619E+01	0.3608E+00	0.3622E+02	0.3681E+00	0.1438E+00
U3	0.1106E-01	0.3000E-02	0.6535E+00	0.1493E+01	0.3343E+00	0.3533E+02	0.3774E+00	0.1536E+00
U4	0.1413E-01	0.3000E-02	0.6546E+00	0.1369E+01	0.2971E+00	0.3327E+02	0.4008E+00	0.1539E+00
U5	0.1730E-01	0.3000E-02	0.6518E+00	0.1286E+01	0.2651E+00	0.3109E+02	0.4288E+00	0.1476E+00
U6	0.2057E-01	0.3000E-02	0.6525E+00	0.1213E+01	0.2415E+00	0.2998E+02	0.4447E+00	0.1419E+00
U7	0.2385E-01	0.3000E-02	0.6543E+00	0.1122E+01	0.2187E+00	0.2933E+02	0.4546E+00	0.1388E+00
U8	0.2722E-01	0.3000E-02	0.6535E+00	0.1110E+01	0.2084E+00	0.2827E+02	0.4716E+00	0.1329E+00
U9	0.3058E-01	0.3000E-02	0.6515E+00	0.1103E+01	0.1970E+00	0.2690E+02	0.4957E+00	0.1255E+00
U10	0.3395E-01	0.3000E-02	0.6530E+00	0.1093E+01	0.1862E+00	0.2566E+02	0.5196E+00	0.1189E+00
U11	0.3764E-01	0.3000E-02	0.7033E+00	0.1062E+01	0.1836E+00	0.2606E+02	0.5116E+00	0.1208E+00
U12	0.4159E-01	0.3000E-02	0.7529E+00	0.1039E+01	0.1789E+00	0.2597E+02	0.5135E+00	0.1202E+00
U13	0.4581E-01	0.3000E-02	0.8038E+00	0.1019E+01	0.1726E+00	0.2555E+02	0.5218E+00	0.1179E+00
U14	0.5033E-01	0.3000E-02	0.8523E+00	0.9962E+00	0.1665E+00	0.2523E+02	0.5284E+00	0.1161E+00
U15	0.5512E-01	0.3000E-02	0.9032E+00	0.9635E+00	0.1610E+00	0.2524E+02	0.5283E+00	0.1160E+00
U16	0.6018E-01	0.3000E-02	0.9525E+00	0.9383E+00	0.1545E+00	0.2489E+02	0.5356E+00	0.1141E+00
U17	0.6554E-01	0.3000E-02	0.1004E+01	0.9325E+00	0.1484E+00	0.2408E+02	0.5536E+00	0.1097E+00
U18	0.7143E-01	0.3000E-02	0.1103E+01	0.9149E+00	0.1434E+00	0.2374E+02	0.5617E+00	0.1077E+00
U19	0.7787E-01	0.3000E-02	0.1204E+01	0.8999E+00	0.1375E+00	0.2316E+02	0.5758E+00	0.1045E+00
U20	0.8485E-01	0.3000E-02	0.1304E+01	0.8788E+00	0.1319E+00	0.2277E+02	0.5856E+00	0.1025E+00
U21	0.9263E-01	0.3000E-02	0.1453E+01	0.8409E+00	0.1290E+00	0.2329E+02	0.5725E+00	0.1049E+00

TABLE 2. LOWER SURFACE DESIGN DATA

ALTITUDE = 37,000 FT   MACH = 0.77   CHORD = 16.159 FT

SLOT	X/C	W	CN	W/Z	Uz/Ue	RW	BETA	CPS
L1	0.1001E-01	0.3000E-02	0.1938E+01	0.9045E+00	0.5776E+00	0.9759E+02	0.1366E+00	0.3447E+00
L2	0.1296E-01	0.3000E-02	0.6515E+00	0.1536E+01	0.3086E+00	0.3182E+02	0.4190E+00	0.8923E-01
L3	0.1614E-01	0.3000E-02	0.6537E+00	0.1478E+01	0.2792E+00	0.3042E+02	0.4383E+00	0.8726E-01
L4	0.1937E-01	0.3000E-02	0.6549E+00	0.1413E+01	0.2553E+00	0.2942E+02	0.4532E+00	0.8617E-01
L5	0.2272E-01	0.3000E-02	0.6527E+00	0.1371E+01	0.2372E+00	0.2829E+02	0.4713E+00	0.8334E-01
L6	0.2607E-01	0.3000E-02	0.6527E+00	0.1323E+01	0.2197E+00	0.2726E+02	0.4891E+00	0.8083E-01
L7	0.2948E-01	0.3000E-02	0.6528E+00	0.1292E+01	0.2063E+00	0.2623E+02	0.5083E+00	0.7787E-01
L8	0.3290E-01	0.3000E-02	0.6511E+00	0.1269E+01	0.1939E+00	0.2514E+02	0.5304E+00	0.7454E-01
L9	0.3633E-01	0.3000E-02	0.6530E+00	0.1239E+01	0.1820E+00	0.2418E+02	0.5514E+00	0.7167E-01
L10	0.3980E-01	0.3000E-02	0.6538E+00	0.1236E+01	0.1740E+00	0.2319E+02	0.5749E+00	0.6857E-01
L11	0.4354E-01	0.3000E-02	0.7036E+00	0.1192E+01	0.1723E+00	0.2383E+02	0.5595E+00	0.7088E-01
L12	0.4754E-01	0.3000E-02	0.7525E+00	0.1153E+01	0.1692E+00	0.2420E+02	0.5510E+00	0.7230E-01
L13	0.5183E-01	0.3000E-02	0.8018E+00	0.1121E+01	0.1650E+00	0.2431E+02	0.5486E+00	0.7281E-01
L14	0.5640E-01	0.3000E-02	0.8532E+00	0.1091E+01	0.1598E+00	0.2417E+02	0.5516E+00	0.7251E-01
L15	0.6124E-01	0.3000E-02	0.9035E+00	0.1067E+01	0.1531E+00	0.2369E+02	0.5629E+00	0.7107E-01
L16	0.6663E-01	0.3000E-02	0.1003E+01	0.1035E+01	0.1504E+00	0.2401E+02	0.5554E+00	0.7227E-01
L17	0.7256E-01	0.3000E-02	0.1103E+01	0.1015E+01	0.1451E+00	0.2363E+02	0.5643E+00	0.7116E-01
L18	0.7931E-01	0.3000E-02	0.1254E+01	0.9787E+00	0.1413E+00	0.2387E+02	0.5586E+00	0.7212E-01
L19	0.8686E-01	0.3000E-02	0.1401E+01	0.9400E+00	0.1366E+00	0.2403E+02	0.5548E+00	0.7279E-01
L20	0.9550E-01	0.3000E-02	0.1604E+01	0.8860E+00	0.1362E+00	0.2543E+02	0.5244E+00	0.7771E-01

Individual slot flows will be adjustable from the cockpit, enabling chordwise suction distribution to be varied in flight. This section will only deal with the suction system in the wing; the suction pump will be discussed in Section 6.4.

Ducting Concept - The ducting system for the baseline aircraft evolved over time based on both LFC system requirements and structural considerations. The resulting system concept is compatible with both disciplines and has relatively few compromises to either discipline.

A typical cross-section of an individual slot is shown in Figure 12. The slot design and fabrication are based on the Task 1 development efforts described in Reference 14. Air is drawn through the slot into the slot duct, through the metering holes into the collector duct, through the collector duct orifice into the suction tube, and from the suction tube through a needle valve into one of two main plenum ducts. There are two plenum ducts extending the length of the wing span: a high-pressure duct for the lower surface, and a low-pressure duct for the upper surface. These ducts lead to the suction pump, which is discussed in Section 4.3.5.3. The schematic of the entire suction system is shown in Figure 13. Dimensions of the slots and metering holes must be selected to provide as uniform suction flow as possible to all slots with low pressure losses. The needle valves will be used to maintain

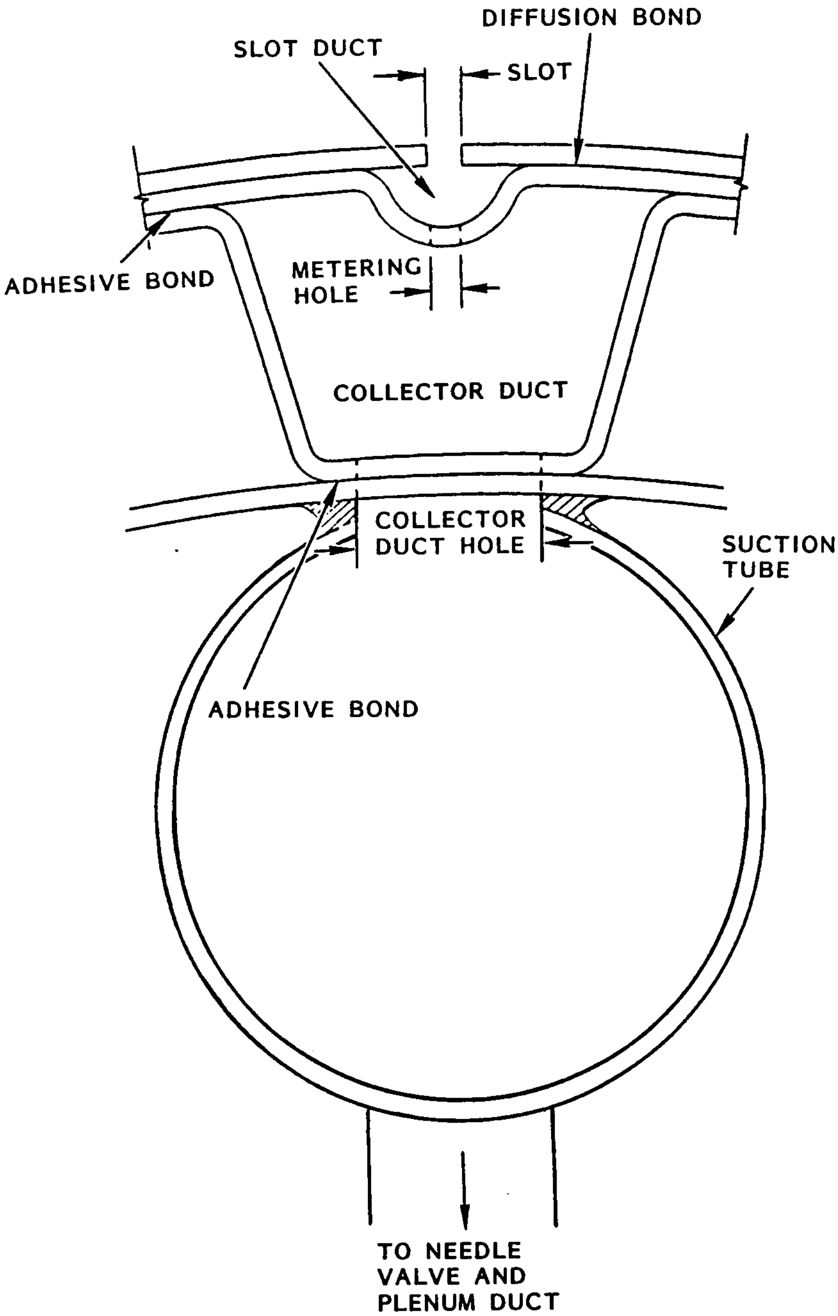

Figure 12. Slot and Ducting Cross Section

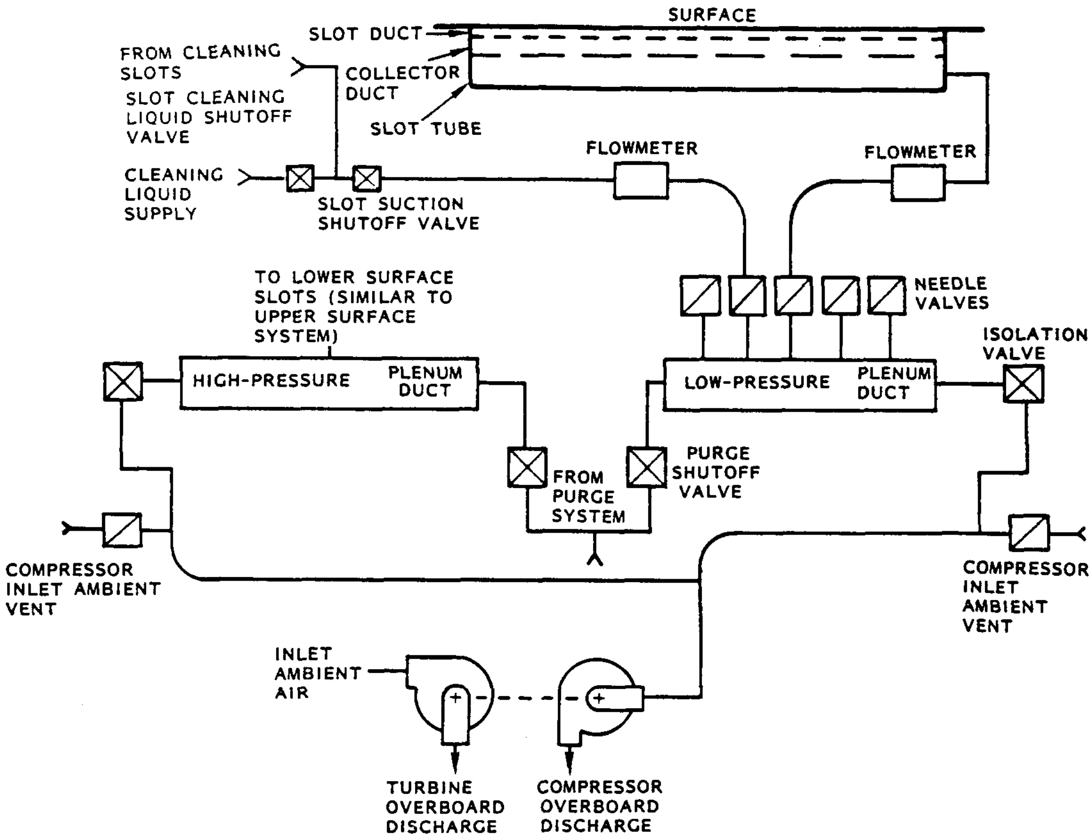

Figure 13. Suction System Schematic

the proper discharge environment for the upstream slot metering holes and provide proper flow metering downstream to match the local pressures within the plenum ducts.

To provide the cleaning and anti-icing capability, two slots have been added on the upper surface forward of the first suction slot solely dedicated to emitting the cleaning/de-icing fluid. On the lower surface, the first five slots have the capability both for cleaning and suction. At low altitudes these seven slots emit the cleaning/de-icing fluid to keep the slots open and the wing surface clean. Upon reaching a certain altitude, the cleaning system will be turned off and high-pressure air from the aircraft's environmental control system will be directed through the cleaning/suction slot geometries. This airflow will remove the cleaning fluid from the slot ducting surfaces to prevent damage to the valves and instrumentation. The cleaning system is discussed in more detail in Section 4.3.5.5.

Ducting Design - The leading-edge metering system configuration has already been illustrated in Figure 12. Table 3 shows typical slot and metering geometry dimensions used in the performance calculations for this particular study. These dimensions were arrived at through the parameter guidelines discussed in Section 6.3.2.1 of Reference 5 and also in Reference 18. However, there are indications that the very low Reynolds number characteristics of the leading-edge slots, together with a very favorable ratio of metering hole spacing to slot duct depth permits some relaxation of the criteria without any penalties to performance.

After entering the slot, flow passes through metering orifices which lead to a collector duct. The flow from these ducts is metered into a suction tube. The spacing of the holes exiting the collector duct is primarily dictated by the requirement to maintain a uniform pressure along the collector duct. The diameters of the metering holes are primarily determined by the requirement to control the pressure within the collector duct to a predetermined level, while matching the required flow to the local pressures within the appropriate suction tube.

Connecting the suction tube to one of the two plenum ducts are a series of lines across the span of the wing, each containing a cockpit-controlled needle valve. This configuration provides in-flight capability for chordwise and spanwise suction flow profile adjustment. This valve is the last metering of the flow before the flow reaches the plenum duct, which has no metering devices, so it is very critical to set the needle valves correctly. Ideally

TABLE 3. LEADING EDGE METERING SYSTEM

TYPICAL NOMINAL DIMENSIONS						
SURFACE	x/c	PLENUM DUCT	SLOT DUCT METERING		COLLECTOR DUCT METERING	
			SPACING (IN)	DIAM (IN)	SPACING (IN)	DIAM (IN)
UPPER	0.017	HP	0.500	0.053	2.000	0.075
	0.046	HP	0.500	0.072	2.000	0.095
	0.100	HP	0.500	0.087	2.000	0.113
LOWER	0.019	LP	0.500	0.056	2.000	0.048
	0.052	LP	0.500	0.076	2.000	0.064
	0.087	LP	0.500	0.091	2.000	0.095

the flow from all the slots will pass through the needle valves and enter the plenum duct at the correct pressure to ensure even flow to the suction pump. Instrumentation will measure the flow through each needle valve, and these instruments will help ensure that neither too much or too little suction is applied. If too much suction is applied, the boundary layer will become too thin with a corresponding loss of performance because of the increased sensitivity of the boundary layer to given surface imperfections that will result in increased external drag on transition. If too little suction is applied, air could enter the slot at one point, travel spanwise, and exit the same slot, tripping the boundary layer.

4.3.5.3 Suction Units

The suction system for the baseline configuration incorporates two interchangeable fuselage-mounted suction units, each powered by an independent gas turbine power unit. Each unit includes flow and pressure ratio capacity sufficient to pump half of the flow from each surface and discharge the total pumped flow at the freestream flight velocity of Mach 0.77 at 37,000 ft altitude. Since the various laminarized surfaces have different surface pressures, it is necessary to design the suction pump to accommodate the various levels of inlet pressure while discharging all of the flow at the same pressure level.

Suction Requirements - The suction requirements and external aerodynamics of the wing airfoil are consistent with the baseline airfoil developed for this aircraft. These include wing surface C_p distribution, distributed suction requirements, and boundary layer characteristics for both the upper and lower surfaces.

The laminarized surfaces are as follows:

Wing upper	2126 ft^2
Wing lower	2074 ft^2
*Horizontal tail - each surface	383 ft^2
*Vertical tail - total	675 ft^2

A laminarized surface is the total area over which laminar boundary-layer flow exists, and consists of the slotted surface forward of the front spar and the area aft of the front spar to where the boundary layer becomes turbulent. The laminarized wing areas are the total for the airplane and include adjustments for 50 percent nominal chord laminarization and airfoil surface curvature. The (*) figures are measurements for the empennage. There will be no active suction in the empennage on the revised HLFC baseline configuration, but the capability exists if a performance benefit study warrants its addition.

Suction Pump Characteristics - The most practical suction pump configuration for meeting the suction requirements of the baseline aircraft is a compact axial flow compressor which incorporates a high-pressure compressor pumping the total flow with additional lower flow boost units integrally located on the inlet to raise the pressure of the low-pressure flows to the inlet pressure of the high-pressure compressor.

A rudimentary suction unit design was completed for the purpose of establishing conceptual size, weight, and general layout of the suction unit. While this analysis obviously lacks the refinements of an optimized design, it is reasonably accurate for satisfying the present requirements and serves to illustrate some of the required considerations. The suction pump for this unit is shown in Figure 14, which illustrates the unit partially sectioned. The suction pump consists of a forward frame, a two-stage low-pressure or boost element, a mid-frame, a four-stage high-pressure element, and a scroll diffusor. The forward frame serves as the attachment for the aircraft suction system low-pressure duct and houses boost element variable inlet guide vanes. These vanes provide a control for matching the boost element flow conditions under varying flight suction requirements. The two-stage boost element is sized to meet upper wing and empennage suction flow and pressure ratio requirements. The two stages operate at a modest pressure ratio compatible with the distorted inlet conditions that will undoubtedly exist with the suction flow. The mid-frame serves as the transition duct for the boost element exhaust flow to the inlet of the high pressure element. It also provides the introduction of the high-pressure suction flow into the high-pressure compressor. Variable inlet guide vanes are required in the high-pressure suction flow into the high-pressure compressor. Variable inlet guide vanes are required in the high-pressure suction flow entry path for operation in conjunction with the boost element variable inlet guide vanes to assure a proper match between the boost and high-pressure elements.

The high-pressure element is a four-stage unit of moderate stage loading. A three-stage unit would require stage loadings that are high but consistent with foreseeable practice for conventional engine compressors. However, the anticipated inlet distortions and mismatch to which this unit will be subjected dictate the use of a more conservative four-stage configuration. Both the boost and high-pressure elements operate on a common shaft.

The exhaust diffuser collects the discharge flow of the suction pump and turns it through 90°, while reducing the flow velocity to 0.3 Mach and allowing the passage of the suction pump drive shaft axially through the center of the scroll. The flow thus exits the scroll in a round duct at a right angle to the axis of the suction pump. The diffusor/scroll also provides for a

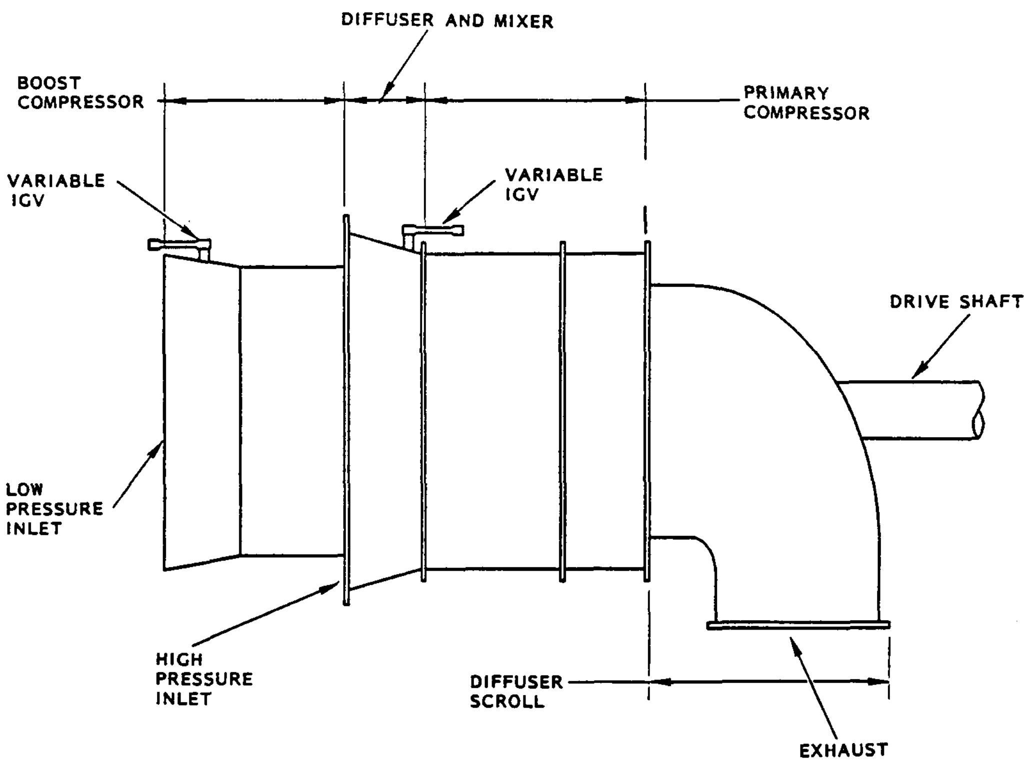

Figure 14. Suction Pump

rigid mounting between the suction pump and drive unit. This includes a mounting for the drive shaft housing as well as an external truss structure to maintain shaft alignment and absorption of the torque between the suction pump and the power unit.

The suction pumps are driven by independent power units provided with ram inlets exhausting at essentially freestream velocity. The independent drive was adopted because it has no impact on the primary propulsion units and can therefore be independently sized. In previous studies, alternative systems were considered and include geared, bleed, and bleed/burn systems. The penalties of the more complex systems led to their elimination. A conventional but advanced technology shaft engine was adopted for this study. The total suction unit weight was evaluated at 536 lb; this figure includes both the suction pump and the power unit.

