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SUMMARY REPORT

Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft

LOCKHEED-GEORGIA COMPANY
Marietta, Georgia 30063

CONTRACT NAS 1-14631
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Hampton, Virginia 23665

FOREWORD

Contract NAS 1-14631 between the National Aeronautics and Space Administration and the Lockheed-Georgia Company, effective October 1976, provided for the evaluation of laminar-flow-control system concepts for subsonic commercial transport aircraft. The contract was sponsored by the Aircraft Energy Efficiency (ACEE) Project Office of the Langley Research Center with D.B. Snow, A. L. Braslow, and M. C. Fischer serving as NASA Technical Monitors. This document submitted in fulfillment of DRL-005 of the subject contract, constitutes the summary report.

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1.0 INTRODUCTION

The recognition of potential long-term shortages of petroleum-based fuel, evidenced by dramatic increases in costs and periods of limited availability since 1973, has emphasized the need for improving the fuel efficiency of long-range transport aircraft. In 1976, in response to this need, the NASA established the Aircraft Energy Efficiency (ACEE) program with the objective of maintaining the U.S. competitive advantage through the development of new technology for fuel efficiency. Of all advanced technology concepts currently under consideration for application during the next two decades, Laminar Flow Control (LFC) offers the greatest potential for improving the fuel efficiency of transport aircraft. Consequently, LFC is included as one element of the ACEE program and the NASA has formulated a three-phase program with the goal of developing LFC technology to permit application to aircraft in the 1990 period.

Both the theoretical methods and engineering and design techniques requisite to the application of LFC have been reasonably well-known since the mid 1940's. The validity of this background and the potential of LFC were partially evaluated in the 1960-1966 period by Northrop as a part of the X-21A LFC Demonstration Program (Ref. 1-4). More recent studies, described in Reference 5, have evaluated the potential economic advantages of LFC in the proposed airline environment. However, a conclusion common to all previous evaluations is that significant advances are required in both the operational verification and development of basic design criteria for LFC prior to the incorporation of this technology on a production transport.

This report is a summary of the final study report, "Evaluation of Laminar-Flow-Control System Concepts for Subsonic Commercial Transport Aircraft," published as NASA CR-15923, and describes the work accomplished by Lockheed during the first phase of the program directed toward the satisfaction of these requirements. Section 3.0 provides background information defining the overall study plan, assumptions basic to all study tasks, and the technology level appropriate to long-range commercial transport aircraft entering service in 1993. Section 4.0 summarizes the analyses conducted to select mission parameters, the parametric analyses conducted to define optimum aircraft configurational parameters, and the resultant baseline configuration. The baseline aircraft defined in this section was used as a vehicle for the evaluation and development of alternative LFC system concepts summarized in Section 5.0. In this section, alternatives are evaluated in the general areas of aerodynamics, structures and materials, LFC systems, leading-edge region cleaning, and integration of auxiliary systems. Based on these evaluations, concepts in each area are selected for further development and testing and ultimate incorporation in the final study aircraft. The integration of selected system concepts into the final LFC configuration and the economic and operational characteristics of this configuration relative to a similarly-optimized advanced technology turbulent transport are summarized in Section 6.0. Investigations devoted to the definition of requirements for future LFC system development are summarized in Section 7.0.

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2.0 SYMBOLS AND ABBREVIATIONS

Symbols

a	speed of sound, m/s (ft/s)
b	wing span, m(ft)
c	local wing chord, m(ft)
C_D	drag coefficient
c_f	skin friction coefficient
C_L	lift coefficient
C_p	pressure coefficient
c_s	slot spacing, cm(in)
e	span efficiency factor
F_n	net thrust, N(lb)
H	cruise altitude, m(ft)
M	mach number
m	mass, kg(lb)
N	natural logarithm of the ratio of a boundary-layer disturbance amplitude to its amplitude at neutral stability
P	absolute pressure, N/m^2 (lb/in ²)
R	Reynolds number
R_c	wing chord Reynolds number
R_s	length Reynolds number
R_n	boundary layer crossflow Reynolds number
R_θ	boundary layer momentum thickness Reynolds number
S	area, m ² (ft ²)
s	surface distance, m(ft)
t/c	wing thickness-to-chord ratio, measured streamwise

T	absolute temperature, °K(°F)
U	potential flow velocity, m/s(ft/s)
U _o	free stream velocity, m/s(ft/s)
U _e	velocity at edge of boundary layer, M/S(ft/s)
w	slot width, mm(in)
x/c	chord location
x	streamwise coordinate, m(ft)
y	spanwise coordinate, m(ft)
z	coordinate normal to surface, m(ft)
α	angle of attack, rad(deg)
β	slot design parameter
η	cruise power ratio, wing semispan location
Λ	wing sweep angle, rad(deg)
μ	absolute viscosity, Ns/m ² (lb s/ft ²)
ν	kinematic viscosity, M ² /s (ft ² /s)
ρ	density, kg/m ³ (lb/ft ³)

Subscripts

o	free-stream
s	slot
e	edge of boundary layer
z	sucked height of boundary layer

Abbreviations

APU	auxiliary power unit
AR	aspect ratio
ATC	air traffic control
BPR	bypass ratio
DOC	direct operating cost, ¢/skm(¢/ssm)

ECS environmental control system
 EPNdB effective perceived noise level, decibels
 FS wing front spar, fuselage station
 LE Leading edge
 L/D lift to drag ratio
 LFC laminar flow control
 OWE operating empty weight, kg(lb)
 PL payload, kg(lb)
 P&WA Pratt & Whitney Aircraft
 RS wing rear spar
 RSS relaxed static stability
 SAS stability augmentation system
 SFC specific fuel consumption, $\frac{\text{mg/s}}{\text{N}} \left(\frac{\text{lb/hr}}{\text{lb}} \right)$
 SSM seat statute mile
 TOGW takeoff gross weight, kg(lb)
 T/W thrust-to-weight ratio
 W/S aircraft wing loading, $\text{kg/m}^2(\text{lb/ft}^2)$
 WS wing station

3.0 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 plan employed to achieve study objectives, design criteria, and the assumed technology level.

3.1 STUDY OBJECTIVES

The study described in this report has two primary objectives:

- (1) The evaluation of alternatives in the design of laminar-flow-control subsonic commercial transports for operation in the 1990's time period.
- (2) The definition of requirements for detailed subsystem development in subsequent program phases.

3.2 STUDY PLAN

The general approach used in conducting the study is illustrated in the flow chart of Figure 1. The existing technology data base was used in conjunction with airline inputs and independent mission analyses to define requirements for a 1993 commercial transport and establish a reference baseline configuration for subsequent use in evaluating advanced system concepts. In the Concept Evaluation Phase, analytical investigations, design studies, and subsystem testing were conducted to evaluate alternative concepts in the following areas:

- (1) Aerodynamics
- (2) Structures and materials
- (3) Suction systems
- (4) Leading-edge region cleaning
- (5) Integration of auxiliary systems

Upon completion of the concept evaluations and test programs, the optimum LFC system elements were integrated into the baseline configuration as a part of the Configuration Selection and Assessment task. To assess the relative advantages of LFC, the LFC transport configuration selected in this process was compared to an advanced technology turbulent configuration optimized for the same mission.