The performance characteristics of the suction pump for the baseline HLFC transport are provided in the following:

Power at cruise altitude	200 H.P.
Mass flow at cruise altitude	300 Lb/Min
Pump speed	50,000 RPM
Pump pressure ratio	4.0
Pump inlet pressure	4.1 psia
Pump inlet temperature	460^{o} R
Cruise altitude	31,685 ft
Mission fuel	2577.8 Lb

Two suction pumps are required for each HLFC transport.

4.3.5.4 Controls

Control of the LFC suction system presents a number of complex and unique problems. The required suction flow levels and distributions for reliable laminarization are subject to the effects of production tolerance and deterioration, in addition to the variable flight conditions. The needle valves and excess capacity of the suction pump are required to negate the effects of production tolerances and deterioration, as well as the limited variations in flight conditions. It is apparent that sufficient range is not likely to exist to absorb all of these influences over the entire flight spectrum and a control system to accommodate these variables would become extremely complex. In the interest of simplifying the control system, thereby improving the reliability and reducing the cost and maintenance, active suction is applied only during the cruise portion of the mission and at higher altitudes during climb and descent. This approach will allow the cleaning/de-icing system to function on the ground and at lower altitudes, in order to eliminate the contamination incurred during operation in those conditions and prevent damage to the suction system.

With this approach, the major control of the suction flow becomes that of optimizing the suction requirements between start cruise and end cruise. An appreciable change in both level and distribution of wing surface C_p values occurs between these conditions, particularly in the differentials between the upper and lower surfaces. The internal suction system pressures are dictated by these C_p values. The suction pump uses variable inlet guide vanes in both the low pressure and high pressure inlets. These vanes adjust the duct suction pressures to the varying upper and lower wing surface C_p values while maintaining desired suction flows and an acceptable match between the primary and boost elements of the suction pump.

However, this does not provide discrete control to accommodate the change in the chordwise C_p distributions. The suction system is designed to minimize sensitivity to this change through correct selection of metering holes and their spacing. To further ensure that laminar flow is maintained throughout changing conditions, variable needle valves are installed in the lines between the suction tubes and the main plenum ducts. These valves are controlled from the cockpit, and instrumentation will be present to display the amount of suction flow through each slot and the spanwise slot flow distribution. An automatic control system will monitor the suction flow and alter the needle valves as required to maintain prescribed suction levels.

The remaining control problems are primarily operational in nature and consist of:

(1) Suction unit starting at both sea level static and altitude.

(2) Unit failure in cruise.

(3) Atmospheric conditions at cruise.

(4) Sea level static system checkout.

Starting the units at altitude will present some problems because the pressures at the suction pump inlet are appreciably below ambient. In the shutdown condition, a significant pressure ratio exists across the suction pump. This pressure ratio exceeds the capabilities of the suction pump until rotational speeds near design are achieved. This means that the suction pump would be stalled throughout the start range until near design speeds are attained during the start up. This is unacceptable due to power requirements and potential damage to the pump. To avoid this problem, valves are provided in the ducting system near the pump inlets to isolate the suction ducting and vent the pump inlet to ambient air during the start cycle, as shown on Figure 15. When the suction unit reaches a prescribed rotor speed, the vent valve will slowly close while the isolation valve slowly opens according to a prescribed schedule. This operation may be carried out either by an automatic system operated by a "start-run" switch or manually by the flight engineer.

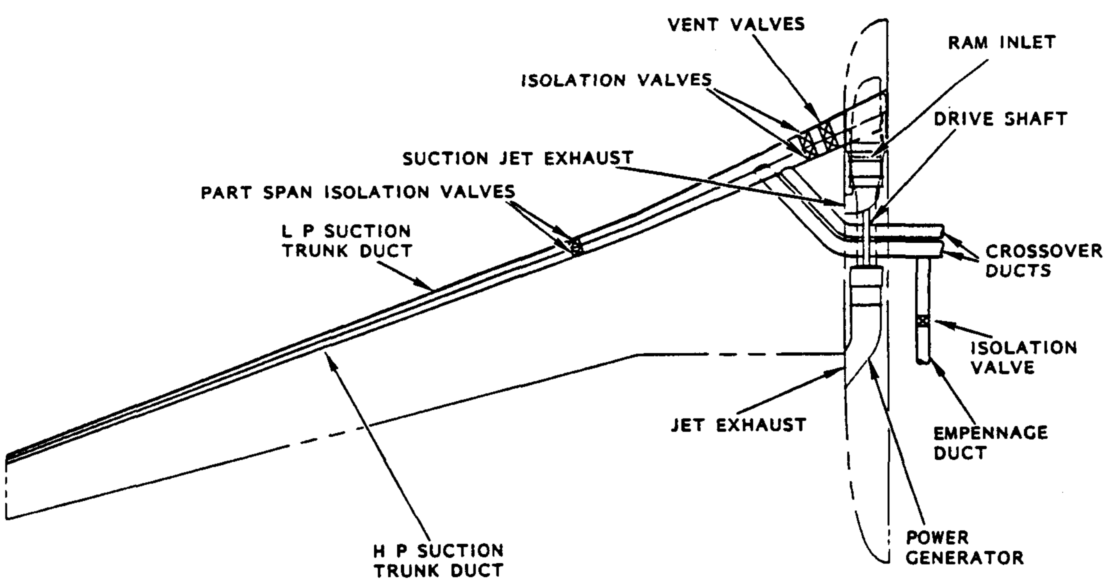

Figure 15. Wing Suction System Schematic

In the event of an inflight suction unit failure, instrumentation at the suction pump inlet and discharge will immediately sense the failure and shut the unit down while simultaneously closing the isolation valves to that unit. After the isolation valves have closed, the valves located in the low- and high-pressure suction plenum ducts near the wing mid-semispan, shown in Figure 14, will also close, allowing only inboard wing suction.

In Figure 15, there is an allowance for ducting back to the empennage. This figure includes the empennage duct to show how it would tie into the ducting network. In the empennage itself, the suction systems would be very similar to those in the wings. In the event of an inflight suction unit failure (the situation mentioned above), the empennage valve will close simultaneously, eliminating empennage suction.

In the event of slot blockage, such as the incidence of rain and ice crystals in the cruise mode and subsequent failure of the slot cleaning/de-icing system, immediate shutdown of the suction system would be required to prevent pump stall as a result of airflow starvation. This would be accomplished through sensing an abrupt increase in pump pressure ratio, signaling interference with the suction flow ingestion, and automatically shutting the system down. Provision could be made for automatic re-start, or re-start could be the responsibility of the flight engineer. An incremental increase in primary propulsion engine thrust could be automatically accomplished to compensate for the temporary delaminarization.

A pre-flight suction system checkout must be accomplished at sea level static conditions prior to initiation of the flight. This may be accomplished by the flight engineer and would consist of a normal start with the suction unit rotor speed limited to a low value to minimize ingestion of contaminants to the suction system and prevent excessive noise in the terminal area. This start would duplicate the cruise start and valving sequence except for the reduced rotor speed. Since all wing surface C_p values are zero under static conditions, the high rotor speeds are not required. When the suction unit reaches the prescribed speed, suction system pressures and flows, pump pressure ratio, and pump and power unit operational parameters (i.e., oil pressure, turbine temperature, fuel flow, etc.) may be compared to prescribed limits. An adverse atmospheric condition would be simulated by a signal selected by the flight engineer to actuate the automatic shut-down sequence. It is expected that this ground check may be normally accomplished in a total time of less than 4 minutes.

4.3.5.5 Leading Edge Region Cleaning

Since the earliest consideration of applying laminar flow control to an operational aircraft, the potential problems attending leading-edge roughness due to insect contamination and ice accumulation have been a continuing concern. The insect alleviation and anti-icing systems designed for this LFC aircraft will provide protection from wing-surface slot contamination due to insects at low altitudes and a method of de-icing the leading edge at all altitudes of operation. The cleaning/de-icing systems will emit a fluid through the wing-surface slots which will clean the wing surface and prevent icing, and then purge the system of this liquid so that suction may be safely started. The flow of this fluid will be controlled and monitored from the cockpit.

Cleaning/De-Icing System - The cleaning/de-icing system, Figure 16, will use selected slots around the leading edge to discharge a small flow of liquid onto the surface. This liquid forms a protective film over the surface to prevent insect accretion and prevent/remove ice buildup. The design requirements for this liquid flow have been demonstrated to provide a liquid film sufficient to prevent accretion in a high-density insect environment. The liquid used is a 60 percent propylene glycolmethyl ether, PGME/40 percent water mixture. All components used in the system will be suitable for use with the PGME liquid, and all components containing the PGME liquid mixture will be located in a well-ventilated area with sufficient drainage provision to prevent entrapment of any liquid leakage. The system will be designed to prevent a flammable mixture of PGME and air from forming in the vicinity of any ignition source in the event of any system leaks.

The cleaning/de-icing system, illustrated schematically in Figure 15 interfaces with the suction system, the purge system, and the nitrogen pressurization system. The major components of the system are the liquid

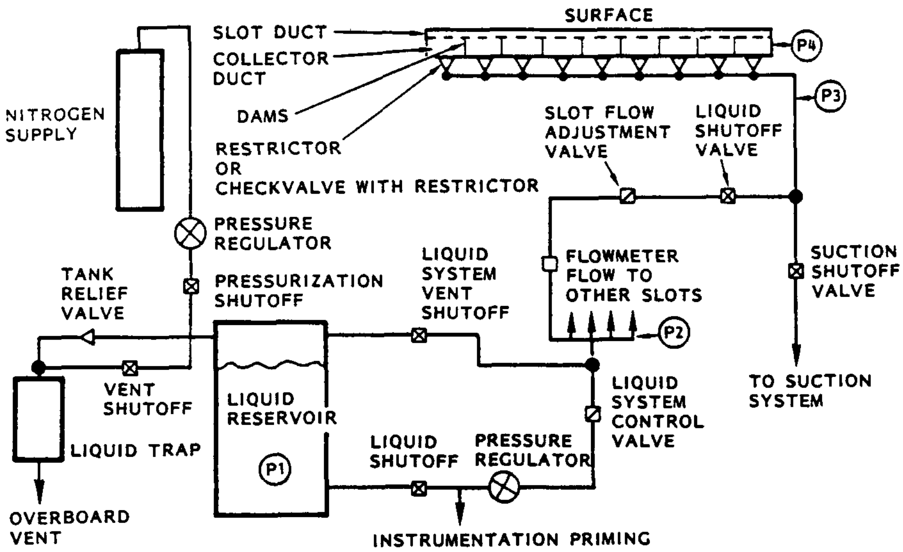

Figure 16. Cleaning/Anti-Icing System

supply tank and the fluid distribution system. This system will deliver the PGME mixture through the six 3-way valves at the interface with the suction system to the seven cleaning/anti-icing slots. These slots (two dedicated cleaning slots and five dual-purpose slots) will be located near the leading edge. Liquid flow control will be provided by adjustment of the supply tank nitrogen pressurization system pressure. Flow distribution will be regulated by adjustable throttling valves located upstream of each 3-way valve.

The supply tanks will be installed so that liquid is supplied from the bottom of the tank through the single port located near one end of the tank. The two-port connector at the other end of the tank will provide for pressurization/venting and for liquid return/servicing overflow as illustrated in Figure 16. The cleaning/anti-icing system will interface with the nitrogen pressurization system upstream of the pressure regulator. This nitrogen pressure regulator will be controlled from the cockpit and will connect to the nitrogen pressurization shutoff valve. Downstream of the shutoff valve, the vent/pressurization line will connect to an overboard vent through parallel lines.

A port on the tank connects through the liquid shutoff valve and filter to the flowmeter. The line between the liquid filter and flowmeter is connected to the remaining port near the top of the supply tank through a fluid return line containing the liquid vent shutoff valve. A tank fill and drain line tees into the fluid supply line between the tank outlet and the liquid shutoff valve. This line provides for servicing of the tank with the PGME/water solution for tank draining, and contains a manual shutoff valve. The fluid return line likewise connects through a tee to a manual shutoff valve to provide an overflow for tank servicing. This connection is made between the liquid vent shutoff valve and the tank. For both manual shutoff valves described above, provision is made for draining PGME fluid clear of the aircraft. Liquid is plumbed from the flowmeter to a manifold plenum located in the wing leading edge area. The manifold is provided with ports for connecting six slot cleaning lines. These six slot lines are routed from the manifold to liquid flow adjustment valves also located in the wing root area. Each valve is connected to corresponding slot suction line at the 3-way suction/cleaning selection valve located in the wing root. The 3-way valves provide a mechanical interlock to avoid inadvertent delivery of cleaning liquid to the needle valves. All valves are remotely controlled from the cockpit.

Purge System - The air purge system (Figure 17) will be designed to remove liquid from the cleaning/anti-icing ducting and to clear all slots of liquid before the initiation of suction. This is necessary to prevent contamination of the suction system with residual cleaning liquid. Due to the numerous points in the system where liquid may be entrapped, the system is designed so the cleaning/anti-icing system may be vented to draw as much liquid as possible back into the tanks and then purge the residual liquid out through the slots. This system interfaces with the suction and cleaning/anti-icing systems.

The remotely operated valves in this system are controlled from the aircraft cockpit. Electrical control interconnections are made to prevent either the suction or the purge valve from being energized to the open position unless the other valve is fully closed.

A high-pressure gaseous nitrogen supply is used to provide pressurization for the liquid reservoirs of the cleaning/de-icing systems, and instrumenta-

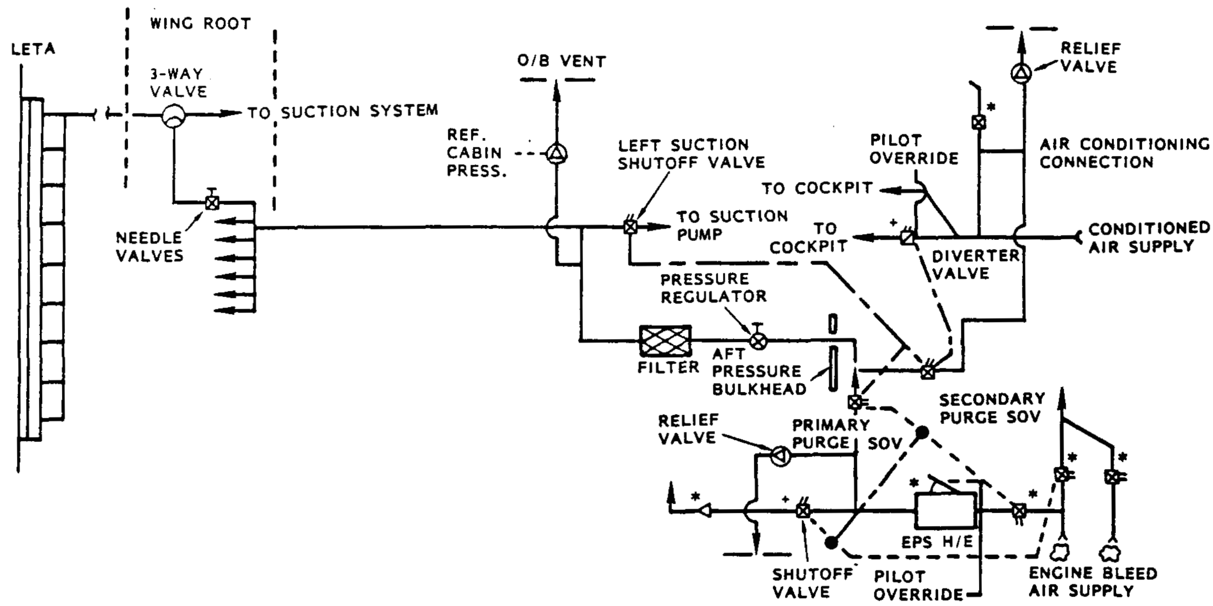

Figure 17. Purge System Schematic

tion purge. The system also provides pneumatic operation of the purge system shutoff valves and pressure regulator. The nitrogen source provides nitrogen at a regulated pressure of about 350 psig. The system configuration is shown schematically in figure 18. To provide protection from excessive regulated pressure, a line is teed into the nitrogen line downstream of the pressurization shutoff valve and connects to an overboard vent through a pressure relief valve.

4.3.6 Aircraft Systems

The normal aircraft systems presumed to be used in the study aircraft are those generally accepted by industry as being viable candidates for improvement or upgrading during the next decade. Examples of such improvement may be further miniaturization of electronic systems, higher pressure hydraulic systems to reduce hydraulic actuator sizes, and the major changes involving fly-by-wire flight control systems incorporating active controls.

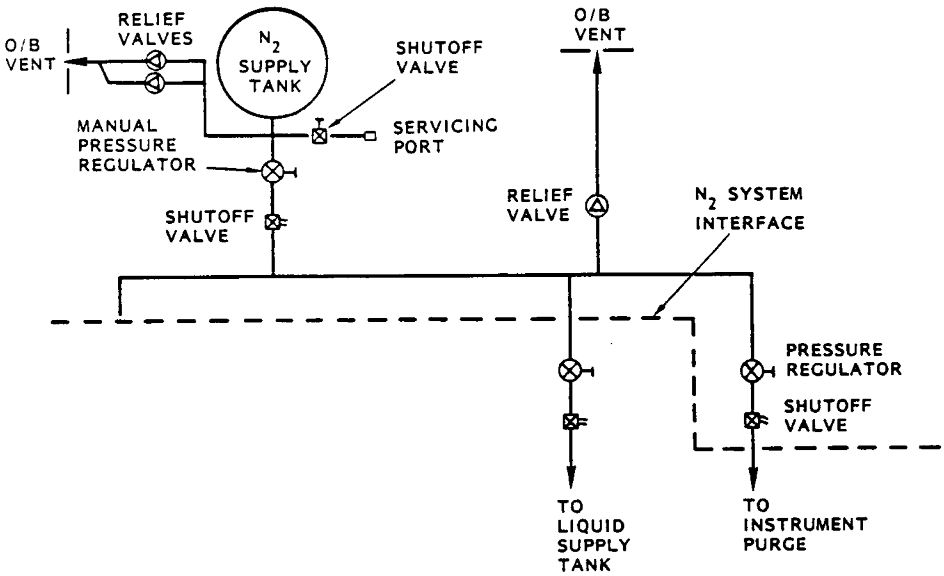

Figure 18. Nitrogen Pressurization System

5.0 BASELINE CONFIGURATION DEVELOPMENT

The plan developed for the realization of contract objectives requires the development of study baseline aircraft to be used as vehicles for the evaluation of alternative LFC system concepts during subsequent study phases. This section summarizes the analyses conducted in the process of developing the baseline configurations. The baseline configurations consist of advanced technology turbulent flow aircraft, as well as hybrid LFC aircraft, all sized to perform the mission characteristics described in Section 4.2. As mentioned previously, the Lockheed GASP computer program has been used to size and define all aircraft in this study.

5.1 TURBULENT FLOW AIRCRAFT SELECTION

Parametric data for turbulent flow aircraft are presented in Figure 19 for wing sweep angles varying from 25° to 40° and at a cruise Mach number of 0.77. The data in Figure 19 summarize the output of the GASP and include mission characteristics; weights; wing data; miscellaneous data such as lift-to-drag ratio, engine thrust, and HLFC data when appropriate. These data are arranged in columns starting with a reference configuration with wing sweep of 25° followed by Options 1 through 3 for wing sweep angles of 30°, 35°, and 40°, respectively. In columns D-1 through D-3 the percentage change in each aircraft design parameter as compared to that for the reference configuration is displayed.

Parametric data for turbulent flow aircraft presented in Figure 19 show a slight superiority of the Option 1, 30° sweep configuration based on an overall comparison of minimum fuel burned, maximum lift-to-drag ratio, L/D, and minimum gross weight. Accordingly, the Option 1 configuration was selected as the baseline turbulent flow aircraft. A general arrangement drawing is presented in Figure 20 with a listing of pertinent design and aerodynamic parameters. These parameters include a take off gross weight of 616,125 lbs, lift to drag ratio of 26, thrust per engine of 30,195 lbs, a wing aspect ratio of 13.54, wing span of 255.9 feet, and a critical field length of 7,558 feet.

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TURBULENT BASELINE SWEEP (25, 30, 35, & 40 DEGREES) STUDY

COMPARISON - PERCENT CHANGE FROM BASELINE

	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
PAYLOAD - LB	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
RANGE OF RADIUS - NM	6,500.00	6,500.00	6,500.00	6,500.00	0.00	0.00	0.00
SPEED - M	0.77	0.77	0.77	0.77	0.00	0.00	0.00
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	30,681.00	32,119.00	32,005.00	31,960.00	4.68	4.31	4.16
CFL - FT	6,803.00	7,557.50	8,310.00	9,148.00	11.09	22.15	34.47
MID-POINT CFL - FT	5,423.00	5,516.00	5,627.00	5,783.00	1.71	3.76	6.63
GROSS WEIGHT - LB	624,106.00	616,125.00	614,534.00	617,780.00	-1.27	-1.53	-1.01
STRUCTURAL WEIGHT	131,099.00	128,023.00	125,825.00	126,262.00	-2.34	-4.02	-3.68
PROPULSION SYSTEM	36,070.00	35,625.00	35,759.00	36,070.00	-1.23	-0.86	0.00
SYSTEMS & EQUIP.	23,345.00	23,253.00	23,249.00	23,336.00	-0.39	-0.41	-0.03
OPERATING EQUIP.	5,352.00	5,317.00	5,325.00	5,342.00	-0.65	-0.50	-0.18
OPERATING WEIGHT	195,866.00	192,218.00	190,158.00	191,010.00	-1.86	-2.91	-2.47
ZERO FUEL WEIGHT	328,366.00	324,718.00	322,658.00	323,510.00	-1.11	-1.73	-1.47
L.F. CLEAN FLUID	0.00	0.00	0.00	0.00			
FUEL	295,729.00	291,401.00	291,869.00	294,266.00	-1.46	-1.30	-0.49
PAYLOAD	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
USEFUL LOAD	428,229.00	423,901.00	424,369.00	426,766.00	-1.01	-0.90	-0.34
WING DATA							
AREA - SQ FT	5,136.08	4,835.39	4,478.44	4,479.50	-5.85	-12.86	-12.78
WEIGHT - LB	61,521.00	58,978.00	56,930.00	57,287.00	-4.13	-7.46	-6.88
WEIGHT - LB/SQ FT	11.97	12.19	12.71	12.78	1.82	6.12	6.76
ASPECT RATIO	13.03	13.54	13.67	13.78	3.91	4.91	5.75
BASIC SWEEP - DEG	25.00	30.00	35.00	40.00	20.00	40.00	60.00
MAT SWEEP - DEG	31.32	35.53	39.88	44.23	13.44	27.34	41.21
LOADING - LB/SQ FT	118.66	124.42	130.01	134.66	4.85	9.56	13.48
FUEL VOL. RATIO	1.00	1.00	1.00	1.00	0.00	0.00	0.00
SPAN - FT	258.68	255.91	251.24	248.41	-1.07	-2.87	-3.97
C.F LB/SPAN FT	0.00	0.00	0.00	0.00	ERR	ERR	ERR
MAC - FT	24.04	22.88	22.24	21.83	-4.82	-7.46	-9.19
t/c - %	12.26	13.49	14.62	15.48	10.03	19.24	26.26
MISCELLANEOUS							
L/D	25.97	25.99	25.77	25.62	0.07	-0.77	-1.34
ML/D	19.99	20.01	19.84	19.72	0.07	-0.77	-1.34
CRUISE SFC	0.56	0.56	0.56	0.56	0.00	0.00	0.00
CL MAX T.O.	2.73	2.60	2.46	2.30	-4.76	-9.89	-15.75
CRUISE CL	0.50	0.52	0.54	0.56	4.36	8.53	12.10
THRUST/ENGINE - LB	30,681.00	30,195.00	30,289.00	30,599.00	-1.58	-1.27	-0.26
THRUST/WEIGHT	0.19	0.19	0.19	0.19	-0.30	0.26	0.75
VERT AREA - SQ FT	473.23	439.52	407.00	374.13	-7.12	-13.99	-20.94
HORIZ AREA - SQ FT	426.12	418.84	429.56	442.07	-1.70	0.80	3.74