The concept evaluations, subsystem tests, and configuration assessment activities provide a sound basis for the definition of requirements for subsystem development in subsequent phases of the NASA LFC Program.

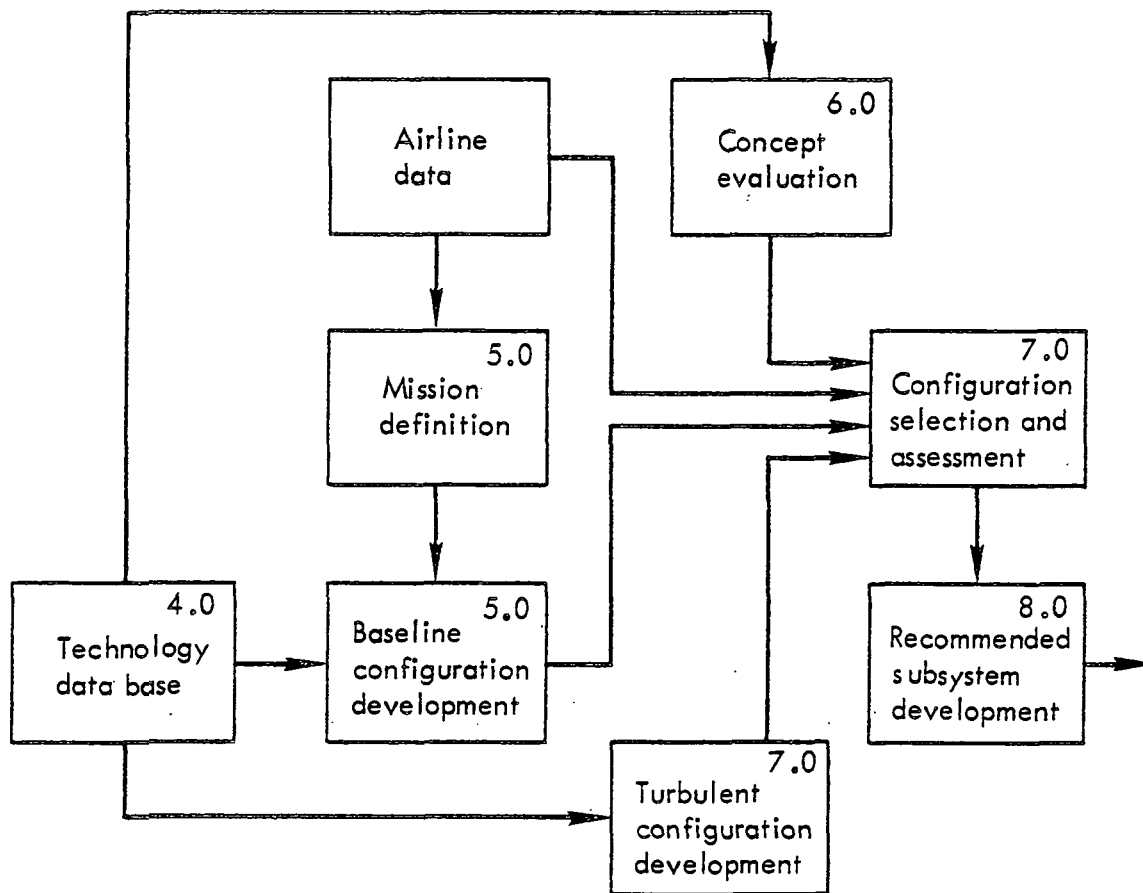


Figure 1. Study plan

3.3 LIFE CYCLE

The assumed life cycle for study aircraft is shown in Figure 2. For initial passenger operation in 1993, the following technology levels are appropriate:

Airframe technology level - 1988
 Engine technology level - 1987

3.4 DESIGN CRITERIA

The development of study aircraft was based on satisfaction of the design criteria outlined below:

- (1) The study aircraft have a design life objective of 90 000 flight hours. This corresponds to a warranty service life of about 45 000 flight hours.
- (2) The study aircraft satisfy the requirements for type certification in the transport category under Federal Aviation Regulation - Part 25, and are capable of operating under pertinent FAA rules.

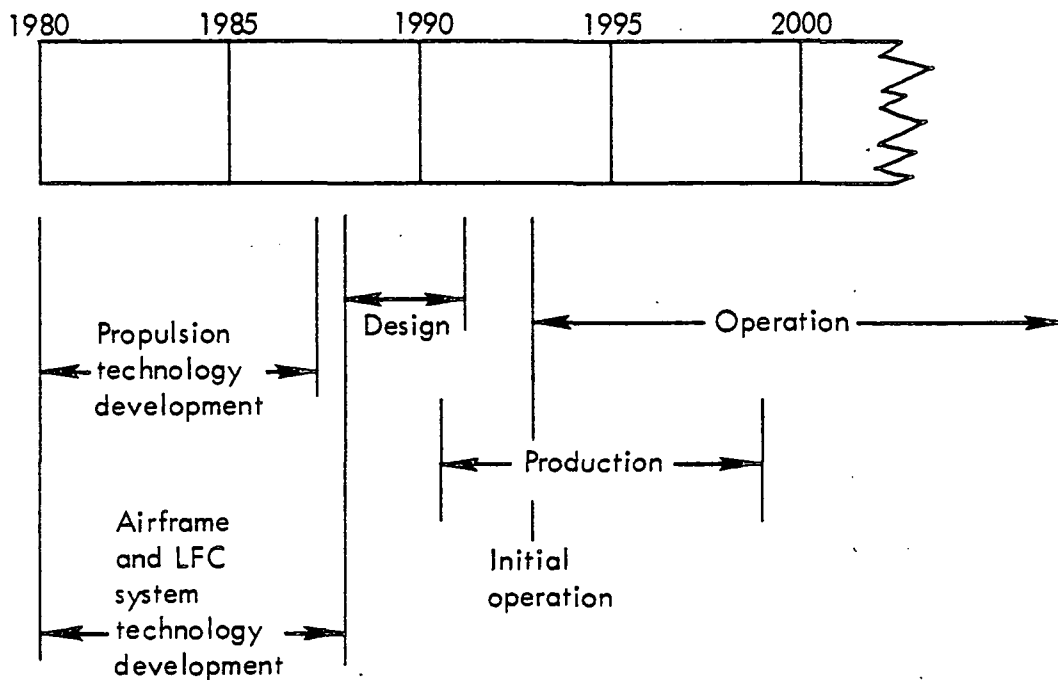


Figure 2. Life cycle

(3) The study aircraft satisfy the following noise criteria:

- o Takeoff sideline FAR 36 - 10 EPNdB
- o Takeoff flyover FAR 36 - 6 EPNdB
- o Approach flyover FAR 36 - 5 EPNdB

These levels are 2 EPNdB below the standards currently proposed as a part of NPRM 75-37C in Reference 6.

- (4) The study aircraft are provided with fuel reserves in accordance with the requirements of FAR 121.645. In addition to the fuel reserve allowances specified in this regulation, the LFC study aircraft are designed with adequate reserve fuel to accommodate loss of the LFC system due to weather phenomena during three percent of the mission cruise time.
- (5) The basic design criteria for LFC systems developed as a part of the X-21 Program represent the most comprehensive set of guidelines currently available. Therefore, the criteria established by this program and reported in Reference 7 form the basis for the definition of LFC systems for the study aircraft.

3.5 REFERENCE TECHNOLOGY LEVEL

As a preliminary to the parametric configuration analyses and subsequent configuration optimization activities leading to the definition of final study aircraft, the level of technology likely to be available for application in the early-1990 period was established. This section sum-

marizes the reference technology level assumed for all configuration development activities.

3.5.1 Aerodynamics

The aircraft of 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. Advanced technology secondary active trailing-edge flaps 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.

3.5.2 Flight Controls

The flight control system incorporates the elements of active control technology which promise significant improvements in the efficiency of large transport aircraft.

The system encompasses the following modes of control:

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

The major improvements offered by the above systems are: minimization of airframe weight, incorporation of automatic trouble-shooting, and improved ride characteristics.

3.5.3 Propulsion Systems

The Pratt & Whitney Aircraft STF-477 engine (Ref. 8) was chosen as the primary propulsion units for the study aircraft. This engine uses a low-pressure spool consisting of a one-stage fan and three low-pressure compressor stages. These components include advanced blading aerodynamics and seals for better component efficiency and lower noise while maintaining good component life and performance retention. The low-pressure spool is driven by a five-stage uncooled turbine, incorporating higher loading and advanced aerodynamics and seals. The high-pressure spool incorporates a ten-stage compressor driven by a two-stage highly-loaded turbine, both incorporating technology advances similar to the low-pressure spool. The high-pressure turbine also includes advanced metallurgy, cooling, and coating technologies. Relative to 1976 engine technology, this engine provides a 12.5% reduction in TSFC and a 22% reduction in weight.

3.5.4 Structures and Materials

The selection of materials for the major structural components of the study configuration was based on the lowest cost per unit of weight reduction.

Using the procedures of Reference 9, the full benefits of advanced materials were realized by sizing the total airplane, including the power plant and other systems, to take advantage of the lower structural weights. As a result of these analyses, advanced materials are used extensively in both primary and secondary structure.

Utilization of advanced materials for 66% of the airframe weight results in study aircraft which weigh about 67% as much as comparable current transports.

3.5.5 LFC Systems

The basic design technology for LFC suction surface and metering systems was developed as a part of the X-21 Program in the early 1960's and represents the most comprehensive set of guidelines currently available. Therefore, the criteria and limits established by that program and reported in Reference 7 were used as the basis for the definition of slot and metering configurations. These criteria were augmented by limited static testing of slot/metering configurations and a Lockheed-funded low-speed wind-tunnel test of the laminarizing characteristics of a full-scale leading-edge test panel.

3.5.6 Aircraft Systems

The aircraft systems 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 improvements include 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.

4.0 BASELINE CONFIGURATION DEVELOPMENT

Realization of contract objectives requires the development of a study baseline aircraft to be used as a vehicle for the evaluation of alternative LFC system concepts during subsequent study phases. The analyses conducted in the process of developing the baseline configuration included a definition of the study mission requirements, parametric configuration analyses for selection of aircraft geometry, engine, and operational parameters, and definition of the selected configuration.

4.1 MISSION DEFINITION

As the first phase in the development of a study baseline, the Lockheed-California Company performed analyses to determine the size and mission characteristics for LFC aircraft to be introduced in the 1993 time period. The basis of these analyses was the development of estimates of present geographical traffic distribution, the projection of total demand by market area to the year 2000, and the calculation of the number of aircraft of various sizes required to satisfy the projected demand.

The mission analyses resulted in the selection of the following mission parameters:

Design Range	12 038 km (6500 n mi)
Average Stage Length	6112 km (3300 n mi)
Cruise Speed	M = 0.80 - 0.85
Capacity	400 passengers
Production Quantity	350

The mission profile to be used in the design and analyses of the LFC airplane is the standard international flight profile for maximum range and minimum fuel.

4.2 PARAMETRIC CONFIGURATION ANALYSES

An extensive parametric analysis of alternative aircraft configurations was conducted to select optimum aircraft geometry, engine, and operational parameters for the specified mission requirements. A conventional wide-body fuselage configuration, sized for 400 passengers and 16 874 kg (37 200 lb) of belly cargo, was used for the analyses. The parametric configurations use two LFC suction units mounted in the fuselage near the wing root. A weight penalty of 6.786 kg/m² (1.39 lb/ft²) in addition to the basic structural weight is assumed for the areas where LFC suction is applied. Laminarized areas are approximately 75% of the exposed wing area and 65% of the exposed empennage area. Four fuselage-mounted engines are assumed for the parametric configurations.

The Lockheed Generalized Aircraft Sizing Program (GASP) was employed for the parametric configuration analyses. As the initial step in the analysis, 11 cruise-altitude/cruise-Mach number combinations were defined with cruise altitudes ranging from 10 973 to 13 411 m (36 000 to 44 000 ft) and Mach numbers ranging from 0.70 to 0.85.

Two phases were required to develop optimum configuration parameters for each cruise-altitude/cruise-M combination. In the first phase, wing loading was varied from 415 to 610 kg/m² (85 to 125 lb/ft²) and aspect ratio was varied from 10 to 14, to establish optimum configuration geometry independent of airport performance constraints. In the second phase, engine bypass ratio, cruise power ratio, and aspect ratio were varied parametrically to optimize airport performance for each configuration geometry. Engine bypass ratios ranging from 6.0 to 13.0 and cruise power ratios ranging from 0.70 to 0.90 were considered. The maximum cruise power setting was constrained to a value of 0.90 to assure satisfactory climb performance with LFC off to an altitude approaching the initial cruise altitude.

Following are the primary criteria for selecting baseline candidates:

- (1) Near minimum direct operating cost for a 6112 km (3300 n mi) mission.
- (2) Moderate aspect ratio to assure sufficient LFC duct volume and provide adequate design flexibility.
- (3) Use of fuel volume in wing and wing center section.
- (4) A moderate block fuel penalty at the basic design range of 12 038 km (6500 n mi).

The optimum configurations for the 11 cruise Mach number/altitude combinations are described in Table 1.