Figure 19A. Turbulent Baseline Parametric Data; M=0.77

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	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.88	0.88	0.88	0.88	-0.11	-0.11	-0.22
BASIC WING AREA	4,375.96	4,119.77	3,932.24	3,816.55	-5.85	-10.13	-12.78
TOTAL WING AREA	5,136.08	4,835.39	4,615.29	4,479.50	-5.85	-10.13	-12.78
BAT AREA - % TOTAL	14.79	14.79	14.79	14.79	0.00	0.00	0.00
TOTAL/BASIC	1.17	1.17	1.17	1.17	0.00	0.00	0.00
L.E. SUCTION - % C							
L.F.TRANSITION - % C							
ENG LOC - % MAC							
FUSELAGE WT/SQ FT	4.06	4.05	4.05	4.05	-0.24	-0.24	-0.24
WING WT. EQUATION	13.00	13.00	13.00	13.00			

NOTES:

1. REFERENCE = TURBULENT AIRCRAFT, 25 BASIC SWEEP
2. OPTION 1 = TURBULENT AIRCRAFT, 30 BASIC SWEEP
3. OPTION 2 = TURBULENT AIRCRAFT, 35 BASIC SWEEP
4. OPTION 3 = TURBULENT AIRCRAFT, 40 BASIC SWEEP

Figure 19B. Concluded

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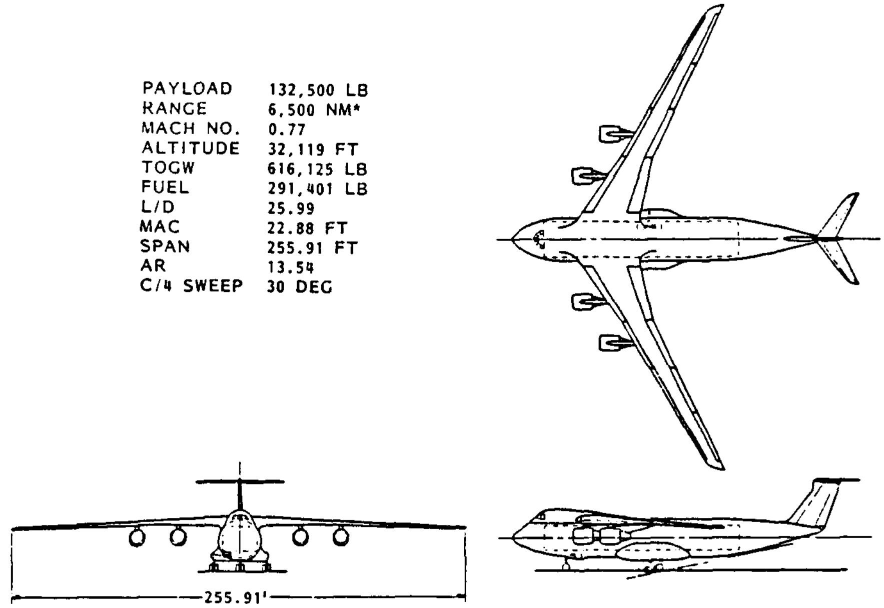
PAYLOAD	132,500 LB
RANGE	6,500 NM*
MACH NO.	0.77
ALTITUDE	32,119 FT
TOGW	616,125 LB
FUEL	291,401 LB
L/D	25.99
MAC	22.88 FT
SPAN	255.91 FT
AR	13.54
C/4 SWEEP	30 DEG



*SEE FIGURE 3

Figure 20. Turbulent Flow Baseline Design Concept

Other features of the aircraft include nose loading capability only, landing gear flotation for hard surface runways, full span wing fuel tanks, no leading edge high lift devices, 25 percent chord trailing edge flaps, accommodations for 3 pilots, one loadmaster, and two bunks for the long range mission.

5.2 HLFC GROUNDRULES

The ground rules for the conduct of the 21 parametric sizing studies for hybrid LFC aircraft are listed in figure 21 for the baseline configurations. Highlights of these groundrules include provisions for active suction on the wing and empennage from the leading edge to 15 percent of the chord and activation of the HLFC system only at initial cruise altitude. Turbulent flow is assumed to occur during 6 percent of cruise flight time to assure mission completion should atmospheric conditions preclude the use of HLFC for short periods during cruise. The 12 percent excess cruise thrust provides the capability to maintain cruise altitude and/or speed with the HLFC system inactive. A low wing, aft fuselage mounted engine configuration similar to that of the TAFAD study constitutes the baseline aircraft. Included in the sizing program is a limiting transition Reynolds number based on the distance from the wing leading edge to the desired percent chord for laminar flow. This function prevents unrealistic parametric optimizations of HLFC configurations in the sizing process.

5.3 HLFC AIRCRAFT SELECTION

Initial parametric sizing data for the HLFC aircraft are presented in Figure 22 in the same general format as that for the turbulent flow aircraft in Figure 19 but with the addition of HLFC peculiar data. These HLFC peculiar data include weight of the leading edge cleaning fluid (Figure 22A), chordwise extent of leading edge suction, chordwise location of transition point from laminar to turbulent flow, and all other system weight additions (Figure 22B).

- WING & EMPENNAGE ACTIVE SUCTION = 15% CHORD
- WING FRONT AND REAR BEAM @ 15 & 65 % CHORD
- HLFC ACTIVATED ONLY UPON REACHING INITIAL CRUISE ALTITUDE
- TURBULENT FLOW = 6% CRUISE TIME
- 12% MINIMUM EXCESS CRUISE THRUST AVAILABLE
- WING T.E. FLAPS = 25% WING CHORD
- INDEPENDENT HLFC SUCTION POWER SYSTEM
- ACCOMMODATIONS = 3 PILOTS, 1 LOADMASTER, AND 2 BUNKS

Figure 21A. HLFC Aircraft Ground Rules

- LOW-WING CONFIGURATION
- P&W STF-686 AFT FUSELAGE MOUNTED ENGINES
- NOSE LOADING CAPABILITY ONLY
- HARD SURFACE LANDING GEAR
- AERO SURFACE L.E. HOT AIR ANTI-ICE SYSTEM DELETED
- FULL SPAN WING FUEL TANKS
- L.E. DEVICE DELETED

Figure 21B. Concluded

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HLFC SWEEP & ENGINE LOCATION STUDY

COMPARISON - PERCENT CHANGE FROM REFERENCE

	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
PAYLOAD - LB	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
RANGE OF RADIUS - NM	6,500.00	6,500.00	6,500.00	6,500.00	0.00	0.00	0.00
SPEED - M	0.77	0.77	0.77	0.77	0.00	0.00	0.00
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	32,119.00	31,665.00	30,462.00	31,357.00	-1.35	-5.15	-2.37
CFL - FT	7,557.00	8,267.00	9,713.00	8,408.00	9.39	28.52	11.26
MID-POINT CFL - FT	5,516.00	2,200.00	2,168.00	2,187.00	-60.11	-60.69	-60.35
GROSS WEIGHT - LB	616,125.00	594,548.00	585,144.00	592,945.00	-3.50	-5.02	-3.76
							ERR
STRUCTURAL WEIGHT	128,023.00	141,036.00	135,941.00	140,401.00	10.16	6.18	9.68
PROPULSION SYSTEM	35,625.00	34,731.00	33,905.00	34,393.00	-2.50	-4.82	-3.45
SYSTEMS & EQUIP.	23,253.00	23,636.00	23,308.00	23,572.00	1.64	0.23	1.37
OPERATING EQUIP.	5,317.00	5,015.00	4,994.00	5,009.00	-5.67	-6.07	-5.79
OPERATING WEIGHT	192,218.00	204,418.00	198,148.00	203,375.00	6.34	3.08	5.80
ZERO FUEL WEIGHT	324,718.00	336,918.00	330,648.00	335,875.00	3.75	1.82	3.43
L.E. CLEAN FLUID	0.00	4,285.00	3,787.00	4,223.00			
FUEL	291,401.00	253,330.00	250,686.00	252,828.00	-13.06	-13.97	-13.23
PAYLOAD	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
USEFUL LOAD	423,901.00	385,830.00	383,186.00	385,328.00	-8.98	-9.60	-9.09
WING DATA							
AREA - SQ FT	4,835.39	4,867.83	4,497.80	4,844.00	0.67	-6.96	0.17
WEIGHT - LB	58,978.00	69,765.00	65,510.00	69,453.00	18.28	11.07	17.76
WEIGHT - LB/SQ FT	12.19	14.33	14.56	14.33	17.50	19.41	17.55
ASPECT RATIO	13.54	13.86	14.18	13.95	2.36	4.72	3.02
BASIC SWEEP - DEG	30.00	20.00	25.00	20.00	-33.33	-16.66	-33.33
BAT SWEEP - DEG	35.53	25.00	30.05	25.00	-29.63	-15.56	-29.63
LOADING - LB/SQ FT	124.42	118.90	126.69	119.17	-4.43	1.82	-4.21
FUEL VOL. RATIO	1.00	1.00	1.00	1.00	0.00	0.00	0.00
SPAN - FT	255.91	259.74	252.56	260.00	1.49	-1.30	1.59
C.F LB/SPAN FT	0.00	16.49	14.99	16.24	ERR	ERR	ERR
MAC - FT	22.88	22.68	22.89	22.58	-0.87	0.04	-1.31
t/c - %	13.49	11.74	12.67	11.82	-12.97	-6.07	-12.37
MISCELLANEOUS							
L/D	25.99	30.91	30.78	30.92	18.93	18.43	18.96
ML/D	20.01	23.80	23.70	23.80	18.93	18.43	18.96
CRUISE SFC	0.56	0.57	0.57	0.57	2.85	3.39	2.85
CL MAX T.O.	2.60	2.53	2.44	2.53	-2.69	-6.15	-2.69
CRUISE CL	0.52	0.49	0.49	0.48	-6.27	-5.70	-7.60
THRUST/ENGINE - LB	30,195.00	27,321.00	25,999.00	26,936.00	-9.51	-13.89	-10.79
THRUST/WEIGHT	0.19	0.18	0.17	0.18	-6.23	-9.33	-7.30
VERT AREA - SQ FT	439.52	567.50	530.38	547.00	29.11	20.66	24.45
HORIZ AREA - SQ FT	418.84	639.56	621.90	610.00	52.69	48.48	45.64

Figure 22A. Parametric Sizing Data for HLFC Aircraft; M=0.77, Initial Concepts

The comparison of parametric data for HLFC configurations presented in Figure 22, i.e., Options 1 - 3, shows mixed results. First, a comparison of HLFC Options 1 and 2 for wing sweep effects with the same engine location shows slightly higher lift to drag ratio for the Option 1 case but slightly lower gross weight and fuel burned for the Option 2 case. Option 1 was deemed superior because it was felt that less leading edge cross flow effects would be encountered for the lower wing sweep of Option 1, 20^{o}, as compared to the Option 2 higher wing sweep case, 25^{o}. The comparison of data for HLFC Option 1 and Option 3 for the same wing sweep geometry but with the engines moved forward 5.6 feet on the fuselage shows identical lift-to-drag ratio for both cases and essentially negligible but lower gross weight and fuel burned for Option 3. The HLFC Option 1 was deemed superior because it was felt that more difficulties in maintaining laminar flow would be encountered for Option 3

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	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.88	0.77	0.77	0.77	-11.59	-11.47	-11.47
BASIC WING AREA	4,119.77	4,149.11	3,581.17	4,122.00	0.71	-13.07	0.05
TOTAL WING AREA	4,835.39	4,867.83	4,497.80	4,844.00	0.67	-6.96	0.17
BAT AREA - % TOTAL	14.79	14.76	20.37	14.90	-0.23	37.70	0.71
TOTAL/BASIC	1.17	1.17	1.25	1.17	-0.04	7.00	0.12
L.E. SUCTION - % C		15.00	15.00	15.00			
L.F.TRANSITION - % C		50.00	50.00	50.00			
ENG LOC - % MAC		100.00	100.00	75.00	ERR	ERR	ERR
FUSELAGE WT/SQ FT	4.05	4.21	4.20	4.20	3.79	3.59	3.77
					ERR	ERR	ERR
					ERR	ERR	ERR
					ERR	ERR	ERR
					ERR	ERR	ERR
					ERR	ERR	ERR
					ERR	ERR	ERR
WING WT. EQUATION	13.00	13.00	13.00	13.00			

NOTES:

1. [redacted] = TURBULENT AIRCRAFT BASELINE
2. OPTION 1 = HLFC AIRCRAFT, 20 BASIC & 25 BAT
3. OPTION 2 = HLFC SWEEP SENSITIVITY, 25 BASIC & 30 BAT
4. OPTION 3 = HLFC OPTION 1, ENGINE LOCATION @ 75 % MAC

HLFC SYSTEM WEIGHT ADDITIONS

STRUCTURE							
WING - LB	0.00	568.00	510.00	564.00	BASE	-10.21	-0.70
HORIZ - LB	0.00	91.00	88.00	86.00	BASE	-3.29	-5.49
VERT - LB	0.00	80.00	75.00	77.00	BASE	-6.25	-3.75
TOTAL - LB	0.00	739.00	673.00	727.00	BASE	-8.93	-1.62
SUCTION SYSTEM							
ENGINES - LB	0.00	537.00	535.00	534.00	BASE	-0.37	-0.55
DUCTING - LB	0.00	951.00	926.00	949.00	BASE	-2.62	-0.21
MISC - LB	0.00	666.00	663.00	662.00	BASE	-0.45	-0.60
TOTAL - LB	0.00	2,154.00	2,124.00	2,145.00	BASE	-1.39	-0.41
CLEANING SYSTEM							
SYSTEM - LB	0.00	375.00	331.00	369.00	BASE	-11.73	-1.60
TRAPPED FLUID - LB	0.00	589.00	521.00	580.00	BASE	-11.54	-1.52
MISSION FLUID - LB	0.00	4,285.00	3,787.00	4,223.00	BASE	-11.62	-1.44
TOTAL - LB	0.00	5,249.00	4,639.00	5,172.00	BASE	-11.62	-1.46
TOTAL DELTA WT. - LB	0.00	8,142.00	7,436.00	8,044.00	BASE	-8.67	-1.20
		OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3

Figure 22B - Concluded

Figure 22B. Concluded

with the engines in close proximity with the wing upper surface than for Option 1. Accordingly, the Option 1 HLFC configuration was selected as the initial baseline HLFC aircraft. Pertinent design and aerodynamic parameters include a takeoff gross weight of 594,548 lbs, lift-to-drag ratio of 30.9, thrust per engine of 27,321 lbs, a wing aspect ratio of 13.86, wing span of 259.7 feet, and a critical field length of 8,267 feet.

Refinements were made in the aerodynamic and structural inputs to the HLFC initial baseline configuration sizing process to include (1) a reduction in duct weights from a previous study (Ref. 15) and (2) a change in laminar flow time loss in cruise flight condition from 10 percent to the desired 6 percent. These input changes to the sizing program resulted in very small changes in the weights and performance of the HLFC revised baseline aircraft. The revised parametric sizing data for the baseline HLFC aircraft is contained in Option 1 of Figure 23. For example, as compared to the initial HLFC baseline aircraft the revised HLFC baseline aircraft takeoff gross weight is 591,636 lbs, versus 594,548 lbs, the lift-to-drag ratio is 30.8 versus 30.9, thrust per engine is 26,990 lbs, versus 27,231 lbs, and the wing aspect ratio is 13.87 versus 13.86. A general arrangement drawing of the baseline HLFC aircraft is presented in Figure 24, along with other pertinent design and aerodynamic parameters including a wing span of 258.85 feet and a critical field length of 8,383 feet.

5.4 COMPARISON OF TURBULENT AND HLFC AIRCRAFT

The data in Figure 23 enable a comparison to be made between the revised baseline HLFC aircraft (Option 1) and the initial baseline turbulent flow aircraft listed as the reference aircraft in the first column. This comparison shows for the HLFC aircraft a reduction of 13.4 percent in fuel burned, an

TURBULENT B.L./HLFC BASELINE AT 0.77, 0.80, AND 0.77;36K

12-FEB-1987

1986 HLFC CONTRACT STUDY - NASA/AIR FORCE

COMPARISON - PERCENT CHANGE FROM REFERENCE

	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
PAYLOAD - LB	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
RANGE or RADIUS - NM	6,500.00	6,500.00	6,500.00	6,500.00	0.00	0.00	0.00
SPEED - M	0.77	0.77	0.80	0.77	0.00	3.89	0.00
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	32,119.00	31,361.00	30,905.00	36,000.00	-2.35	-3.77	12.08
CFL - FT	7,557.00	8,383.20	7,357.50	6,379.00	10.93	-2.63	-15.58
MID-POINT CFL - FT	5,516.00	2,172.00	2,244.00	2,659.00	-60.62	-59.31	-51.79
GROSS WEIGHT - LB	616,125.00	591,636.00	637,563.00	614,361.00	-3.97	3.47	-0.28
							ERR
STRUCTURAL WEIGHT	128,023.00	139,985.00	153,658.00	154,762.00	9.34	20.02	20.88
PROPULSION SYSTEM	35,625.00	34,057.00	37,102.00	38,179.00	-4.40	4.14	7.16
SYSTEMS & EQUIP.	23,253.00	23,598.00	24,441.00	24,018.00	1.48	5.10	3.28
OPERATING EQUIP.	5,317.00	5,006.00	5,224.00	5,030.00	-5.84	-1.74	-5.39
OPERATING WEIGHT	192,218.00	202,646.00	220,425.00	221,989.00	5.42	14.67	15.48
ZERO FUEL WEIGHT	324,718.00	335,146.00	352,925.00	354,489.00	3.21	8.68	9.16
L.E. CLEAN FLUID	0.00	4,258.00	5,049.00	4,606.00			
FUEL	291,401.00	252,216.00	279,592.00	255,308.00	-13.44	-4.05	-12.38
PAYLOAD	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
USEFUL LOAD	423,901.00	384,716.00	412,092.00	387,808.00	-9.24	-2.78	-8.51
WING DATA							
AREA - SQ FT	4,835.39	4,832.28	5,574.64	5,231.06	-0.06	15.28	8.18
WEIGHT - LB	58,978.00	68,888.00	78,594.00	81,536.00	16.80	33.25	38.24
WEIGHT - LB/SQ FT	12.19	14.25	14.09	15.58	16.87	15.58	27.79
ASPECT RATIO	13.54	13.87	12.15	13.82	2.43	-10.26	2.06
BASIC SWEEP - DEG	30.00	20.00	20.00	20.00	-33.33	-33.33	-33.33
MAT SWEEP - DEG	35.53	25.00	25.00	25.00	-29.63	-29.63	-29.63
LOADING - LB/SQ FT	124.42	119.19	111.32	114.24	-4.20	-10.52	-8.18
FUEL VOL. RATIO	1.00	1.00	1.00	1.00	0.00	0.00	0.00
SPAN - FT	255.91	258.85	260.30	268.86	1.14	1.71	5.06
C.F LB/SPAN FT	0.00	16.44	19.39	17.11	ERR	ERR	ERR
MAC - FT	22.88	22.60	25.27	23.53	-1.22	10.47	2.85
t/c - %	13.49	11.83	10.10	10.57	-12.30	-25.12	-21.64
MISCELLANEOUS							
L/D	25.99	30.76	29.51	31.90	18.35	13.54	22.73
ML/D	20.01	23.68	23.60	24.56	18.35	17.96	22.73
CRUISE SFC	0.56	0.57	0.59	0.56	2.85	5.35	1.42
CL MAX T.O.	2.60	2.53	2.53	2.53	-2.69	-2.69	-2.69
CRUISE CL	0.52	0.48	0.41	0.58	-7.60	-21.67	10.26
THRUST/ENGINE - LB	30,195.00	26,990.00	30,231.00	32,000.00	-10.61	0.11	5.97
THRUST/WEIGHT	0.19	0.18	0.18	0.20	-6.91	-3.24	6.28
VERT AREA - SQ FT	439.52	563.03	634.70	624.38	28.10	44.40	42.05
HORIZ AREA - SQ FT	418.44	641.75	780.81	671.71	53.22	86.42	60.37

Figure 23A. Parametric Sizing Data for HLFC Aircraft; Speed and Altitude Changes

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	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.88	0.78	0.78	0.76	-11.36	-10.79	-12.95
BASIC WING AREA	4,119.77	4,118.31	4,895.84	4,461.92	-0.03	18.83	8.30
TOTAL WING AREA	4,835.39	4,832.28	5,574.64	5,231.06	-0.06	15.28	8.18
SAT AREA - % TOTAL	14.79	14.77	12.17	14.70	-0.16	-17.72	-0.65
TOTAL/BASIC	1.17	1.17	1.13	1.17	-0.02	-2.98	-0.11
L.E. SUCTION - % C		15.00	15.00	15.00			
L.F.TRANSITION - % C		50.00	50.00	50.00			
ENG LOC - % MAC		100.00	100.00	100.00	ERR	ERR	ERR
FUSELAGE WT/SQ FT	4.05	4.20	4.31	4.23	3.74	6.36	4.28
WING WT. EQUATION	13.00	13.00	13.00	13.00			

NOTES:

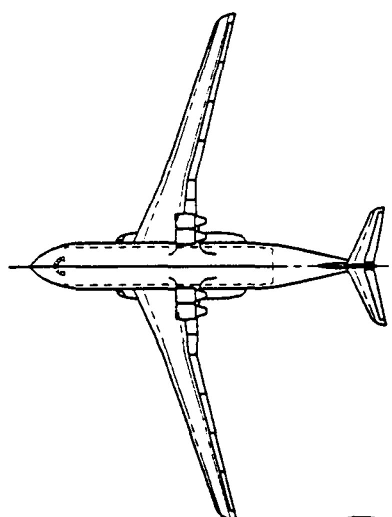
1. REFERENCE = TURBULENT AIRCRAFT
2. OPTION 1 = HLFC BASELINE, M=0.77
3. OPTION 2 = HLFC BASELINE, M=0.80
4. OPTION 3 = HLFC BASELINE, M=0.77, H=36,000 FT

HLFC SYSTEM WEIGHT ADDITIONS

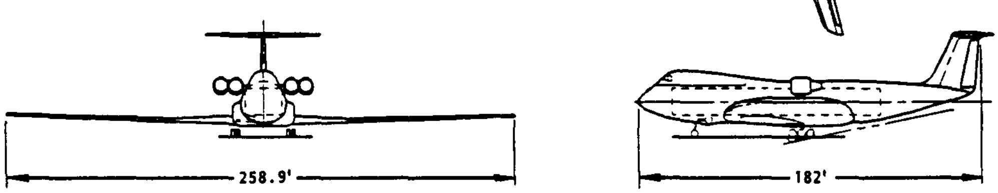
	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
STRUCTURE							
WING - LB	0.00	563.00	657.00	614.00	BASE	16.69	9.05
HORIZ - LB	0.00	91.00	111.00	95.00	BASE	21.97	4.39
VERT - LB	0.00	80.00	90.00	88.00	BASE	12.50	10.00
TOTAL - LB	0.00	734.00	858.00	797.00	BASE	16.89	8.58
SUCTION SYSTEM							
ENGINES - LB	0.00	536.00	563.00	546.00	BASE	5.03	1.86
DUCTING - LB	0.00	569.00	578.00	591.00	BASE	1.58	3.86
MISC - LB	0.00	665.00	698.00	677.00	BASE	4.96	1.80
TOTAL - LB	0.00	1,770.00	1,839.00	1,814.00	BASE	3.89	2.48
CLEANING SYSTEM							
SYSTEM - LB	0.00	373.00	442.00	403.00	BASE	18.49	8.04
TRAPPED FLUID - LB	0.00	586.00	694.00	633.00	BASE	18.43	8.02
MISSION FLUID - LB	0.00	4,258.00	5,049.00	4,606.00	BASE	18.57	8.17
TOTAL - LB	0.00	5,217.00	6,185.00	5,642.00	BASE	18.55	8.14
TOTAL DELTA WT. - LB	0.00	7,721.00	8,882.00	8,253.00	BASE	15.03	6.89
	REFERENCE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3

12-FEB-1987

Figure 23B. Concluded



PAYLOAD	132,500 LB
RANGE	6,500 NM*
MACH NO	0.77
ALTITUDE	31,361 FT
TOGW	591,636 LB
FUEL	252,216 LB
L/D	30.8
MAC	22.6 FT
SPAN	258.9 FT
AR	13.87
L.E. SWEEP	20 DEG



*SEE FIGURE 3

Figure 24. HLFC Baseline Concept

increase of 18.4 percent in lift-to-drag ratio, a reduction of 10.6 percent in engine thrust, and a reduction of 4.0 percent in takeoff gross weight. The data also shows a 5.4 percent increase in the operating weight empty of the HLFC aircraft over that for the turbulent flow aircraft. This increase in operating weight for the HLFC aircraft is due primarily to the 7,721 pounds of HLFC peculiar structural weight additions and also to the 53 percent increase in horizontal tail area as compared to the turbulent flow aircraft.