TABLE 1. BASELINE CANDIDATES

Set	Altitude m (ft)	M	η_{CR}	BPR	DOC ϕ/skm (ϕ/ssm)	AR	W/S kg/m^2 (lb/ft^2)
1	12 192 (40 000)	.70	.90	8.40	.961 (1.547)	13.00	571.2 (117.0)
2	12 192 (40,000)	.75	.90	8.40	.936 (1.508)	12.30	556.5 (114.0)
3	12 192 (40 000)	.80	.88	8.40	.922 (1.485)	11.60	549.2 (112.5)
4	12 192 (40 000)	.85	.89	8.40	.916 (1.475)	10.50	541.4 (110.9)
5	10 973 (36 000)	.70	.71	8.40	.936 (1.508)	13.00	610.2 (125.0)
6	10 973 (36 000)	.75	.71	8.40	.920 (1.482)	11.80	585.8 (120.0)
7	10 973 (36 000)	.80	.71	8.40	.911 (1.467)	10.90	576.1 (118.0)
8	10 973 (36 000)	.85	.73	8.40	.905 (1.458)	9.50	571.2 (117.0)
9	13 411 (44 000)	.75	.90	8.40	.999 (1.608)	14.00	524.8 (107.5)
10	13 411 (44 000)	.80	.90	8.40	.990 (1.594)	14.00	518.3 (106.2)
11	13 411 (44 000)	.85	.90	8.40	.997 (1.606)	13.00	516.0 (105.7)

In Figure 3, the DOC data of Table 1 are plotted versus cruise Mach number for selected altitudes. Figure 3 shows that DOC varies less than 0.019 $\phi/s km$ (0.03 $\phi/s s mi$) for the two lowest altitudes for cruise M between 0.75 and 0.85.

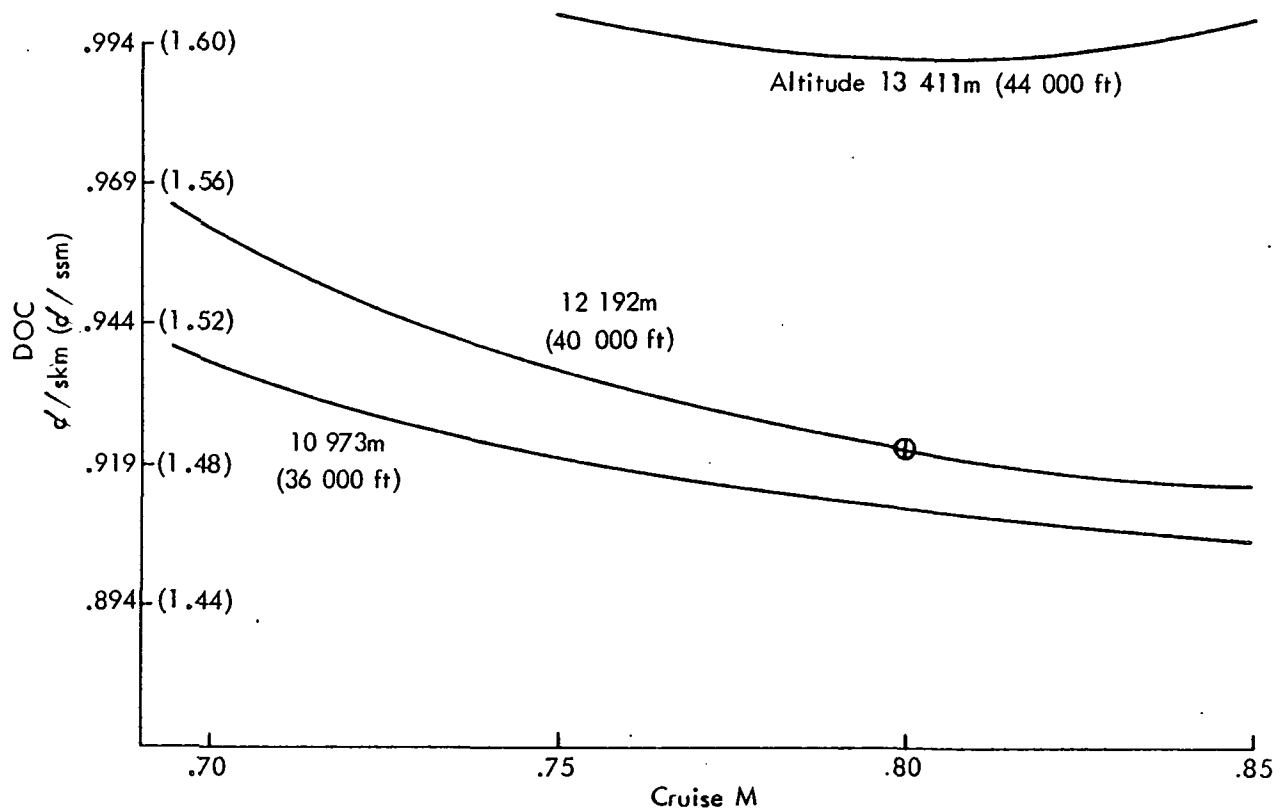


Figure 3. Variation of DOC with cruise M

The leading-edge sweep angle of 0.436 rad (25 deg) associated with $M = 0.80$ is less critical from a leading-edge contamination standpoint than the sweep of .549 rad (31.5 deg) associated with $M = 0.85$. For this reason and the more severe design problems associated with compressibility effects, a cruise M of 0.80 was selected for the baseline aircraft.

The DOC advantage of the 10 973 m (36 000 ft) cruise altitude is also less than 0.019 d/s km (0.03 d/s s mi) as compared to the 12 192 m (40 000 ft) cruise altitude for the range of cruise M considered. However, as illustrated by Figure 4, higher altitudes suffer progressively greater DOC penalties. Since the lower unit Reynolds number associated with increasing altitude is beneficial to LFC because of its influence in reducing sensitivity to surface imperfections, an altitude of 12 192 m (40 000 ft) was selected for the baseline aircraft.

The selected baseline parameters are identified as Set 3 in Table 1.