Examination of the turbulent flow and HLFC aircraft parameters indicates that the tail volume coefficients for both configurations are reasonable. However, the approximately 50 percent larger horizontal tail volume coefficient for the fuselage-mounted engines configuration results from the requirement for a substantially greater center of gravity range, 37 percent MAC, as compared with that for the wing mounted engine configuration of 26 percent as shown in Figure 25.

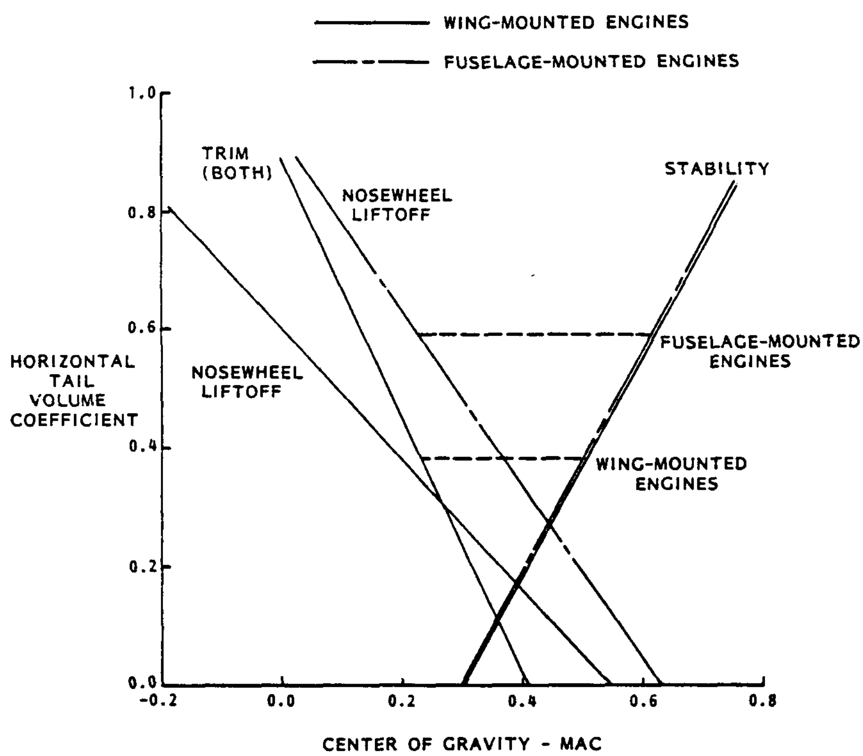


Figure 25. Horizontal Tail Sizing Chart

Aft fuselage mounted engine configurations exhibit wider center of gravity travel because the wing (and its fuel) are displaced aft with respect to the centroid of the payload compartment. This effect is discussed on page 299, Figure 8-10, of Reference 19.

The aft engine system, because of the rearward shift of weight, results in nose wheel lift-off being much more critical for this configuration than for the wing mounted engine configuration, as also shown in Figure 25.

5.5 HLFC AIRCRAFT DEFINITION

5.5.1 Configuration Design

The baseline LFC configuration shown in Figure 24 is a wide-body transport configuration designed to carry a 132,500 pound payload at a range of 6500 nm at M = 0.77 with adequate fuel to account for adverse winds, intermittent LFC disruptions due to atmospheric conditions at cruise altitude, and normal international fuel reserves. A typical payload-range curve is given in Figure 26.

A typical arrangement of 38x108 cargo pallets is shown in Figure 27. The cargo compartment is 19.5' wide, 13.5' high and 110.75' long. In addition to cargo, various vehicles and other equipment may be accommodated in the cargo compartment (See Figure 28).

Two suction pumps are required for the HLFC transport aircraft. A general arrangement of the suction system which is required for the HLFC Transport is shown in Figure 29.

The power unit which is required to drive the suction pump is mounted behind the suction pump. A drive shaft couples the power unit and suction pump together. This arrangement is used to minimize the size and weight of the ducting necessary to laminarize the leading edge. An S-shaped inlet duct provides air to the power unit. The power unit and the suction pump both exhaust through ducts in the side of the pod used to house the suction system. The arrangement of the suction pumps and ducts is shown in Figures 30A and 30B.

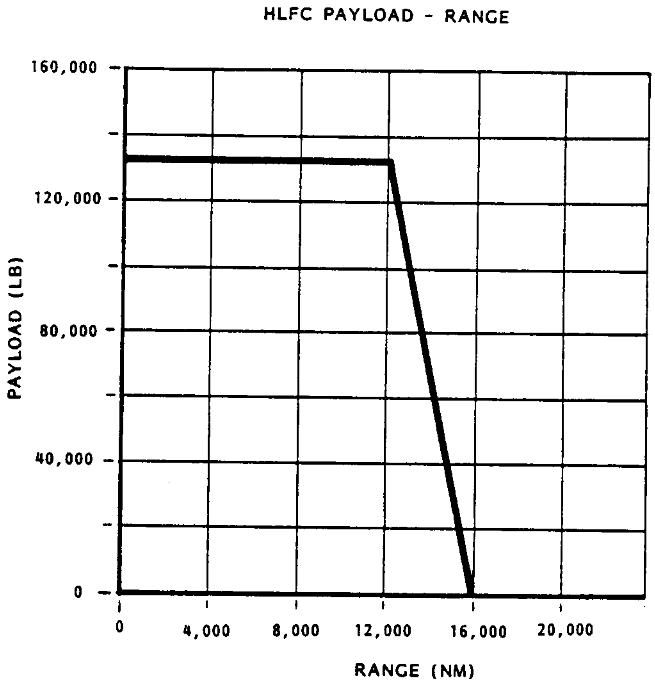


Figure 26. Typical HLFC Concept Payload-Range Curve

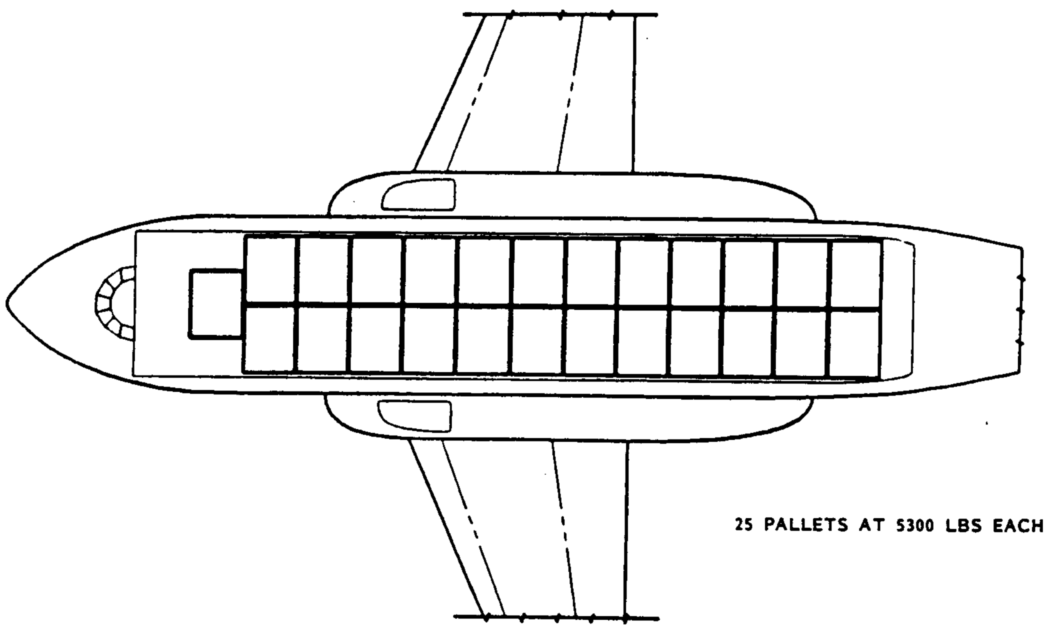


Figure 27. HLFC Concept Cargo Pallets Arrangement

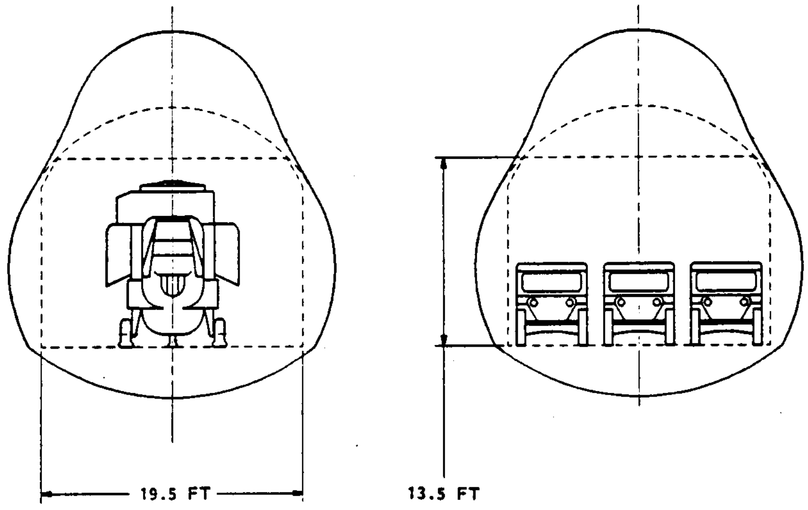


Figure 28. HLFC Concept Arrangement of Vehicles

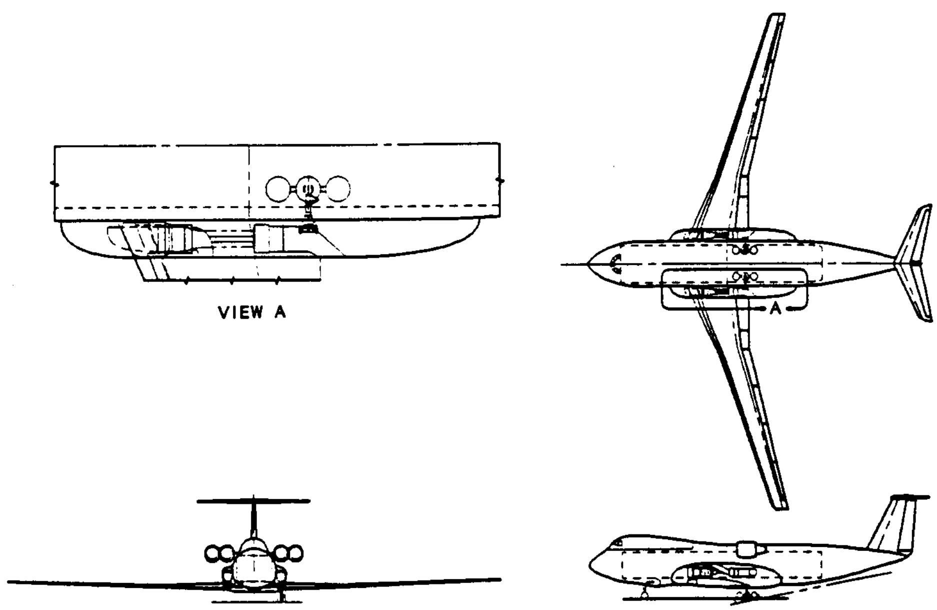


Figure 29. Suction Pump/System General Arrangement

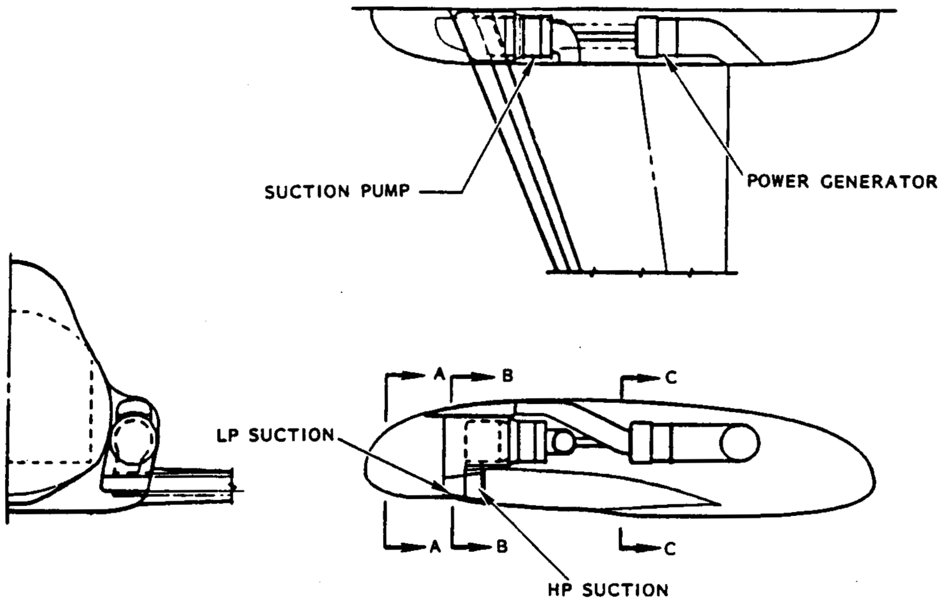


Figure 30A. HLFC Concept Suction Systems Arrangement

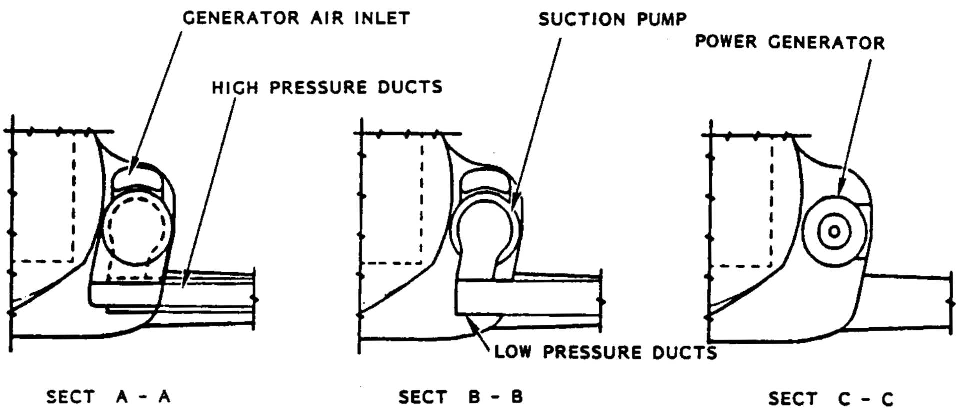


Figure 30B. Concluded

All of the configurations investigated in this study are fuel volume critical because of the large unrefueled range requirement, and therefore use both wing and center section fuel. Since fuel volume sizes the wing, wing size and aircraft weight and drag could be reduced if fuel volume could be obtained elsewhere, as for example, under the fuselage cabin floor.

5.5.1.1 Leading Edge

LFC suction capability is provided only in the leading edge of the wing. The leading edge is removable and it contains a system of chordwise slots with subsurface compartments which are used to control the pressure gradients inside the leading edge (Figure 31).

The leading edge is fabricated in two sections. The upper section is a fixed nose panel and the lower section is removable to provide access for maintenance and adjustment of the LFC suction and slot cleaning equipment. Two full length diaphragms provide substructure support. These members

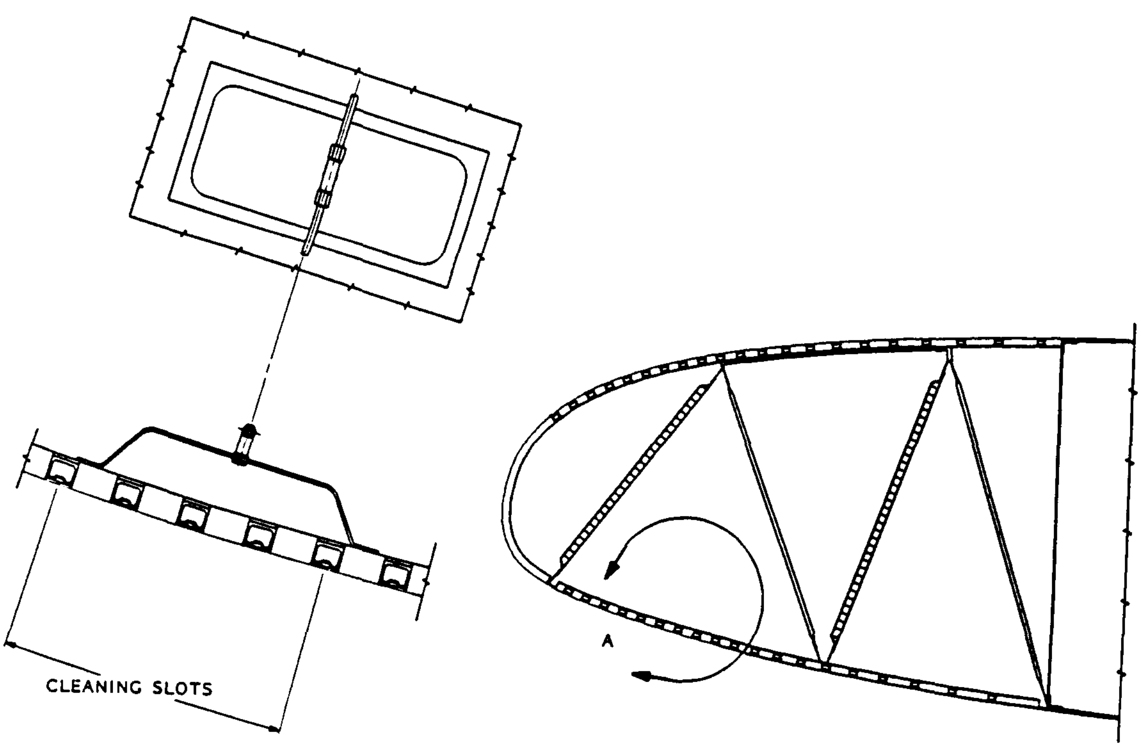


Figure 31. Leading Edge Design Concept

provide support for the upper and lower panels and form the boundaries of the upper and lower surface ducts. All leading edge components are of sandwich construction and feature graphite/epoxy sheets and a corrosion resistant aluminum honeycomb core. The suction slots are cut into the thin guage outer titanium skin which is bonded to the outer panel face sheet. This titanium skin also provides environmental protection for the structure.

5.5.1.2 Fuel Tanks

An auxiliary fuel tank and two main fuel tanks in each wing are the basis for the fuel system (See Figure 32). In addition, an auxiliary fuel tank is located in the center wing box within the fuselage. The main tanks are used to supply fuel to the main engines. The fuel for the LFC suction pump power units will be supplied from the auxiliary center tanks. Fuel transfer between the auxiliary and main fuel tanks is accomplished as required.

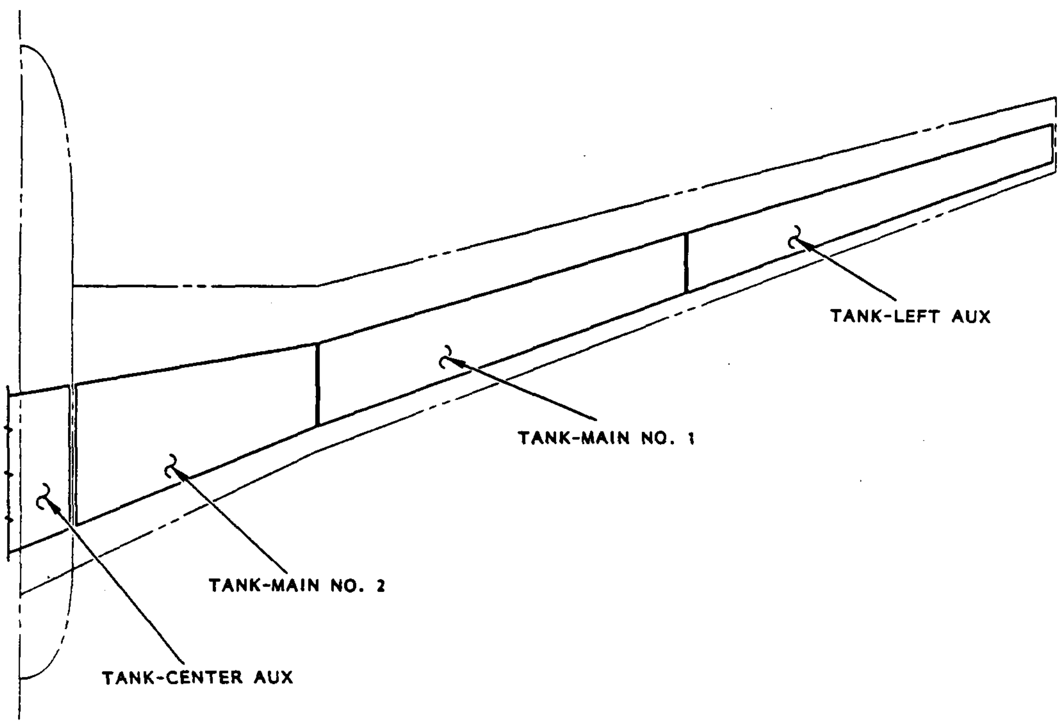


Figure 32. Fuel Tank Arrangement

Access doors in the lower surface of the wing are provided for inspection, maintenance, and repair of the wing structure. All components including boost pumps, fuel probes, and fuel level control valves are removable from the exterior of the lower wing surface. Single point ground pressure fueling is accomplished from the main landing gear wheel well.

5.5.1.3 Empennage

The Empennage is a T tail arrangement as shown in Figure 33.

Construction of the tail is similar to the wing with the exception that the leading edges of the horizontal and vertical tails do not have the slots or plumbing for LFC suction.

The horizontal tail incorporates elevators as part of the trailing edge. A double hinged rudder is attached to the aft spar of the vertical tail. The elevator and rudder are part of the FBW (fly by wire) control system.

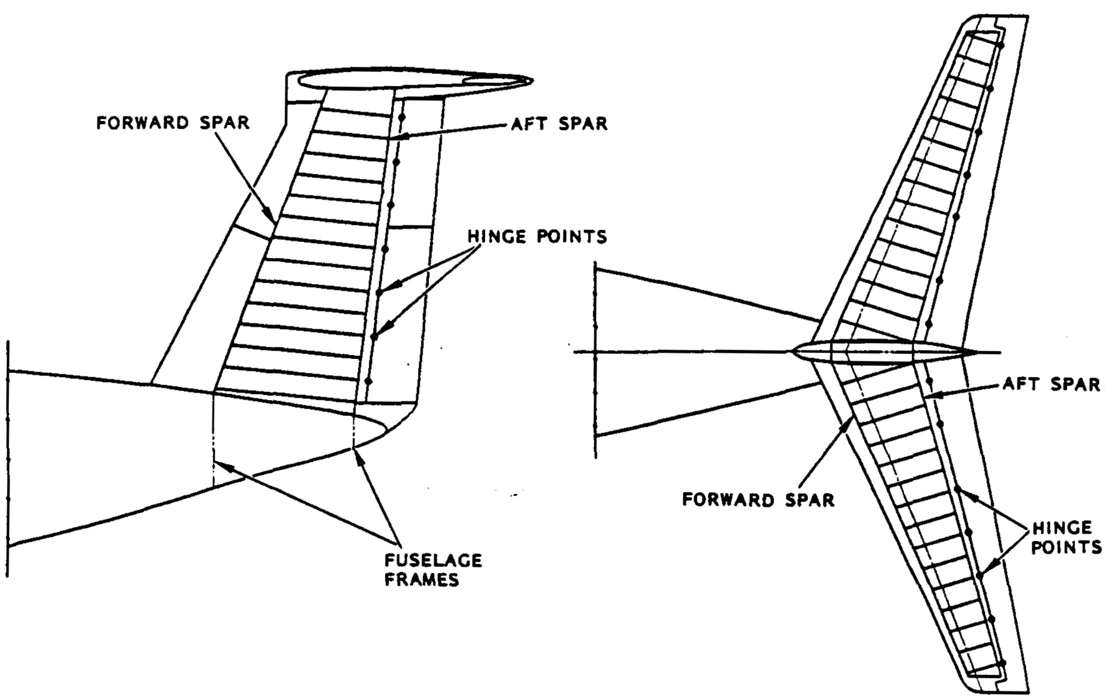


Figure 33. Empennage General Arrangement

5.5.1.4 Landing Gear

A two wheel nose gear and a two strut twelve wheel main gear (Figure 34) comprise the landing gear system.

The main landing gear is fuselage mounted. Each strut retracts into the fuselage. The gear rotates about a longitudinal axis 90° from fully retracted to fully extended. A total of six wheels is mounted on each strut. The wheels are arranged in three pairs of two on each strut. No form of directional steering or swivelling is employed on the main gears.

The nose gear retracts forward into the belly of the aircraft. Nosewheel steering operated by a handwheel controlled by the pilot is provided.

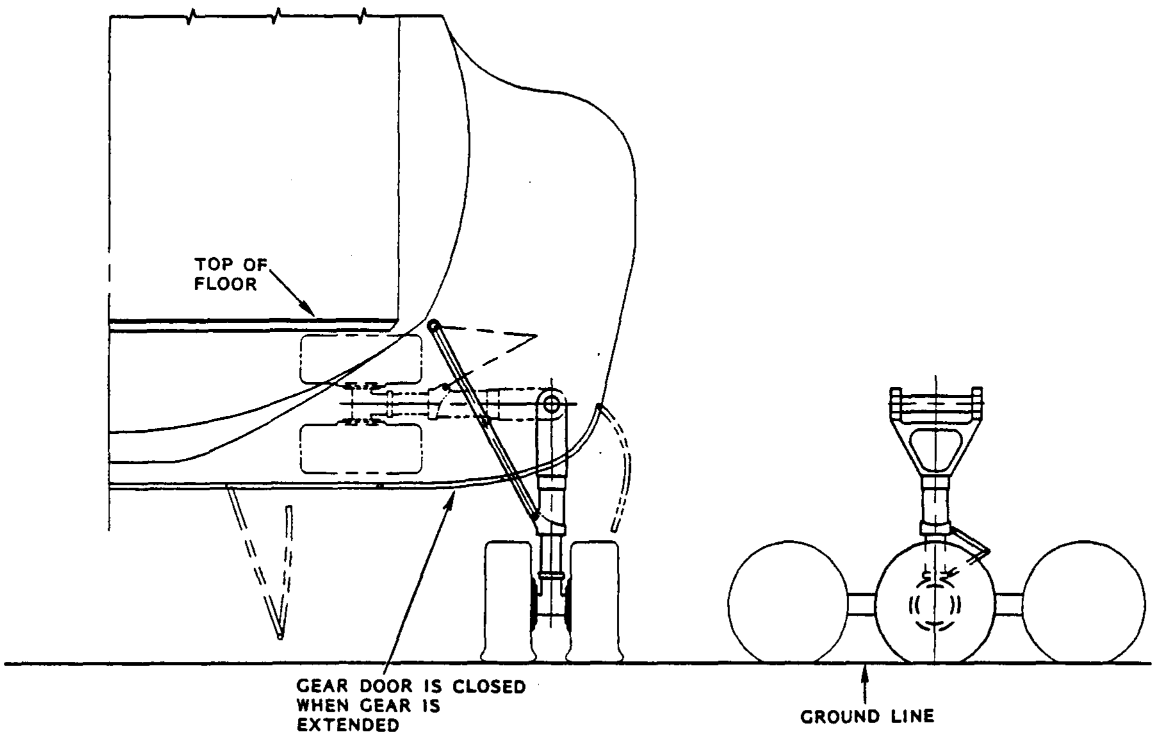


Figure 34. Main Landing Gear

5.5.1.5 High Lift Systems

The high lift system consists of single slot, hinged, full span flaps (Figure 35). The outboard portion of the flaps are provided by drooping the ailerons. Control of the hydro-mechanically operated flaps is accomplished by a single pilot input. Systems to prevent asymmetrical flap operation and flap position indication are also provided.

Secondary flaps of 9.5% chord are built into the entire span of the main flaps. These secondary flaps are used along with the primary flaps in the high lift mode or separately as part of the active control system. The onboard fly-by-wire computer system actuates the secondary flaps in the active control mode by means of electro-hydraulic servo units.

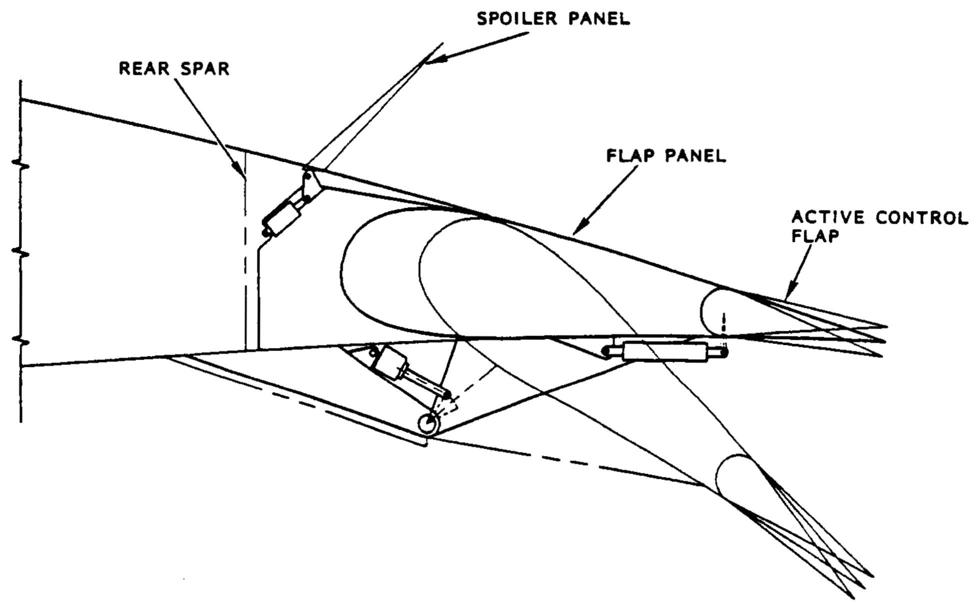


Figure 35. Wing Trailing Edge Design

5.5.2 HLFC Wing Aerodynamics Design

Since 1974, a number of automated design and analysis methods have been developed by Lockheed for wings having extensive regions of laminar flow. These methods are applicable to Natural Laminar Flow (NLF), Laminar Flow Control (LFC), and Hybrid Laminar Flow Control (HLFC) wing design. The design methodologies are depicted in block diagram form in Figure 36. Aerodynamics effort in this contract was concentrated on use of these available HLFC design methods to develop an initial baseline HLFC wing configuration which is close to the final parametric wing defined in the sizing and optimization studies. This objective was achieved, however some additional refinement of wing geometry and applied suction would be required to develop a true "production" configuration with near-minimal suction. The resulting final configuration might then require resizing to finalize the baseline. A summary of the aerodynamic design and derivation of necessary inputs to the suction system design is provided in the sections that follow.

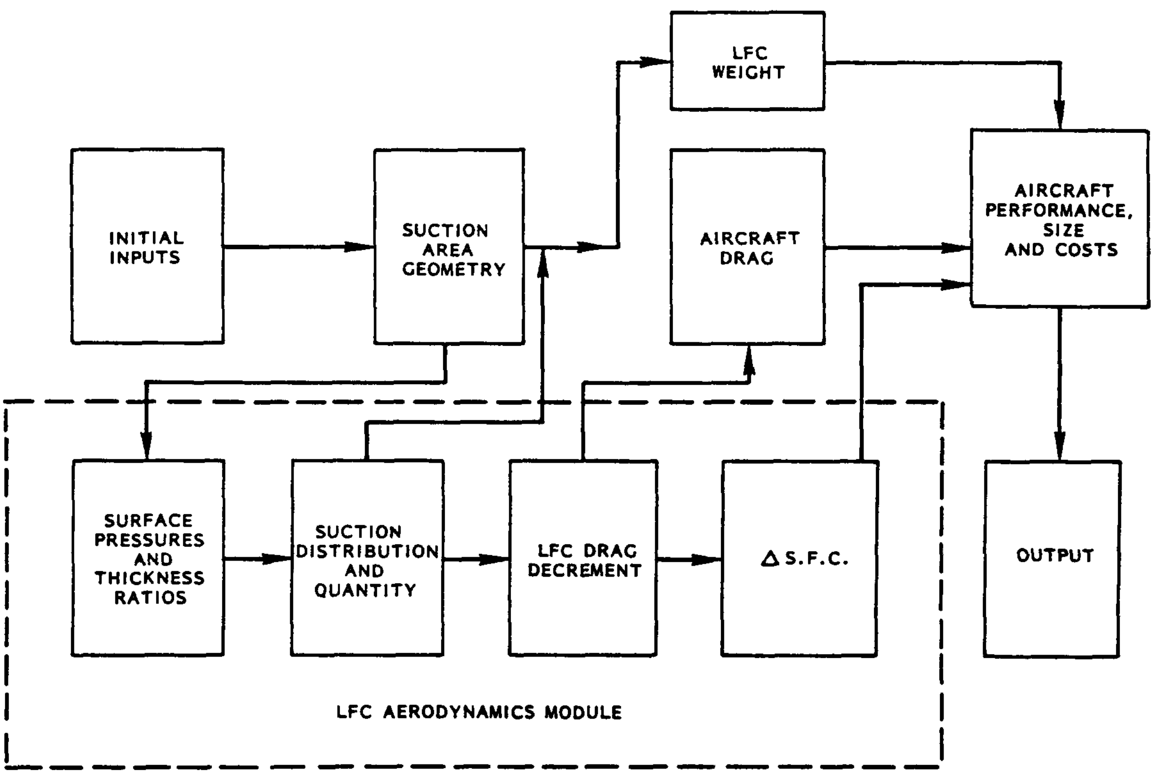


Figure 36. Generalized Aircraft Sizing Program, LFC Subroutine

5.5.2.1 Parametric Sizing of Aircraft Including Suction Requirements and Suction System

As previously outlined in Reference 2 and repeated herein, the HLFC system is characterized in the parametric sizing code with the following inputs:

(1) Type of HLFC suction power

Option 1: Independently-powered suction units (used in this contract)

Option 2: Suction units integrated with primary propulsion

Option 3: Suction units integrated with other aircraft systems

(2) Number and location of HLFC suction units

(3) Parametric geometric description of LFC glove and suction ducts

(4) Parametric suction external pressures and suction distributions

(5) Extent of laminar flow provided by extent of HLFC suction

(6) Parametric incremental costs of HLFC systems (omitted in this study)

5.5.2.2 Determination of Baseline Wing Detailed External Contours

Baseline configuration parametric code outputs were used as a starting place for detailed design of the baseline wing external contours (and surface pressures). The detailed design starting point baseline wing geometry derived from parametric studies is illustrated in Figure 37. As previously explained in Reference 2, the subsequent aerodynamic design followed the procedure outlined in Figure 38.

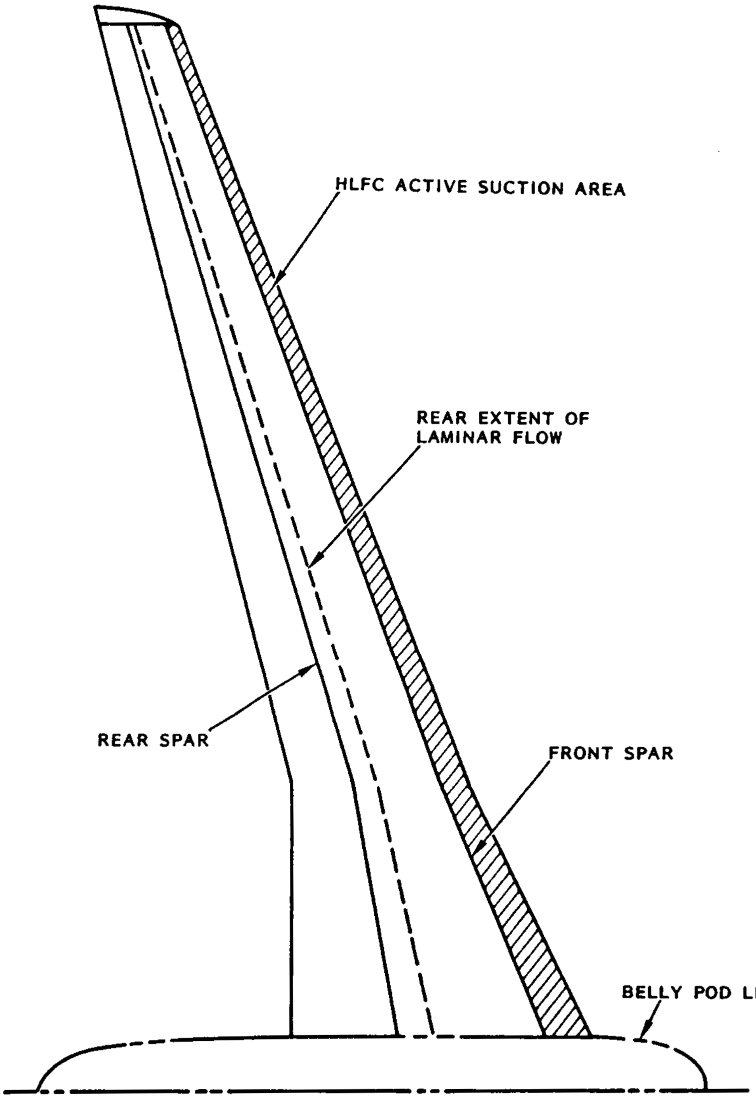


Figure 37. Areas of HLFC and Wing Laminarization

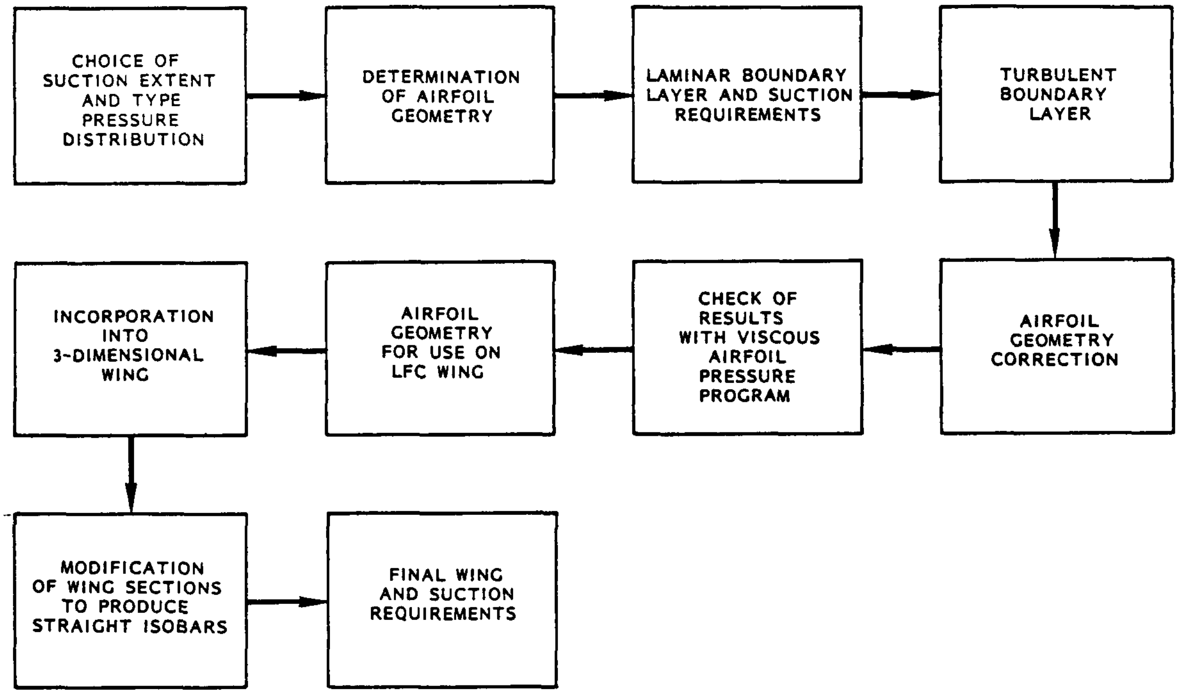


Figure 38. Aerodynamic Design Procedure for LFC and TF Wings

Using the above-mentioned methods, the baseline wing geometry was derived with a typical airfoil shape as illustrated in Figure 39. The shape corresponds to that used at the wing control station at 0.350 nondimensional semispan position. Wing section chordline incidences and thickness ratios at the fuselage side, break station, and tip are indicated below:

Position	Incidence (degrees)	Thickness (t/c)
Side of Fuselage	0.75	0.130
Wing Break Station	1.25	0.118
Wing Tip	-0.25	0.118

5.5.2.3 Baseline Wing Surface Pressure Results

Figure 40 illustrates a typical surface pressure result on the derived baseline wing geometry. This pressure distribution shape is for the 0.488 nondimensional wing station and is the result of viscous three-dimensional

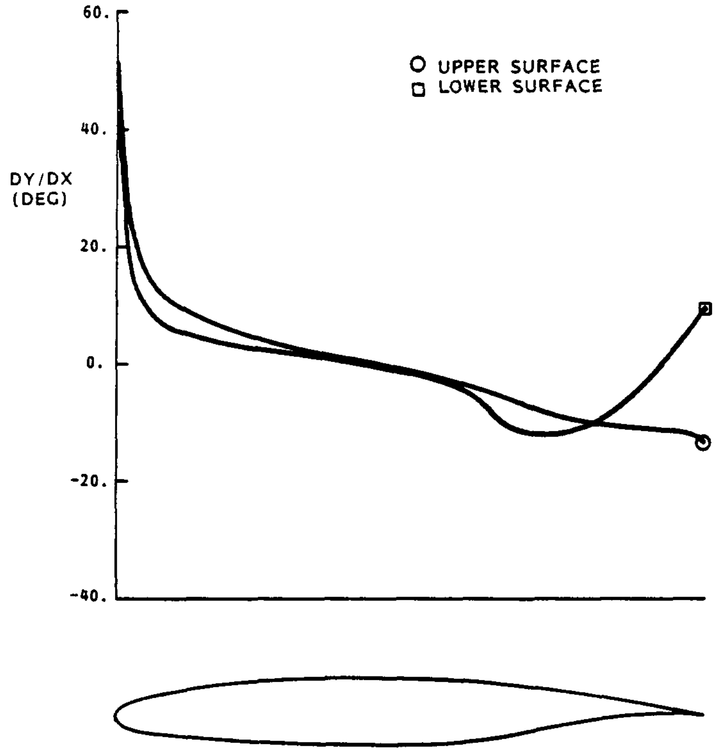


Figure 39. Typical Airfoil Section on Baseline HLFC Wing

flow computations at the basic design point at start-cruise conditions. Surface pressure results from this station and others over the semispan of the wing were used to determine wing boundary layer and boundary layer stability results. Discussion of these results is provided in the sections that follow.

5.5.2.4 Baseline Suction and Boundary Layer Stability Results

Using the wing surface pressure results described above, a suction distribution was developed using the parametric description as the starting point. Changes to airfoil pressures and suction were made to produce better results from the boundary layer and boundary layer stability predictions. The suction distribution from these design iterations, shown in Figure 41, is similar in shape and total suction mass flow to that used in parametric studies, Additional design work is warranted to arrive at an "optimum" wing design. Any additional work is, however, outside the time and cost constraints of the current contract.

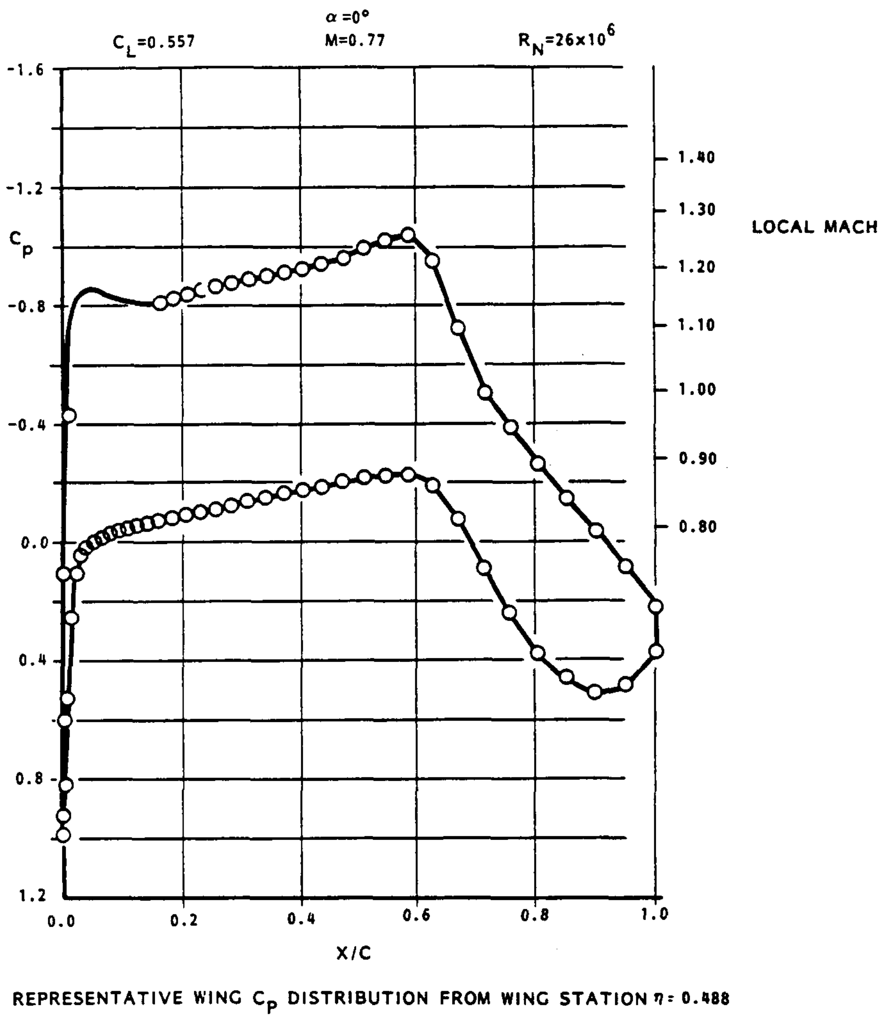


Figure 40. Representative Wing C_p Distribution from Wing Station $\eta = 0.488$

The data in Figure 42 shows the amount of flow required to be suctioned off the boundary layer to maintain laminarized flow on each wing. This flow is typical for the baseline airfoil operating at Mach 0.77 and 37,000 feet altitude. The suction pump used on the aircraft has the capacity to pump 150 percent of the flow of both wings, so there should be no difficulty in operating the pump at off-point conditions and still maintain laminarized flow.