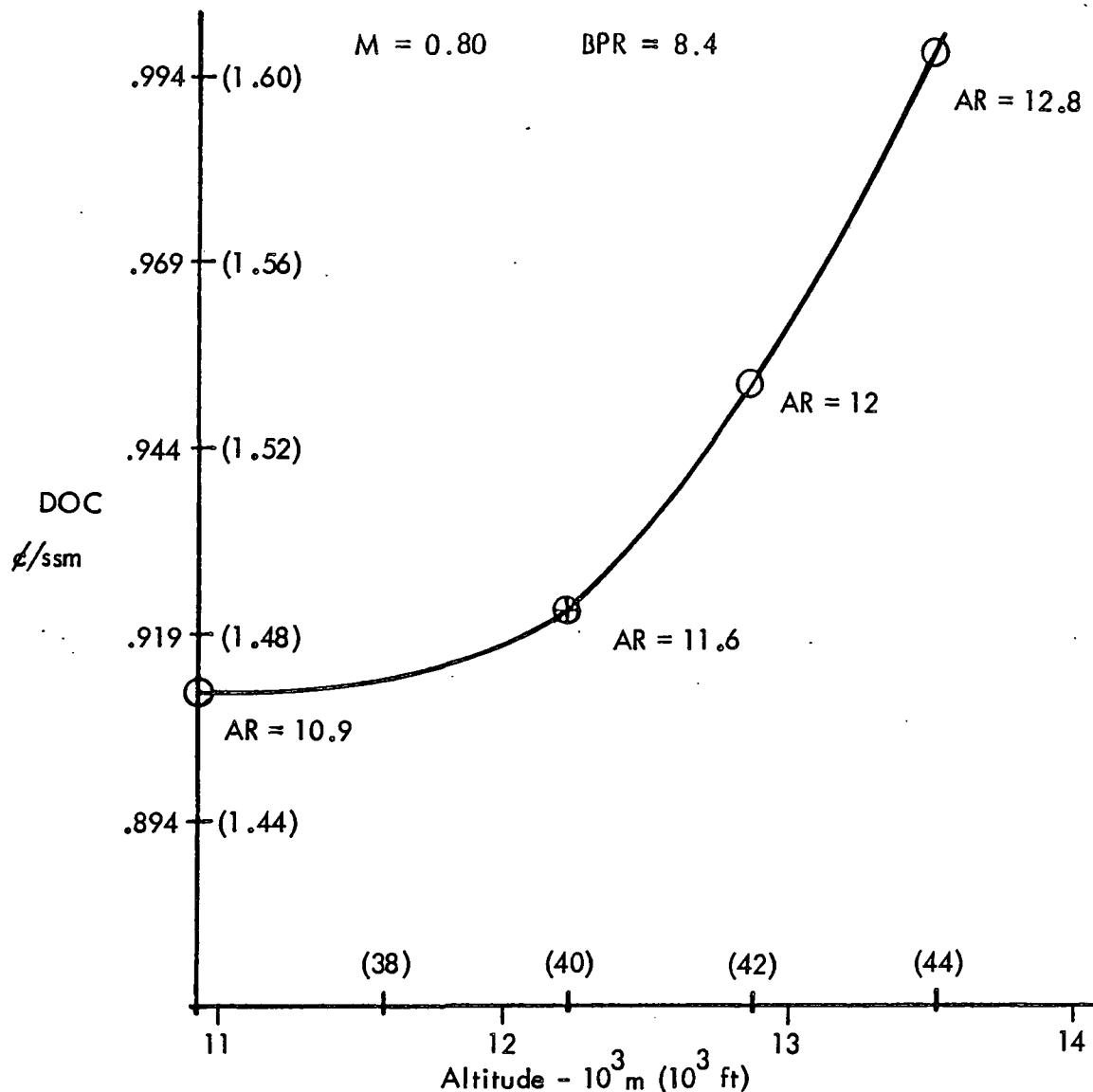
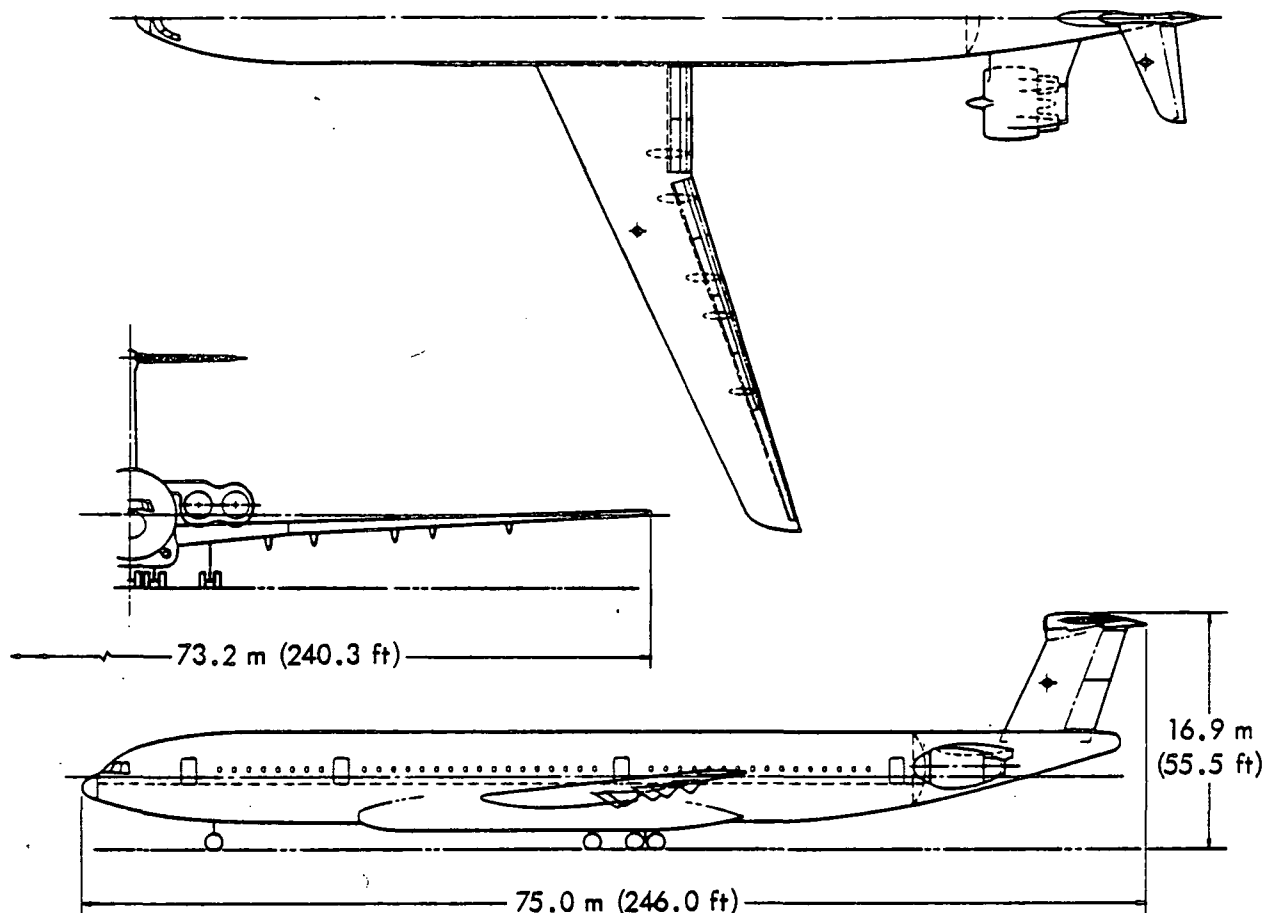


Figure 4. DOC variation with altitude

4.3 CONFIGURATION DEFINITION

The baseline configuration shown in Figure 5 was established for the evaluation of alternative LFC system concepts leading to the final study aircraft configuration. This airplane is a wide-body configuration designed to carry 402 passengers and baggage over an intercontinental range of 12 038 km (6500 n mi) at $M = 0.80$ 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 cabin arrangement accommodates a 10/90 passenger mix. Space for LD-3 cargo containers is provided forward of the wing box and aft of the main landing gear bay. A bulk cargo bay is also provided at the rear of the pressurized belly. These cargo bays accommodate 16 874 kg (37 200 lb) of cargo.