Results of boundary layer crossflow stability calculations using the SALLY code are shown in Figure 43. Note that results indicate that transition is likely to occur near midchord position for both the upper and lower

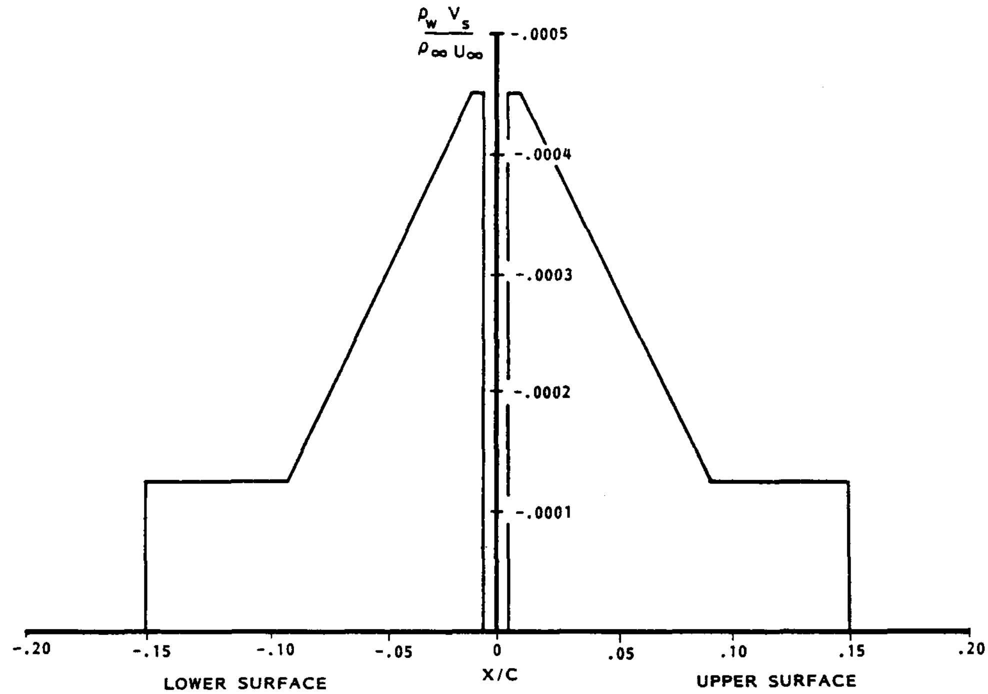


Figure 41. Mass Flow Suction Level

TOTAL SUCTION FLOW REQUIRED FOR ONE WING	SUCTION FLOW
SECTION 1. UPPER SURFACE, FROM WING ROOT TO Y/b = .35	17.66 LB/MIN
SECTION 2. UPPER SURFACE, FROM Y/b = .35 TO Y/b = .56	13.43 LB/MIN
SECTION 3. UPPER SURFACE, FROM Y/b = .56 TO Y/b = .78	15.36 LB/MIN
SECTION 4. UPPER SURFACE, FROM Y/b = .78 TO WING TIP	12.04 LB/MIN
SECTION 1. LOWER SURFACE, FROM WING ROOT TO Y/b = .35	13.08 LB/MIN
SECTION 2. LOWER SURFACE, FROM Y/b = .35 TO Y/b = .56	11.02 LB/MIN
SECTION 3. LOWER SURFACE, FROM Y/b = .56 TO Y/b = .78	11.36 LB/MIN
SECTION 4. LOWER SURFACE, FROM Y/b = .78 TO WING TIP	11.56 LB/MIN
TOTAL SUCTION FLOW FOR ONE WING =	105.51 LB/MIN

Figure 42. Total Suction Flow Across One Wing of HLFC Baseline

surfaces with active suction no farther aft than 15 percent chord. Further design refinement should improve the initial baseline results illustrated. Tollmien-Schlichting instability calculations do not pick up instability on either the upper or the lower surface back to 50 percent chord.

The basic transition N Factor level is compatible with levels demonstrated to be adequate from earlier Lockheed LFC work for NASA as outlined in Reference 12. Based on this work and other Lockheed experience, analysis work was concentrated on crossflow stability verification. For the configurations of this study, the Tollmien-Schlichten stability mode was much less critical than crossflow and was not examined at great length. The leading-edge attachment line momentum thickness Reynolds number, $R_{\theta a.l.}$, was also not studied at great length since the configurations of the study have leading-edge radii, pressure gradients, and sweep similar to previously-studied wings and should have similar, satisfactory leading-edge contamination characteristics.

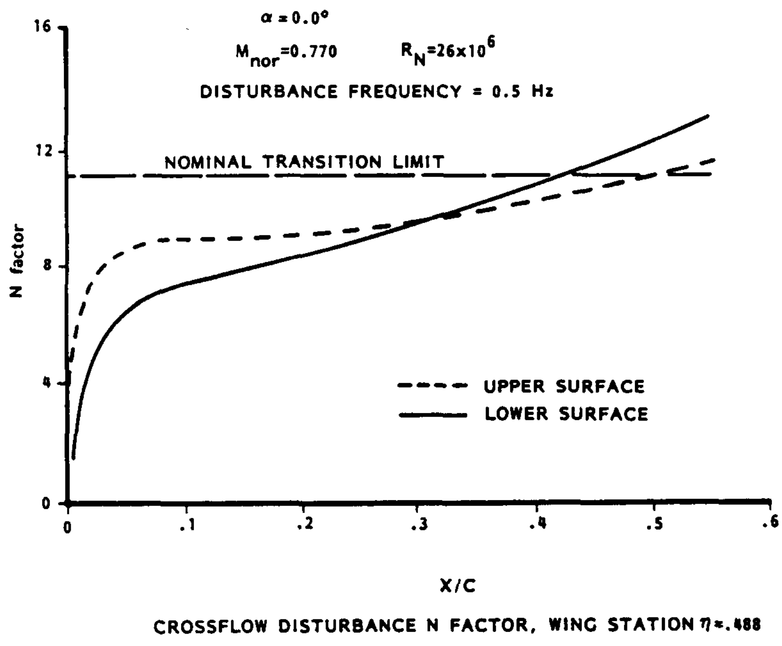


Figure 43. Crossflow Disturbance N Factor, Wing Station η= 0.488

The Gaster bump, leading-edge notch, and initiation of suction nearer the leading edge provide several proven means of avoiding unsatisfactory characteristics should more detailed design indicate that a problem exists. The resulting effects of any such changes on aircraft weights would be very small should they be necessary.

5.5.2.5 Possible Future Wing Refinements

The initial baseline wing can probably be further refined to reduce the likelihood of transition forward of 50 percent chord with some changes to (a) geometries and resultant pressure, (b) suction levels and distributions, and (c) suction surface configuration. Data from the wing external aerodynamics design were used in baseline suction surface determination, internal HLFC geometry design, and verification of suction powerplant size required. Details of this part of the HLFC design are contained in Section 4.4.5 of this report.

6.0 CONFIGURATION SENSITIVITY STUDIES

Sensitivity studies relative to performance and configuration parameters are reviewed in this section for both hybrid LFC and turbulent flow aircraft.

6.1 HLFC AIRCRAFT SENSITIVITY STUDIES

6.1.1 Increase of Cruise Speed or Altitude

Preliminary sensitivity studies were performed on the baseline HLFC aircraft (Option 1, Figure 23) to include the effects on performance of (1) increasing the cruise Mach number from 0.77 to 0.80 (Option 2, Figure 23) and (2) increasing the initial cruise altitude from 32,361 feet to 36,000 feet (Option 3, Figure 23).

As compared to the HLFC aircraft at M = 0.77 cruise speed, the HLFC aircraft at M = 0.80 shows an increase in fuel burned of 10.9 percent, a reduction in lift-to-drag ratio of 4.1 percent, an increase in engine thrust of 12 percent, an increase in gross weight of 7.8 percent, and a reduction in ML/D of 0.3 of one percent.

The effects of an increase in initial cruise altitude from 31,361 feet to 36,000 feet at M = 0.77 cruise speed shows an increase in fuel burned of 1.2 percent, an increase in lift-to-drag ratio of 3.7 percent, an increase in engine thrust of 18.6 percent, and an increase in gross weight of 3.8 percent.

Neither of the two options appears to be beneficial to the performance of the HLFC aircraft. Of the two, the increase in initial cruise altitude to 36,000 feet has the smaller degradation in the overall aircraft performance.

6.1.2 Elimination of HLFC on Empennage

The effects on performance of deleting HLFC from the empennage of the HLFC aircraft is provided in the data for Option 4 in Figure 44. As compared to the baseline turbulent flow aircraft, the HLFC aircraft with no HLFC on the empennage shows a reduction in fuel burned of 13.7 percent, an increase in lift-to-drag ratio of 18.2 percent, a decrease in engine thrust of 11.9 percent, and a decrease in gross weight of 4.2 percent. Except for the insignificant reduction in lift-to-drag ratio, these improvements in performance as compared to the turbulent flow aircraft are slightly better than those for the baseline HLFC aircraft. It appears from these data that elimination of HLFC from the empennage has a favorable overall effect on HLFC aircraft performance and reduces the complexity of the systems as well.

6.1.3 Elimination of HLFC on Lower Wing Surface

The effects on HLFC aircraft performance of deleting HLFC on the lower surface of the wing is provided in the data for Option 5 in Figure 44. As compared to the baseline turbulent flow aircraft, the HLFC aircraft with no

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1986 HLFC CONTRACT STUDY - NASA/AIR FORCE

COMPARISON - PERCENT CHANGE FROM BASELINE

	BASELINE	OPTION 1	OPTION 4	OPTION 5	D - 1	D - 2	D - 3
PAYLOAD - LB	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
RANGE OF RADIUS - NM	6,500.00	6,500.00	6,500.00	6,500.00	0.00	0.00	0.00
SPEED - M	0.77	0.77	0.77	0.77	0.00	0.00	0.00
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	32,119.00	31,361.00	31,496.00	31,867.00	-2.35	-1.93	-0.78
CFL - FT	7,557.00	8,383.20	8,327.10	8,173.30	10.93	10.19	8.15
MID-POINT CFL - FT	5,516.00	2,172.00	2,168.00	2,245.00	-60.62	-60.69	-59.30
GROSS WEIGHT - LB	616,125.00	591,636.00	589,970.00	612,533.00	-3.97	-4.24	-0.58
							ERR
STRUCTURAL WEIGHT	128,023.00	139,985.00	140,477.00	143,021.00	9.34	9.72	11.71
PROPULSION SYSTEM	35,625.00	34,057.00	33,826.00	35,238.00	-4.40	-5.04	-1.08
SYSTEMS & EQUIP.	23,253.00	23,598.00	23,370.00	23,915.00	1.48	0.50	2.84
OPERATING EQUIP.	5,317.00	5,006.00	4,999.00	5,314.00	-5.84	-5.98	-0.05
OPERATING WEIGHT	192,218.00	202,646.00	202,672.00	207,308.00	5.42	5.43	7.85
ZERO FUEL WEIGHT	324,718.00	335,146.00	335,172.00	339,808.00	3.21	3.21	4.64
L.E. CLEAN FLUID	0.00	4,258.00	3,290.00	4,460.00			
FUEL	291,401.00	252,216.00	251,490.00	268,264.00	-13.44	-13.69	-7.93
PAYLOAD	132,500.00	132,500.00	132,500.00	132,500.00	0.00	0.00	0.00
USEFUL LOAD	423,901.00	384,716.00	383,990.00	400,764.00	-9.24	-9.41	-5.45
WING DATA							
AREA - SQ FT	4,835.39	4,832.28	4,837.28	5,047.59	-0.06	0.03	4.38
WEIGHT - LB	58,978.00	68,888.00	69,615.00	71,114.00	16.80	18.03	20.57
WEIGHT - LB/SQ FT	12.19	14.25	14.39	14.08	16.87	17.98	15.50
ASPECT RATIO	13.54	13.87	14.00	13.79	2.43	3.39	1.84
BASIC SWEEP - DEG	30.00	20.00	20.00	20.00	-33.33	-33.33	-33.33
BAT SWEEP - DEG	35.53	25.00	25.00	25.00	-29.63	-29.63	-29.63
LOADING - LB/SQ FT	124.42	119.19	118.83	118.13	-4.20	-4.49	-5.05
FUEL VOL. RATIO	1.00	1.00	1.00	1.00	0.00	0.00	0.00
SPAN - FT	255.91	258.85	260.26	263.86	1.14	1.69	3.10
C.F LB/SPAN FT	0.00	16.44	12.64	16.90	ERR	ERR	ERR
MAC - FT	22.88	22.60	22.54	23.12	-1.22	-1.46	1.08
T/C - %	13.49	11.83	11.80	11.73	-12.30	-12.52	-13.04
MISCELLANEOUS							
L/D	25.99	30.76	30.72	29.24	18.35	18.19	12.50
ML/D	20.01	23.68	23.65	22.51	18.35	18.19	12.50
CRUISE SFC	0.56	0.57	0.57	0.56	2.85	2.67	1.60
CL MAX T.O.	2.60	2.53	2.53	2.53	-2.69	-2.69	-2.69
CRUISE CL	0.52	0.48	0.48	0.49	-7.60	-7.72	-6.27
THRUST/ENGINE - LB	30,195.00	26,990.00	26,597.00	28,270.00	-10.61	-11.91	-6.37
THRUST/WEIGHT	0.19	0.18	0.18	0.18	-6.91	-8.01	-5.82
VERT AREA - SQ FT	439.52	563.03	563.83	583.19	28.10	28.28	32.68
HORIZ AREA - SQ FT	418.84	641.75	636.92	684.84	53.22	52.06	63.50

Figure 44A. Sensitivity Data

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	BASELINE	OPTION 1	OPTION 4	OPTION 5	D - 1	D - 2	D - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.88	0.78	0.78	0.82	-11.36	-10.90	-6.36
BASIC WING AREA	4,119.77	4,118.31	4,112.51	4,307.37	-0.03	-0.17	4.55
TOTAL WING AREA	4,835.39	4,832.20	4,837.28	5,047.59	-0.06	0.03	4.38
BAT AREA - % TOTAL	14.79	14.77	14.98	14.66	-0.16	1.23	-0.91
TOTAL/BASIC	1.17	1.17	1.17	1.17	-0.02	0.21	-0.15
L.E. SUCTION - % C		15.00	15.00	15.00			
L.F. TRANSITION - % C		50.00	50.00	50.00			
ENG LOC - % MAC		100.00	100.00	100.00	ERR	ERR	ERR
FUSELAGE WT/SQ FT	4.05	4.20	4.20	4.22	3.74	3.72	4.06
WING WT. EQUATION	13.00	13.00	13.00	13.00			

NOTES:

1. BASELINE = TURBULENT AIRCRAFT
2. OPTION 1 = HLFC BASELINE, M=0.77
3. OPTION 4 = HLFC NO HLFC ON EMPENN.
4. OPTION 5 = HLFC , NO HLFC ON LOWER SURF.

HLFC SYSTEM WEIGHT ADDITIONS

	BASELINE	OPTION 1	OPTION 4	OPTION 5	D - 1	D - 2	D - 3
STRUCTURE							
WING - LB	0.00	563.00	564.00	295.00	BASE	0.17	-47.60
HORIZ - LB	0.00	91.00	0.00	97.00	BASE	-100.00	6.59
VERT - LB	0.00	80.00	0.00	83.00	BASE	-100.00	3.75
TOTAL - LB	0.00	734.00	564.00	475.00	BASE	-23.16	-35.28
SUCTION SYSTEM							
ENGINES - LB	0.00	536.00	482.00	476.00	BASE	-10.07	-11.19
DUCTING - LB	0.00	569.00	500.00	581.00	BASE	-12.12	2.10
MISC - LB	0.00	665.00	596.00	591.00	BASE	-10.07	-11.12
TOTAL - LB	0.00	1,770.00	1,580.00	1,648.00	BASE	-10.73	-6.89
CLEANING SYSTEM							
SYSTEM - LB	0.00	373.00	288.00	390.00	BASE	-22.78	4.55
TRAPPED FLUID - LB	0.00	586.00	452.00	613.00	BASE	-22.86	4.60
MISSION FLUID - LB	0.00	4,258.00	3,290.00	4,460.00	BASE	-22.73	4.74
TOTAL - LB	0.00	5,217.00	4,030.00	5,463.00	BASE	-22.75	4.71
TOTAL DELTA WT. - LB	0.00	7,721.00	6,174.00	7,584.00	BASE	-20.03	-1.74
	BASELINE	OPTION 1	OPTION 4	OPTION 5	D - 1	D - 2	D - 3

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Figure 44B. Concluded

HLFC on the lower wing surface shows a decrease in fuel burned of 7.9 percent, an increase in lift-to-drag ratio of 12.5 percent, a decrease in engine thrust of 6.4 percent, and a decrease in gross weight of 0.6 percent. These improvements in performance are considerably less than those shown for the baseline HLFC aircraft as compared to the turbulent flow aircraft, showing 41 percent more fuel burned, 32 percent lower lift-to-drag ratio, and 40 percent higher thrust required. It appears from these data that elimination of the HLFC from the lower wing surface has an overall unfavorable effect on the performance of the HLFC aircraft.

6.1.4 Reduction of Aspect Ratio to 10

Sizing runs were made in order to determine the effects of a reduction in wing aspect ratio from the baseline values of over 13 to a more moderate aspect ratio of 10. The sizing data presented in Figure 45 include the HLFC baseline aircraft for aspect ratio 13.87 and aspect ratio 10 data for the HLFC aircraft and a turbulent flow aircraft.

Results indicate that the HLFC concept with aspect ratio 10 compared to the HLFC baseline has a 2.9 percent higher gross weight, 11.5 percent more fuel burned, 12.2 percent decrease in L/D, and 11.7 percent more engine thrust. In addition, the aspect ratio 10 HLFC aircraft has a reduction in wing span from 258.85 feet to 219.35 feet, or 15.3 percent, as compared to the baseline HLFC aircraft. The wing span comparison is shown in Figure 46. Comparing the turbulent flow and HLFC aspect ratio 10 runs in Figure 45 shows that the HLFC configuration has a 4.1 percent reduction in gross weight, 12.1 percent less fuel burned, 15.1 percent higher L/D, and a 9 percent reduction in engine thrust. These differences between the aspect ratio 10 aircraft are slightly smaller, yet very similar to the differences found between the higher aspect ratio turbulent and HLFC baseline aircraft reported in Section 5.4.

HLFC BASELINE / BASELINES WITH ASPECT RATIO = 10

01-MAY-1987

1986 HLFC CONTRACT STUDY - NASA/AIR FORCE

COMPARISON - PERCENT CHANGE FROM BASELINE

	BASELINE	OPTION 1	OPTION 2		(1-B)/B	(1-2)/2	B - 3
PAYLOAD - LB	132,500.00	132,500.00	132,500.00		0.00	0.00	ERR
RANGE OR RADIUS - NM	6,500.00	6,500.00	6,500.00		0.00	0.00	ERR
SPEED - M	0.77	0.77	0.77		0.00	0.00	ERR
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	31,361.00	30,490.00	30,961.00		-2.78	-1.52	ERR
CFL - FT	8,383.20	8,167.60	7,223.50		-2.61	12.79	ERR
MID-POINT CFL - FT	2,172.00	2,525.00	5,322.00		16.25	-52.56	ERR
GROSS WEIGHT - LB	591,636.00	609,041.00	635,230.00		2.94	-4.12	ERR
							ERR
STRUCTURAL WEIGHT	139,985.00	124,756.00	115,112.00		-10.88	8.38	ERR
PROPULSION SYSTEM	36,757.00	37,057.00	38,880.00		0.81	-4.69	ERR
SYSTEMS & EQUIP.	23,590.00	23,737.00	23,090.00		0.59	2.80	ERR
OPERATING EQUIP.	5,006.00	5,236.00	5,549.00		4.59	-5.64	ERR
OPERATING WEIGHT	202,646.00	190,786.00	182,631.00		-5.85	4.47	ERR
ZERO FUEL WEIGHT	335,146.00	323,286.00	315,131.00		-3.54	2.59	ERR
L.E. CLEAN FLUID	4,250.00	4,490.00	0.00				
FUEL	252,216.00	281,260.00	320,094.00		11.52	-12.13	ERR
PAYLOAD	132,500.00	132,500.00	132,500.00		0.00	0.00	ERR
USEFUL LOAD	384,716.00	413,760.00	452,594.00		7.55	-8.58	ERR
WING DATA							
AREA - SQ FT	4,832.28	4,811.49	4,746.11		-0.43	1.38	ERR
WEIGHT - LB	68,888.00	52,714.00	45,414.00		-23.48	16.07	ERR
WEIGHT - LB/SQ FT	14.26	10.96	9.57		-23.15	14.49	ERR
ASPECT RATIO	13.87	10.00	10.00		-27.90	0.00	ERR
BASIC SWEEP - DEG	20.00	20.00	30.00		0.00	-33.33	ERR
HAT SWEEP - DEG	25.00	25.00	37.33		0.00	-33.03	ERR
LOADING - LB/SQ FT	119.19	123.11	130.61		3.29	-5.74	ERR
FUEL VOL. RATIO	1.00	1.00	1.00		0.00	0.00	ERR
SPAN - FT	258.85	219.35	217.86		-15.26	0.68	ERR
C.P LB/SPAN FT	16.45	20.47	0.00		24.44	ERR	ERR
MAC - FT	22.60	25.15	26.38		11.26	-4.67	ERR
t/c - %	11.83	11.93	13.39		0.85	-10.90	ERR
MISCELLANEOUS							
L/D	30.76	27.02	23.40		-12.16	15.48	ERR
ML/D	23.69	20.81	24.25		-12.16	-14.20	ERR
CRUISE SFC	0.58	0.57	0.57		-0.82	1.26	ERR
CL MAX T.O.	2.53	2.33	2.47		-7.91	-5.67	ERR
CRUISE CL	0.49	0.48	0.52		-0.62	-7.68	ERR
THRUST/ENGINE - LB	26,990.00	30,154.00	33,138.00		11.72	-9.00	ERR
THRUST/WEIGHT	0.18	0.20	0.21		8.53	-5.07	ERR
VERT AREA - SQ FT	563.03	605.43	446.11		7.53	35.71	ERR
HORIZ AREA - SQ FT	641.75	624.54	389.56		-2.68	60.33	ERR

Figure 45A. Sizing Data for Aspect Ratio 10 Aircraft

01-MAY-1987

	BASELINE	OPTION 1	OPTION 2		(1-B)/B	(1-2)/2	B - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.78	0.80	0.89		3.05	-10.06	ERR
BASIC WING AREA	4,118.31	4,382.88	4,043.70		6.42	8.39	ERR
TOTAL WING AREA	4,832.30	4,811.49	4,746.11		-0.43	1.38	ERR
SAT AREA - % TOTAL	14.70	8.91	14.00		-39.71	-39.81	ERR
TOTAL/BASIC	1.17	1.10	1.17		-6.44	-6.47	ERR
L.E. SUCTION - % C	15.00	15.00	15.00				
L.F.TRANSITION - % C	50.00	50.00	50.00				
ENG LOC - % MAC	100.00	100.00	100.00				
FUSELAGE WT/SQ FT	4.21	4.23	4.06		0.50	4.19	ERR
WING WT. EQUATION	13.00	13.00	13.00				

NOTES:

1. BASELINE = HLFC BASELINE, M=0.77
2. OPTION 1 = HLFC AR=10
3. OPTION 2 = TURBULENT AR=10

HLFC SYTEM WEIGHT ADDITIONS

	BASELINE	OPTION 1	OPTION 2		(1-B)/B	(1-2)/2	B -3
STRUCTURE							
WING - LB	563.00	556.00	0.00		-1.24	ERR	ERR
HORIZ - LB	91.00	88.00	0.00		-3.30	ERR	ERR
VERT - LB	80.00	86.00	0.00		7.50	ERR	ERR
TOTAL - LB	734.00	730.00	0.00		-0.54	ERR	ERR
SUCTION SYSTEM							
ENGINES - LB	536.00	541.00	0.00		0.93	ERR	ERR
DUCTING - LB	569.00	494.00	0.00		-13.18	ERR	ERR
MISC - LB	665.00	670.00	0.00		0.75	ERR	ERR
TOTAL - LB	1,770.00	1,705.00	0.00		-3.67	ERR	ERR
CLEANING SYSTEM							
SYSTEM - LB	373.00	393.00	0.00		5.36	ERR	ERR
TRAPPED FLUID - LB	586.00	617.00	0.00		5.29	ERR	ERR
MISSION FLUID - LB	4,258.00	4,490.00	0.00		5.45	ERR	ERR
TOTAL - LB	5,217.00	5,500.00	0.00		5.42	ERR	ERR
TOTAL DELTA WT. - LB	7,721.00	7,935.00	0.00		2.77	ERR	ERR

01-MAY-1987

Figure 45B. Concluded

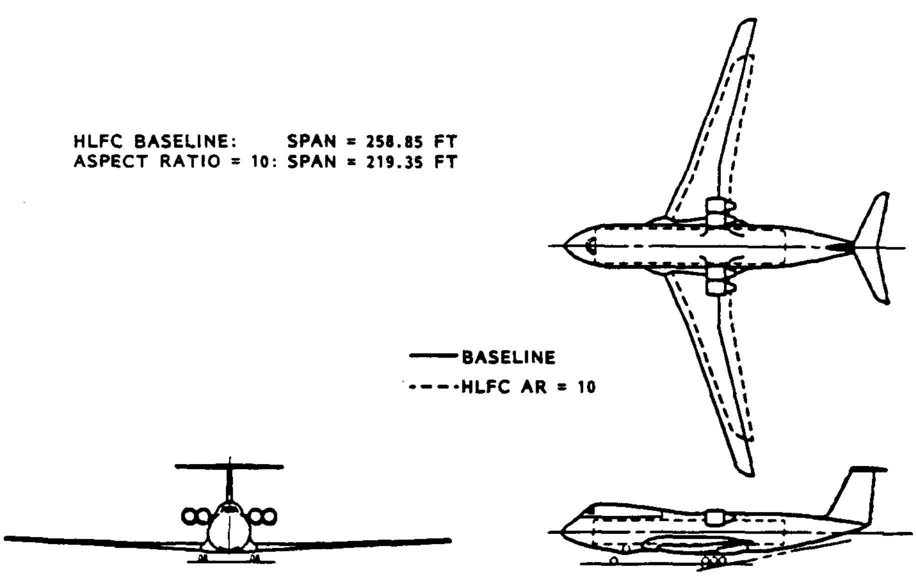


Figure 46. Comparison of HLFC Baseline and HLFC Aspect Ratio 10 Aircraft

6.1.5 High Wing HLFC Configuration

Sizing runs for hybrid LFC transports for the more conventional arrangement of high wings with the engines mounted on the wings were made in order to provide the data for an assessment of the wing-mounted versus the fuselage-mounted engine arrangement of the hybrid LFC baseline configuration. In order to account for the interference of the pylon-mounted engines under the high wing configuration, it was decided that there would be a loss of laminar flow on the lower wing surface in a streamwise direction with an area of loss consisting of the maximum width of the engine at the wing leading edge plus a 7^{o} increase in area over the wing surface to the trailing edge. A plan view of this loss in laminar flow is shown in Figure 47. No upper surface loss of laminar flow is assumed for these sizing runs.

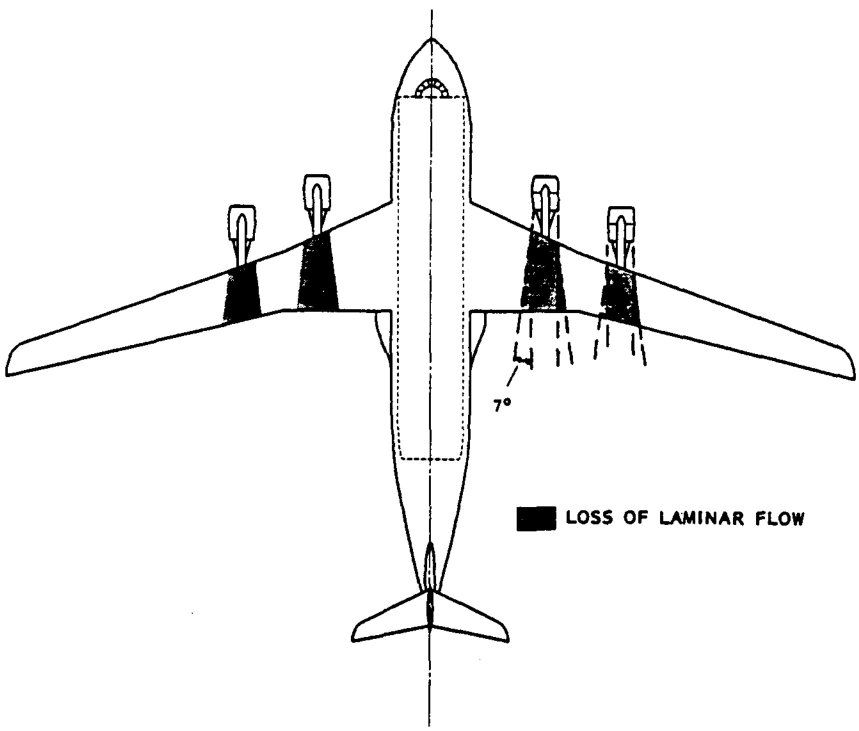


Figure 47. Plan View of Laminar Flow Area Loss for Wing Mounted Engine Configuration; Lower Wing Surface

Sizing data for the high wing configurations are given in Figure 48 for a cruise Mach number of 0.77. It should be noted that the high wing turbulent flow aircraft used for reference here has 20° of wing sweep as contrasted to 30° wing sweep for the previously reported turbulent flow baseline aircraft. As noted in Figure 48, the sizing runs consist of a reference turbulent flow aircraft, an HLFC aircraft with laminar flow on both upper and lower surfaces, and an HLFC aircraft with laminar flow on the upper surface only.

The results of Figure 48 indicate that the HLFC high wing aircraft with laminar flow on both upper and lower surfaces as compared to the turbulent flow aircraft has 10.4 percent lower gross weight, 19.6 percent lower fuel burned, 18.1 percent increase in L/D, 15.3 percent decrease in engine thrust, and 4.8 percent reduction in wing span. These results for the HLFC configuration are the best overall performance data obtained for an HLFC aircraft in

HLFC HI WING (2), & TURB 20 DEG COMPARISON

05-JUN-1987

1986 HLFC CONTRACT STUDY - NASA/AIR FORCE

COMPARISON - % CHANGE FROM 20 DEG. TURBULENT

	TURBULENT	OPTION 1	OPTION 2		(1-T)/T	(2-T)/T	0 - 0
PAYLOAD - LB	132,500.00	132,500.00	132,500.00		0.00	0.00	
RANGE OF RADIUS - NM	6,500.00	6,500.00	6,500.00		0.00	0.00	
SPEED - M	0.77	0.77	0.77		0.00	0.00	
ENDURANCE - HRS							
ALTITUDE - FT	32,306.00	31,950.00	32,005.00		-1.10	-0.93	
CFL - FT	6,271.00	8,153.00	8,172.00		30.01	30.31	
MID-POINT CFL - FT	5,363.00	5,035.00	5,120.00		-6.12	-4.53	
GROSS WEIGHT - LB	636,911.00	570,734.00	589,257.00		-10.39	-7.48	
STRUCTURAL WEIGHT	138,474.00	131,311.00	133,549.00		-5.17	-3.56	
PROPULSION SYSTEM	36,337.00	33,231.00	34,160.00		-8.55	-6.05	
SYSTEMS & EQUIP.	23,575.00	23,042.00	23,294.00		-2.26	-1.19	
OPERATING EQUIP.	5,302.00	4,922.00	5,040.00		-0.72	-4.93	
OPERATING WEIGHT	203,770.00	192,306.00	196,023.00		-5.53	-3.01	
ZERO FUEL WEIGHT	336,270.00	325,006.00	328,523.00		-3.35	-2.31	
L.E. CLEAN FLUID	0.00	3,079.00	4,022.00				
FUEL	300,602.00	241,033.00	256,693.00		-19.81	-14.61	
PAYLOAD	132,500.00	132,500.00	132,500.00		0.00	0.00	
USEFUL LOAD	433,102.00	374,333.00	389,193.00		-13.57	-10.14	
WING DATA							
AREA - SQ FT	5,526.00	4,725.00	4,904.00		-14.50	-11.26	
WEIGHT - LB	68,088.00	62,711.00	64,152.00		-7.90	-5.78	
WEIGHT - LB/SQ FT	12.32	13.27	13.08		7.72	6.17	
ASPECT RATIO	13.09	13.86	13.86		5.88	5.88	
BASIC SWEEP - DEG	20.00	20.00	20.00		0.00	0.00	
RAT SWEEP - DEG	26.82	25.00	25.00		-6.78	-6.78	
LOADING - LB/SQ FT	112.55	117.60	117.01		4.49	3.96	
FUEL VOL. RATIO	1.00	1.00	1.00		0.00	0.00	
SPAN - FT	268.95	255.92	260.75		-4.84	-3.05	
C.P LB/SPAN FT	0.00	13.16	15.42		ERR	ERR	
MAC - FT	24.88	22.35	22.76		-10.17	-8.51	
t/c - %	11.14	11.74	11.75		5.39	5.48	
MISCELLANEOUS							
L/D	26.24	30.99	29.82		18.10	13.58	
ML/D	20.20	23.86	22.73		18.10	12.50	
CRUISE SFC	0.56	0.58	0.57		1.95	1.06	
CL MAX T.O.	2.77	2.45	2.44		-11.55	-11.91	
CRUISE CL	0.48	0.49	0.49		2.71	2.50	
THRUST/ENGINE - LB	31,010.00	26,263.00	27,044.00		-15.31	-12.78	
THRUST/WEIGHT	0.19	0.18	0.18		-5.49	-5.76	
VERT AREA - SQ FT	506.86	453.50	466.55		-10.53	-7.98	
HORIZ AREA - SQ FT	449.96	367.99	381.91		-18.21	-15.11	

Figure 48A. Sizing Data for High Wing Turbulent Flow and HLFC Aircraft; Sweepback 20°

05-JUN-1987

	TURBULENT	OPTION 1	OPTION 2		(1-T)/T	(2-T)/T	0 - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.89	0.78	0.82		-11.64	-6.80	
BASIC WING AREA	4,708.00	4,020.00	4,179.00		-14.64	-11.24	
TOTAL WING AREA	5,526.00	4,735.00	4,904.00		-14.80	-11.26	
SAT AREA - % TOTAL	14.80	14.75	14.70		-0.35	-0.13	
TOTAL/BASIC	1.17	1.17	1.17		-0.06	-0.02	
L.E. SUCTION - % C	15.00	15.00	15.00				
L.E. TRANSITION - % C	50.00	50.00	50.00				
ENG LOC - % MAC							
FUSELAGE WT/SQ FT	4.07	4.19	4.20		2.97	3.22	
WING WT. EQUATION	13.00	13.00	13.00				

NOTES:

1. TURBULENT = TURB. CONFIGURATION, 20 DEGREES SWEEP
2. OPTION 1 = HLFC HI WING, UP. & LOWER SURF. LAMINAR (LOWER SURFACE LOSS BEHIND ENGINES
3. OPTION 2 = HLFC HI WING, LFC UPPER SURFACE ONLY

HLFC SYSTEM WEIGHT ADDITIONS

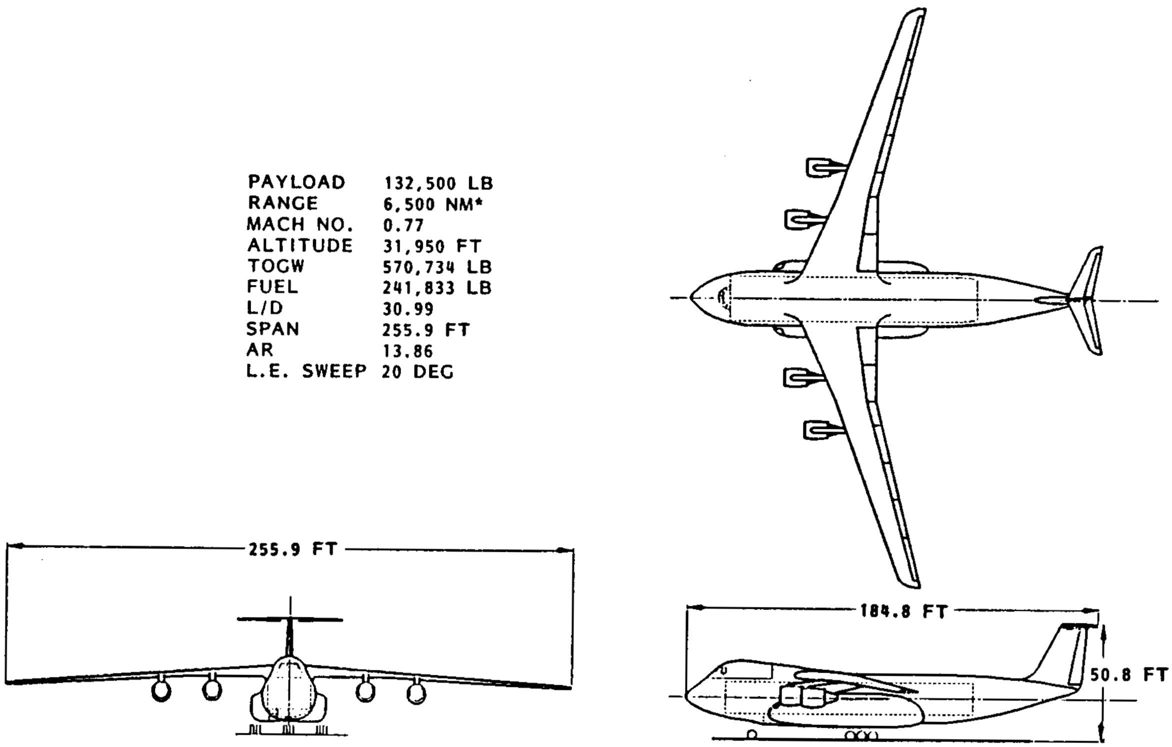
	TURBULENT	OPTION 1	OPTION 2		(1-T)/T	(2-T)/T	
STRUCTURE							
WING - LB	0.00	550.00	572.00		ERR	ERR	
HORIZ - LB	0.00	52.00	54.00		ERR	ERR	
VERT - LB	0.00	64.00	66.00		ERR	ERR	
TOTAL - LB	0.00	666.00	692.00		ERR	ERR	
SUCTION SYSTEM							
ENGINES - LB	0.00	520.00	529.00		ERR	ERR	
DUCTING - LB	0.00	551.00	561.00		ERR	ERR	
MISC - LB	0.00	644.00	656.00		ERR	ERR	
TOTAL - LB	0.00	1,715.00	1,746.00		ERR	ERR	
CLEANING SYSTEM							
SYSTEM - LB	0.00	339.00	352.00		ERR	ERR	
TRAPPED FLUID - LB	0.00	533.00	553.00		ERR	ERR	
MISSION FLUID - LB	0.00	3,879.00	4,022.00		ERR	ERR	
TOTAL - LB	0.00	4,751.00	4,927.00		ERR	ERR	
TOTAL DELTA WT. - LB	0.00	7,132.00	7,365.00		ERR	ERR	

05-JUN-1987

Figure 48B. Concluded

this study task. As compared to the HLFC baseline aircraft with fuselage-mounted engines, this HLFC high wing aircraft has 3.5 percent lower gross weight, 5.0 percent lower operating weight empty, 4.1 percent lower fuel burned, a slight increase in L/D, 2.7 percent decrease in engine thrust, and 1.1 percent reduction in wing span. In the author's opinion, however, these high wing HLFC results are optimistic because of the assumption of no loss of laminar flow on the wing upper surface for this wing-mounted engine configuration. A general arrangement drawing of the high wing HLFC aircraft is presented in Figure 49.

The results for the HLFC high wing aircraft with laminar flow on the upper surface only, as compared to the turbulent flow aircraft, show 7.5 percent lower gross weight, 14.6 percent lower fuel burned, 12.5 percent higher L/D, 12.8 percent decrease in engine thrust, and 3.1 percent reduction in wing span for the HLFC configuration. As compared to the HLFC baseline aircraft with fuselage-mounted engines, this HLFC high wing aircraft is slightly inferior in performance with a negligible difference in gross weight, 1.8 percent increase in fuel burned, 4.0 percent reduction in L/D, and a slight increase in engine thrust. As cited previously, the results for the high wing HLFC configurations are considered to be optimistic because of the assumption of no loss in laminar flow on the upper wing surface.



*SEE FIGURE 3

Figure 49. General Arrangement Drawing of High Wing HLFC Aircraft

6.2 TURBULENT FLOW AIRCRAFT SENSITIVITY STUDIES

6.2.1 Increase of Altitude to 36,000 Feet

Sizing calculations for additional sensitivity studies of the turbulent flow aircraft were made, and the data are presented in Figure 50. The Option 1 sizing run was performed to determine the effect of increase in initial cruise altitude from 32,119 feet to 36,000 feet. As compared to the lower cruise altitude performance, the increase in initial cruise altitude results in 2.1 percent increase in fuel burned, 6.1 percent increase in lift-to-drag ratio, 11.7 percent increase in engine thrust, and 1.6 percent increase in gross weight. These results are similar to those for the HLFC aircraft when the initial cruise altitude is increased to 36,000 feet.

TURBULENT B.L./ BASELINE AT 36,000 FT; 212,000 LB PAYOAD

01-MAY-1987

1986 HLFC CONTRACT STUDY - NASA/AIR FORCE

COMPARISON - PERCENT CHANGE FROM BASELINE

	BASELINE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
PAYLOAD - LB	132,500.00	132,500.00	212,000.00		0.00	60.00	ERR
RANGE OF RADIUS - NM	6,500.00	6,500.00	6,500.00		0.00	0.00	ERR
SPEED - M	0.77	0.77	0.77		0.00	0.00	ERR
ENDURANCE - HRS					ERR	ERR	ERR
ALTITUDE - FT	32,119.00	36,000.00	31,148.00		12.08	-3.02	ERR
CFL - FT	7,557.00	6,589.90	8,847.40		-12.80	17.08	ERR
MID-POINT CFL - FT	5,516.00	6,549.00	5,262.00		18.73	-4.60	ERR
GROSS WEIGHT - LB	616,125.00	625,917.00	916,333.00		1.59	48.73	ERR
							ERR
STRUCTURAL WEIGHT	128,023.00	141,207.00	196,373.00		10.30	53.39	ERR
PROPULSION SYSTEM	35,625.00	38,246.00	48,855.00		7.36	37.14	ERR
SYSTEMS & EQUIP.	23,253.00	23,531.00	27,760.00		1.20	19.38	ERR
OPERATING EQUIP.	5,317.00	5,269.00	7,571.00		-0.90	42.39	ERR
OPERATING WEIGHT	192,218.00	208,253.00	280,559.00		8.34	45.96	ERR
ZERO FUEL WEIGHT	324,718.00	340,753.00	492,559.00		4.94	51.69	ERR
L.E. CLEAN FLUID	0.00	0.00	0.00				
FUEL	291,401.00	285,160.00	423,769.00		-2.14	45.42	ERR
PAYLOAD	132,500.00	132,500.00	212,000.00		0.00	60.00	ERR
USEFUL LOAD	423,901.00	417,660.00	635,769.00		-1.47	49.98	ERR
WING DATA							
AREA - SQ FT	4,835.39	5,136.30	6,436.75		6.22	33.12	ERR
WEIGHT - LB	58,978.00	70,764.00	94,297.00		19.98	59.89	ERR
WEIGHT - LB/SQ FT	12.20	13.78	14.65		12.95	20.11	ERR
ASPECT RATIO	13.54	14.42	13.41		6.49	-0.96	ERR
BASIC SWEEP - DEG	30.00	30.00	30.00		0.00	0.00	ERR
SAT SWEEP - DEG	35.53	35.22	35.59		-0.88	0.18	ERR
LOADING - LB/SQ FT	124.42	118.91	139.06		-4.43	11.77	ERR
FUEL VOL. RATIO	1.00	1.00	1.00		0.00	0.00	ERR
SPAN - FT	255.91	272.14	293.78		6.34	14.80	ERR
C.F LB/SPAN FT	0.00	0.00	0.00		ERR	ERR	ERR
MAC - FT	22.88	22.85	26.53		-0.13	15.94	ERR
t/c - %	13.49	12.37	12.95		-8.30	-3.98	ERR
MISCELLANEOUS							
L/D	25.99	27.57	26.38		6.08	1.50	ERR
ML/D	20.01	21.23	20.31		6.08	1.50	ERR
CRUISE SFC	0.56	0.56	0.57		0.00	0.89	ERR
CL MAX T.O.	2.60	2.60	2.54		0.00	-2.31	ERR
CRUISE CL	0.53	0.60	0.56		14.83	6.04	ERR
THRUST/ENGINE - LB	30,195.00	33,719.00	43,313.00		11.67	43.44	ERR
THRUST/WEIGHT	0.20	0.22	0.19		9.92	-3.55	ERR
VERT AREA - SQ FT	439.52	452.59	705.19		2.97	60.45	ERR
HORIZ AREA - SQ FT	418.84	446.10	602.93		6.51	43.95	ERR

Figure 50A. Turbulent Flow Aircraft Sizing Data

01-MAY-1987

	BASELINE	OPTION 1	OPTION 2	OPTION 3	D - 1	D - 2	D - 3
MISCELLANEOUS (CON'T)							
POWER SETTING	0.88	0.86	0.88		-2.27	-0.57	ERR
BASIC WING AREA	4,119.77	4,376.15	5,484.13		6.22	33.12	ERR
TOTAL WING AREA	4,835.39	5,136.30	6,436.75		6.22	33.12	ERR
BAT AREA - % TOTAL	14.80	14.80	14.80		-0.00	0.00	ERR
TOTAL/BASIC	1.17	1.17	1.17		-0.00	0.00	ERR
L.E. SUCTION - % C							
L.F.TRANSITION - % C							
ENG LOC - % MAC					ERR	ERR	ERR
FUSELAGE WT/SQ FT	4.06	4.07	4.26		0.27	5.00	ERR
WING WT. EQUATION	13.00	13.00	13.00				

NOTES:

1. BASELINE = TURBULENT AIRCRAFT
2. OPTION 1 = TURBULENT AT 36,000 FT
3. OPTION 2 = 212,000 LB PAYOAD TURBULENT

Figure 50B. Concluded

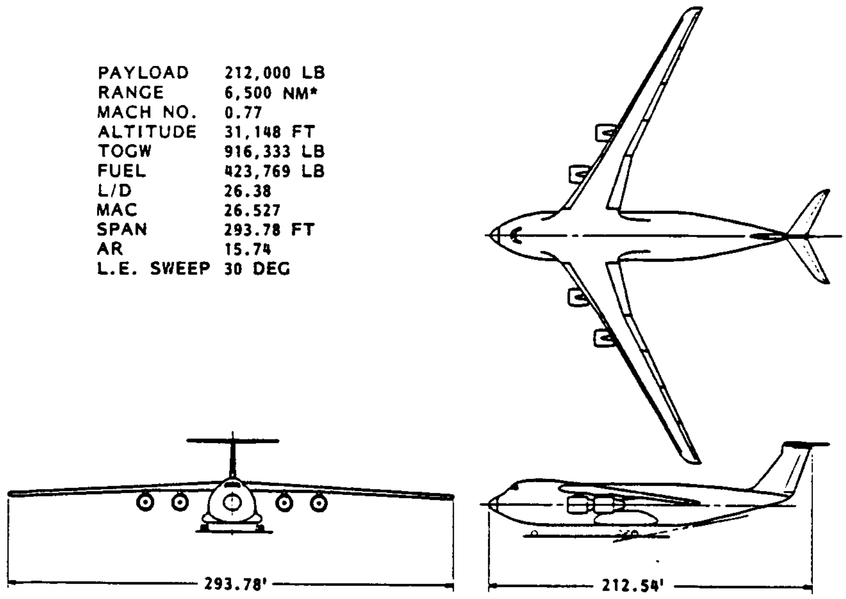
6.2.2 Increase of Payload to 212,000 Pounds

In the study of these advanced technology military transports, it was desired to determine the performance data for a turbulent flow aircraft sized for the payload derived in the TAFAD study resulting from an in-depth mission analysis of the Congressionally Mandated Mobility Study. This study established an optimum payload of 212,000 pounds for rapid deployment.