	Area	AR	Sweep	Taper
Wing (base)	452.8 m ² (4874.4 ft ²)	11.60	L.E. .436 rad (25°)	.350
Horizontal	41.2 m ² (443.9 ft ²)	5.00	1/4 Ch .349 rad (20°)	.400
Vertical	50.0 m ² (538.5 ft ²)	1.50	1/4 Ch .436 rad (25°)	.800
TOGW	257 174 kg (566 961 lb)			
Engine	151 kN (33 978 lb)			

Figure 5. General arrangement

As shown in Figure 5, the baseline is a low-wing T-tail monoplane with four aft-fuselage mounted propulsion engines. An independently-driven LFC suction unit is located in a fairing under each wing root. The wing has a moderate sweep of 0.436 rad (25°) at the leading edge with an aspect ratio of 11.6. Full-span flaps, including drooped ailerons, provide the required airport performance. Leading-edge high-lift devices are not required. Partial span spoilers are incorporated. Small-chord secondary flaps incorporated into the main flaps provide upper-surface pressure gradient and shock position control for off-design operation and serve as active controls to minimize structural requirements. The wing and empennage surfaces are laminarized to 75% and 65% chord, respectively. A combination cleaning/deicing system is incorporated in the leading-edge region of laminarized surfaces.

Table 2 summarizes the characteristics of the baseline configuration.

TABLE 2. BASELINE CONFIGURATION CHARACTERISTICS

<u>Item</u>	<u>Value</u>	
Gross Weight	257 174 kg	(566 961 lb)
Operating Weight	124 054 kg	(273 488 lb)
Block Fuel	80 213 kg	(176 837 lb)
Reserve Fuel	14 441 kg	(31 836 lb)
Wing Area	452.8m ²	(4874 ft ²)
Aspect Ratio		11.6
Thickness Ratio		0.122
L. E. Sweep	.436 rad	(25°)
Horizontal Tail Area	41.2m ²	(444 ft ²)
Vertical Tail Area	50.0m ²	(539 ft ²)
Body Length/Diameter	75.0m/6.45m	(246 ft/254 in)
Engines (4-STF477)-SLST	151 kN	(33 978 lb)
OW/GW		0.482
Payload/GW		0.150
T/W		0.230
W/S	566.3 kg/m ²	(116 lb/ft ²)
TOFL	3046.5m	(9995 ft)
V _{APP}	264.8 km/hr	(143 kn)

5.0 CONCEPT EVALUATION

The predominant effort in this study was devoted to the evaluation of options available for the design and development of future LFC commercial transport aircraft. The evaluation of these options included analytical investigations, design studies, and subsystem testing to evaluate alternative concepts in the following areas:

- (1) Aerodynamics
- (2) Structures and materials
- (3) Suction systems
- (4) Leading-edge region cleaning
- (5) Integration of auxiliary systems

This section summarizes the results of these concept evaluation activities and defines the characteristics of systems selected for integration into the final study configuration.

5.1 AERODYNAMICS

In the evaluation of alternative aerodynamic concepts, primary efforts were devoted to the development of solutions to the basic problems of LFC wing design. Included were extensive analyses of alternative airfoil sections as required to minimize both suction system requirements and the complexity of the suction surface design. For selected airfoil sections, three-dimensional analyses were conducted and conceptual LFC wings were defined.

Studies were conducted as required to develop conceptual high-lift systems compatible with both specified airport performance requirements and the peculiar constraints imposed by the integration of LFC surfaces into the wing. The final LFC wing design, based on a supercritical pressure distribution, is compatible with both operational requirements and systems requirements of the final study configuration.

5.1.1 Design Objectives

Following are the objectives for the aerodynamic design of LFC wings:

- (1) Low shock loss and minimum drag
- (2) Straight wing isobars
- (3) Low cross-flow except near wing leading edge
- (4) Low attachment line Reynolds number (R_θ) values
- (5) Minimum overall suction level

- (6) Good off-design and LFC-off performance
- (7) Adequate aircraft maneuverability and high-lift performance without leading-edge devices.

5.1.2 Airfoil/Boundary-Layer Analysis

The airfoil analysis and design for this study was based on the airfoil developed as a part of the systems study of Reference 5. A variety of design variations were evaluated in the selection and evaluation of interim airfoils. High-speed wind-tunnel testing was conducted to obtain data on an advanced supercritical airfoil designed for laminar flow control and verify theoretical estimates of pressure distributions.

The design perturbations required as a result of this testing led to the final study airfoil shown in Figure 6. The design pressure distribution for this airfoil is shown in Figure 7.