Figure 50 includes data for the turbulent flow airlifter capable of transporting 212,000 pound payloads over the same global range mission as the baseline. This turbulent flow aircraft, as expected, is very large as compared to the turbulent baseline. The 60 percent increase in payload results in a 48.7 percent increase in gross weight, 45.4 percent more fuel burned, and 44 percent higher thrust per engine as compared to the turbulent baseline aircraft. A general arrangement drawing of the aircraft is presented in Figure 51.

This large aircraft has a gross weight of 916,333 pounds, mission fuel requirement of 423,769 pounds, wing aspect ratio of 13.4, thrust per engine of 43,313 pounds, and a lift-to-drag ratio of 26.4. The wing span of 293.78 feet as compared to 222.8 feet for the C-5 aircraft as shown in Figure 52.

PAYLOAD	212,000 LB
RANGE	6,500 NM*
MACH NO.	0.77
ALTITUDE	31,148 FT
TOGW	916,333 LB
FUEL	423,769 LB
L/D	26.38
MAC	26.527
SPAN	293.78 FT
AR	15.74
L.E. SWEEP	30 DEG



*SEE FIGURE 3

Figure 51. General Arrangement of 212,000 LB Payload Turbulent Flow Aircraft

WING SPANS	
C-5	222.71'
GLOBAL RANGE TRANSPORT	293.78'

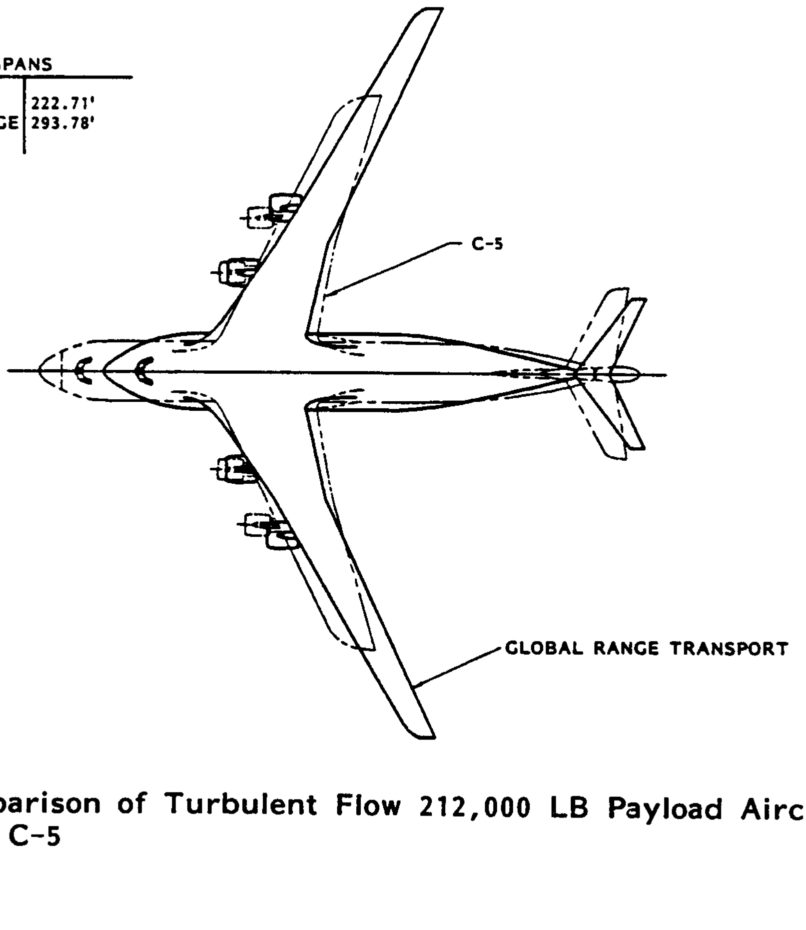


Figure 52. Comparison of Turbulent Flow 212,000 LB Payload Aircraft With C-5

6.2.3 Reduction of Aspect Ratio to 10

A comparison of performance characteristics of the turbulent baseline aircraft and the aspect ratio 10 turbulent aircraft are obtained from the data of Figures 50 and 45, Option 2. The results show that the turbulent flow aircraft with aspect ratio 10, as compared to the turbulent baseline aircraft, has a 1.5 percent increase in gross weight, 9.8 percent more fuel burned, a 9.7 percent decrease in L/D, a 9.7 percent increase in thrust required, and a 14.9 percent reduction in wing span. The difference in wing span of 255.9 feet for the baseline turbulent aircraft and 217.86 feet for the aspect ratio 10 turbulent aircraft is shown in Figure 53.

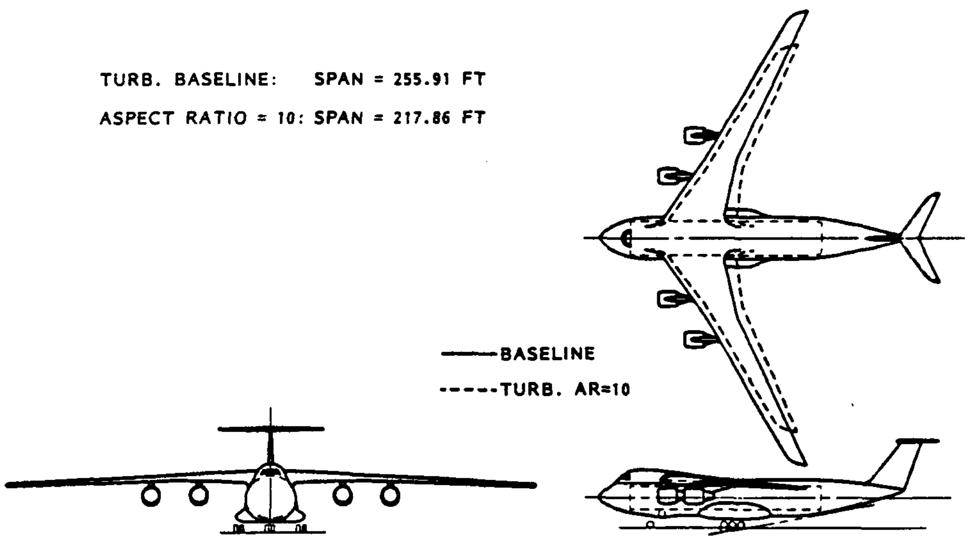


Figure 53. Comparison of Turbulent Flow Baseline and Aspect Ratio 10 Aircraft

7.0 ASSESSMENT OF HLFC BENEFITS AND SELECTED CONFIGURATIONS

In this preliminary design system study a considerable amount of aircraft sizing data has been generated to establish baseline turbulent flow and hybrid LFC aircraft configurations which perform the global range mission requirements. These results have been discussed in Section 5. In addition, certain sensitivity studies have been made including changes in performance parameters and also changes to the aircraft configuration concept as described in Section 6. It is the purpose of this section of the report to provide an overall assessment of the results of the study including comments on final selected HLFC configurations.

A summary of the significant study results are provided in Figure 54 showing changes in HLFC performance parameters relative to the baseline turbulent flow aircraft. These results have been discussed in more detail previously in Sections 5 and 6. A review of the data in Figure 54 shows that the largest benefits of HLFC in reduction of fuel consumption and with the least increase in aircraft operating weight are obtained with the high wing, engines on wing HLFC configuration. As compared to the turbulent flow baseline aircraft, the high wing HLFC aircraft shows 17 percent reduction in fuel burned, 19.2 percent increase in lift-to-drag ratio, an insignificant increase in operating weight, and 7.4 percent reduction in gross weight. The second best HLFC configuration is the low wing, fuselage mounted arrangement with no HLFC on the empennage. This configuration shows 13.7 percent reduction in fuel burned, 18.2 percent increase in lift-to-drag ratio, 5.4 percent increase in operating weight, and 4.2 percent reduction in gross weight. This configuration with no HLFC on the empennage is favored over the low wing HLFC initial baseline aircraft because of the reduced complexity of elimination of HLFC peculiar equipment for the empennage. The candidate for the fourth selected configuration was determined from the results of the high wing HLFC with no lower surface laminar flow and the low wing baseline aircraft operated at initial cruise altitude of 36,000 feet. The results show approximately the same percentage reduction in fuel burned, but the considerably lower operating weight and gross weight of the high wing configuration is considered more favorable as compared to the higher altitude operation case. As expected, the aspect ratio 10 HLFC configuration resulted in reduced operating weight and the benefits in fuel consumption and lift-to-drag ratio were very low as compared to the higher aspect ratio turbulent flow baseline aircraft.

In summary, the final selected HLFC configurations obtained from the parametric sizing studies of M = 0.77 HLFC global range military aircraft are listed below in order of highest priority:

1. High wing with wing mounted engines and no HLFC on empennage.

2. Low wing with fuselage mounted engines and no HLFC on empennage.

3. Low wing with fuselage mounted engines and including HLFC on empennage.

4. High wing with wing mounted engines and no HLFC on lower wing surface.

5. Low wing with fuselage mounted engines and increased initial cruise altitude to 36,000 feet.

A further assessment of the above selected HLFC configurations is deemed necessary. It should be noted that the performance of the high wing with wing mounted engines configurations is based on the assumption that there is no loss of laminar flow on the upper wing surface. In the author's opinion this

CHANGE, PERCENT-RELATIVE TO TURBULENT FLOW BASELINE AIRCRAFT

	HLFC BASELINE	NO HLFC ON EMPENNAGE	NO LOWER SURFACE HLFC	ALTITUDE 36,000 FT	ASPECT RATIO 10	HIGH WING ENGINES ON WING, HLFC	HIGH WING ENGINES ON WING; NO LOWER SURFACE HLFC
WEIGHTS							
OPERATING EMPTY	5.4	5.4	7.9	15.5	-0.7	0.2	1.9
GROSS	-4.0	-4.2	-0.6	-0.3	-1.1	-7.4	-4.4
FUEL CONSUMPTION	-13.4	-13.7	-7.9	-12.4	-3.5	-17.1	-11.9
LIFT TO DRAG RATIO	18.4	18.2	12.5	22.7	4.0	19.2	13.6

Figure 54. Summary of HLFC Aircraft Results Relative to Turbulent Flow Baseline

is an optimistic assumption which cannot be validated at this time for an HLFC aircraft with wing mounted engines. Preliminary flight tests of a natural laminar flow gloved wing section just outboard of the engine on a Boeing 757 aircraft have been made to determine the effects of engine noise on boundary layer transition as reported in Reference 20. These flight test results showed for the conditions of the tests a negligible effect of engine power on transition on the upper surface and small effects on the lower surface. It is felt, however, for conditions involving longer laminar runs such as those for the HLFC configurations of this study that the effects of the engine on laminar boundary layer transition are incomplete. Furthermore, it is expected that engine effects on transition could be more pronounced for the multi-engine arrangements of this study. Further research and development work in this important area is warranted.

In the ranking of selected configurations listed above, the low wing with fuselage mounted engines and including HLFC on the empennage received a high ranking. It is felt, however, that a preferred configuration will not have HLFC on the empennage in order to simplify the design concept and provide a more practical aircraft.

The operation of the HLFC aircraft at 36,000 feet initial cruise altitude provides a notable increase, 3.7 percent, in lift-to-drag ratio as compared to the baseline HLFC aircraft operating at 31,361 feet. This improvement in lift-to-drag ratio, however, is accompanied by an 18 percent increase in engine thrust. This large increase in engine thrust is attributable to the relatively high by pass ratio of 6.97 of the STF-686 engine used in this study. Since operation at higher altitudes is more favorable to the attainment and preservation of laminar flow, additional investigations of high altitude operations with lower by pass ratio engines is warranted.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Preliminary design system studies of the application of hybrid laminar flow control to military transports sized to perform global range mission characteristics show significant performance benefits obtained for the hybrid LFC aircraft as compared to counterpart turbulent flow aircraft. The parametric aircraft sizing studies included the development of a considerable data base covering both sensitivity studies of baseline aircraft as well as changes in the overall design concepts of the aircraft configurations. The study results at M = 0.77 show that the largest benefits of HLFC are obtained with a high wing with engines on the wing configuration. As compared to the turbulent flow baseline aircraft, the high wing HLFC aircraft shows 17 percent reduction in fuel burned, 19.2 percent increase in lift-to-drag ratio, an insignificant increase in operating weight, and 7.4 reduction in gross weight. For this high wing configuration the performance data are based on the assumption that there is no upper surface loss in laminar flow with engines mounted on the wings. It is felt that this is an optimistic assumption especially for the longer laminar runs for the HLFC conditions of this study and for the multi-engine configurations. The second best HLFC configuration is the low wing, fuselage mounted arrangement with no HLFC on the empennage. This configuration shows 13.7 percent reduction in fuel burned, 18.2 percent increase in lift-to-drag ratio, 5.4 percent increase in operating weight, and 4.2 percent reduction in gross weight as compared to the turbulent flow aircraft.

Sensitivity studies included the determination of the effects on performance of increase in cruise Mach number from 0.77 to 0.80, increase in initial cruise altitude to 36,000 feet, and elimination of HLFC on the lower wing surface. These changes generally resulted in degradation in performance as compared to the baseline aircraft characteristics. As expected, the reduction in aspect ratio from the baseline value of about 13 to a value of 10 resulted in very low improvements in fuel consumption and lift-to-drag ratio.

In view of the superior performance of the high wing with engines mounted on the wing HLFC configuration, it is recommended that further research and development be conducted to provide the necessary data base for validation of the effects of engine operation on laminar boundary layer transition for flight Reynolds numbers corresponding to large, long range transport aircraft. Operation at higher altitudes of 36,000 feet and above are more favorable to the attainment and preservation of laminar flow. The data in this study show a moderate increase in lift-to-drag ratio for operation at initial cruise altitude of 36,000 feet, but with an attendant large increase in engine thrust for the relatively high by pass ratio engines used in this study. It is recommended that additional studies be made of high altitude operations with lower by pass ratio engines.

All HLFC aircraft in this study have been sized without the use of leading-edge high lift devices on the wings. In view of the favorable effects of leading-edge high lift systems on the airfield performance and the shielding effects for HLFC operations, it is recommended that additional sizing studies be conducted on the two best HLFC configurations of this study with the addition of leading-edge high lift systems.

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APPENDIX A

GENERAL AIRCRAFT SIZING PROGRAM (GASP)

The Lockheed Generalized Aircraft Sizing and Performance (GASP) computer program is used to size and define the aircraft in this study. The methodology of this program is outlined in Figure A-1.

GASP controls the interaction of the program modules provided by the various technical disciplines and the inputs provided for the specific configuration. GASP then generates a component buildup of drag and weight, and integrates these results into total aircraft drag and weight. Propulsion system size is defined by matching cruise thrust requirements or, if required, by mismatching these requirements so as to oversize the engine at cruise to provide additional takeoff thrust. The capability of sizing a configuration with a fixed-size propulsion system is also available. The aircraft size required for the mission is defined by an automated iterative process. GASP has been used in a number of previous studies (References 3, 5, 6, 8, 11, 12,

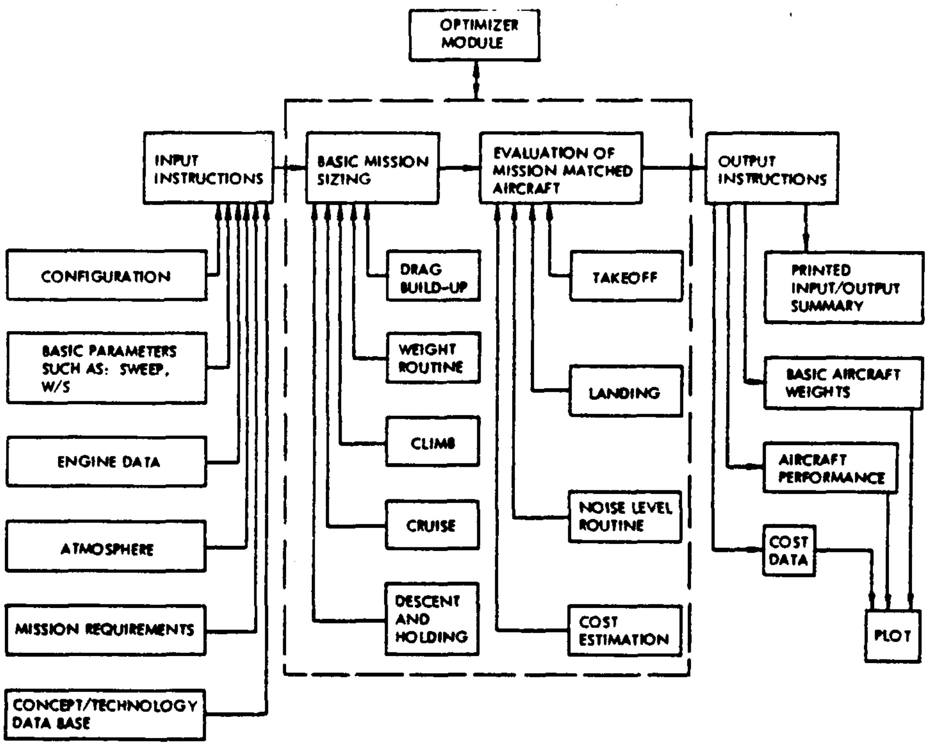

Figure A-1. Generalized Aircraft Sizing and Performance (GASP) Program

13, 14, 15) to synthesize aircraft for design variables such as wing loading, aspect ratio, cruise power setting, Mach number, range, payload, and field performance; and to define aircraft optimized to figures of merit such as minimum direct operating cost, gross weight, acquisition cost, fuel usage, and life cycle cost. These studies have encompassed conventional and assault transports as well as loiter/endurance missions. Turbofan and propfan propulsion systems were examined and various advanced materials were evaluated.

The general method of parametric analysis to be used is illustrated in Figure A-2. Aircraft characteristics are generated by GASP for parametric variations of sizing variables. For these data, performance constraints such as one-engine-out climb gradient capability, field length requirements, fuel volume availability, and landing approach speed can be generated and suitable constraints imposed on the resulting configuration. The two carpet plots in Figure A-2 provide a parametric evaluation in which the constraining performance variables are takeoff field length and second-segment climb gradient. These parameters are presented as a function of aspect ratio (AR) and initial cruise power setting (the percent of available cruise thrust required at the initial cruise point) for a given wing loading.

Specific field length and gradient capabilities, as determined from these carpet plots, along with a requirement that the engines have five percent excess available cruise thrust (= 0.95), define the group of acceptable configurations inside the hatched area in the middle section in Figure A-2. If desired, the complete carpet plots of aircraft characteristics such as gross weight and life cycle costs can be generated to show the impact of sizing constraints on the various figures of merit. However, the optimum values of the figures of merit will be defined by the envelope of constraint lines shown in this plot.

Another method of parametric analysis is provided by a numerical optimizer that has been coupled with the sizing program. This provides the capability of automatically selecting aircraft that minimize a given figure of merit while simultaneously meeting a defined set of constraints.

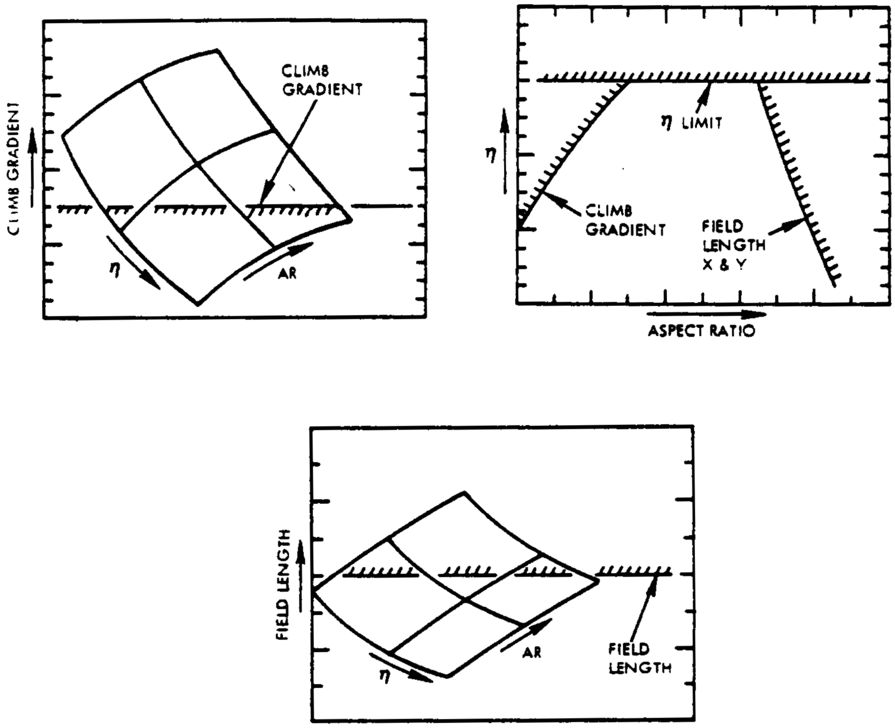

Figure A-2. Typical Parametric Selection Procedure

Input requirements to the GASP program that are of particular significance include: (a) mission definition, (b) design payload and speed, (c) concept and technology definition, and (d) economic ground rules. Other inputs, including atmospheric data, geometric characteristics, and optimizer inputs and constraints are also required.

Installed engine performance data in the form of thrust and SFC are provided by the propulsion organization for both turbofan and propfan installations. For propfans, this requires coupling of a specific turboshaft engine with a specific propeller design. For a given propeller design, an optimum propeller disc loading can be defined for a given altitude (density ratio), cruise Mach number, number of blades, and tip speed. Since the altitude and speed requirements are variable, aircraft are sized for several disc loading combinations.

In addition, routines are incorporated in GASP to calculate the wing scrubbing drag due to the propwash of wing-mounted propellers and to include

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this in the airframe drag buildup. Based on recent NASA/industry studies, our current propfan studies do not include swirl drag penalties; however, a method to incorporate this effect is available if later data indicates this penalty exists.

Concept and technology definitions are required input to the GASP program in terms of weight, performance, and/or cost adjustment factors. The weight, performance, and cost relationships upon which the GASP program operates are based on conventional concept and current technology definitions. Therefore, for each unique concept and/or technology, factors that reflect their influence on weight, performance, and other characteristics will be developed to a degree that is consistent with the conceptual design of each concept/technology integration.

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15. Supplementary Notes

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Final Report

16. Abstract A Study was conducted to evaluate the application of hybrid laminar flow control (HLFC) to global range military transport aircraft. The global mission included the capability to transport 132,500 pounds of payload 6,500 nautical miles, land and deliver the payload and without refueling return to 6,500 nautical miles to a friendly airbase. The preliminary design studies show significant performance benefits obtained for the HLFC aircraft as compared to counterpart turbulent flow aircraft. The study results at M = 0.77 show that the largest benefits of HLFC are obtained with a high wing with engines on the wing configuration. As compared to the turbulent flow baseline aircraft, the high wing HLFC aircraft shows 17 percent reduction in fuel burned, 19.2 percent increase in lift-to-drag ratio, an insignificant increase in operating weight, and 7.4 reduction in gross weight.

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