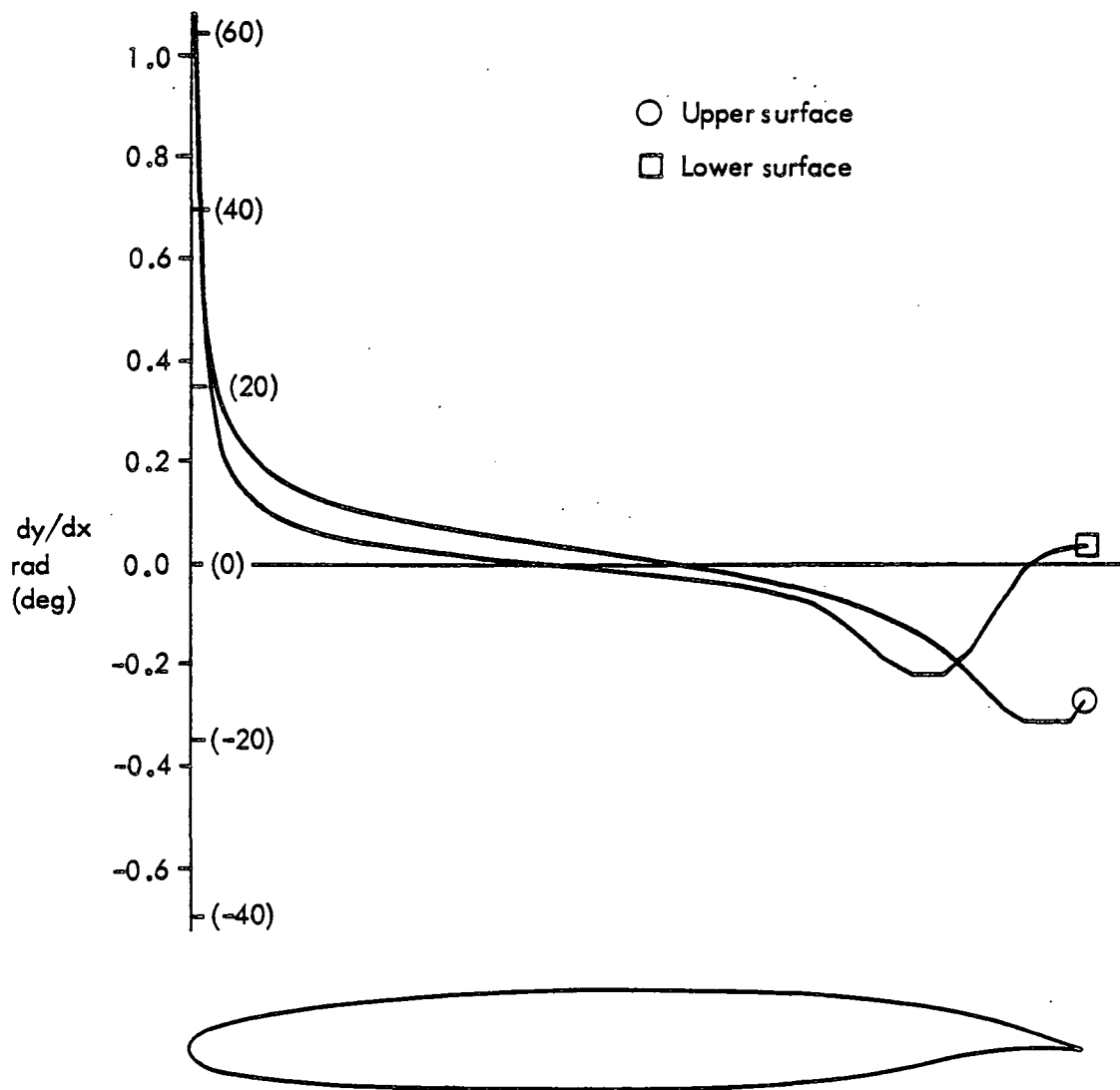


Figure 6. Selected LFC Airfoil

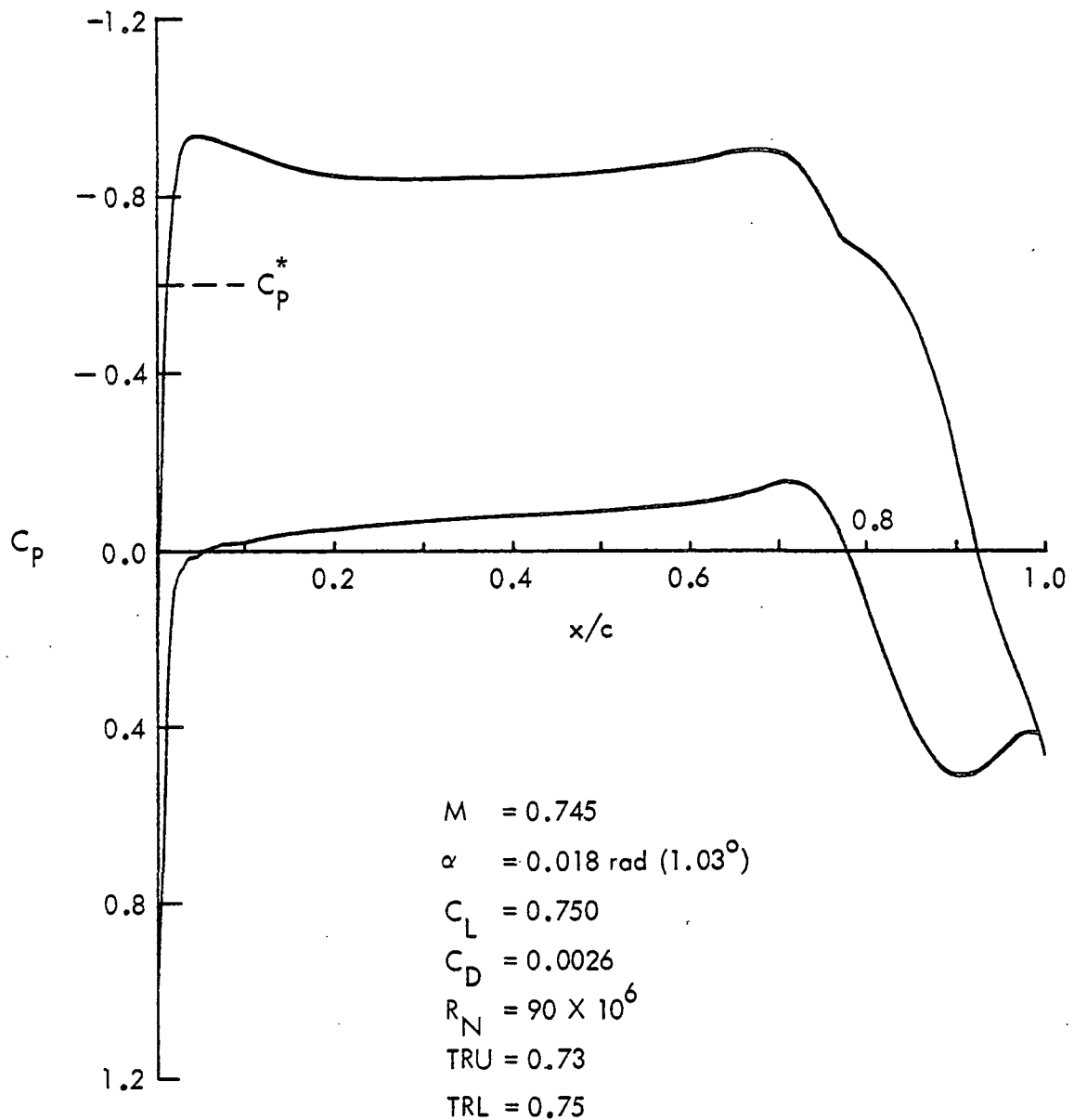


Figure 7. Viscous pressure distribution at mach - 0.745, $C_L = 0.750$

For the boundary layer analysis calculations on the final baseline airfoil, the suction distribution was revised to eliminate suction near the airfoil nose. This revision was made to accommodate the leading edge cleaning system. The final suction distribution is shown in Figure 8. The upper and lower surface N factors for the final airfoil shown in Figure 9 are below the acceptable value of 11.

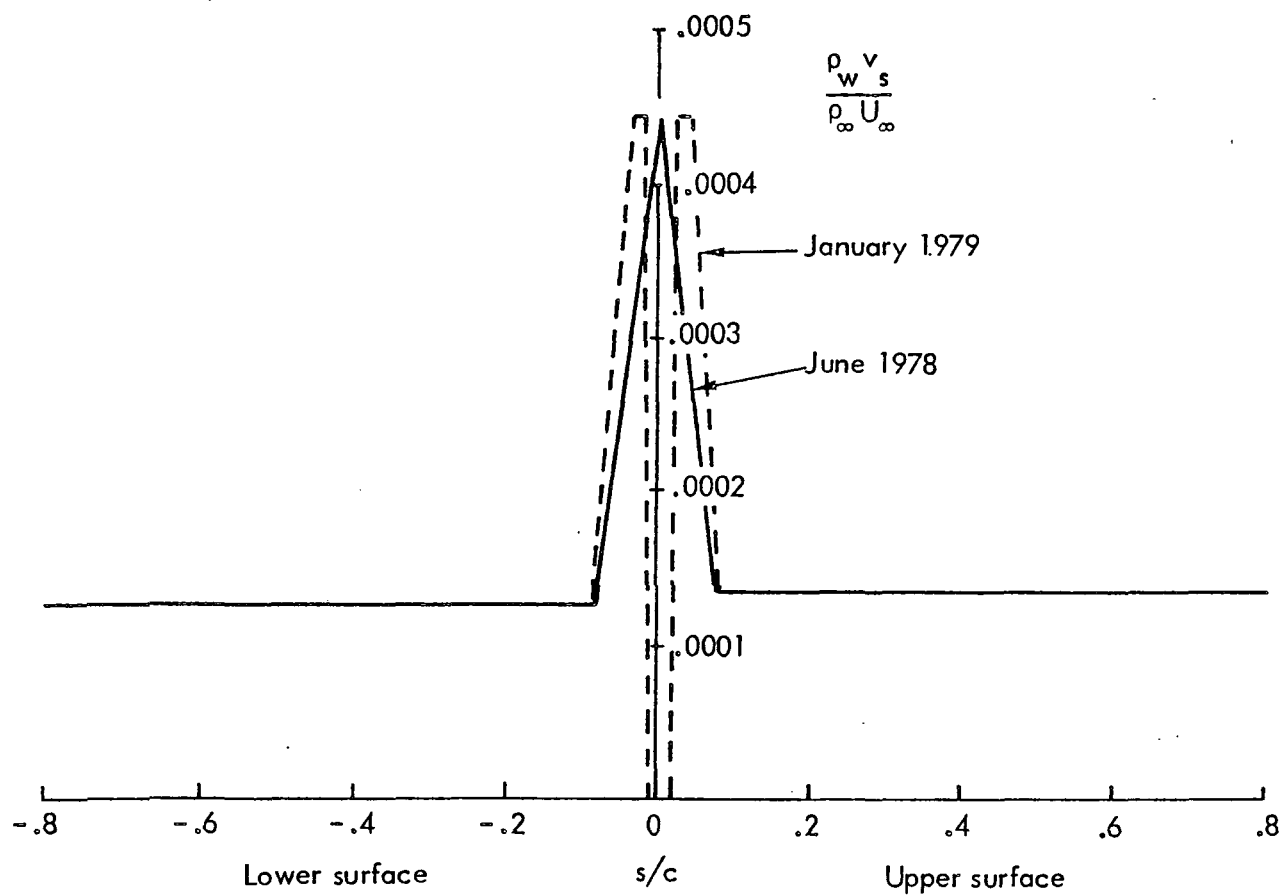


Figure 8. Suction distribution

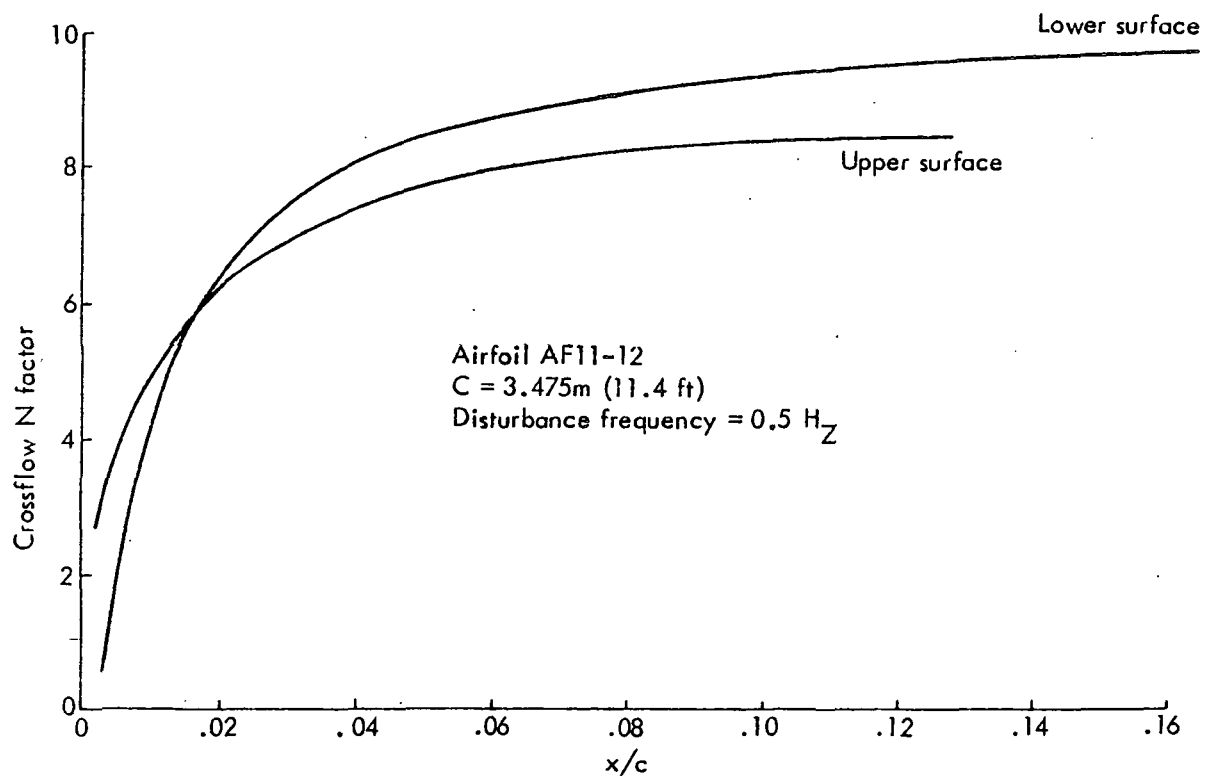


Figure 9. Final LFC Airfoil factors

5.1.3 Wing Analysis and Design

For a preliminary design of the wing for the study aircraft, inviscid transonic solutions were obtained using the Bailey-Ballhaus 3 Transonic Wing Program (TWP). To approximate viscous effects, the final baseline wing was lofted using "fluid" sections represented by the actual airfoil shape with the addition of the boundary layer displacement thickness added to the ordinates.

A series of modifications to the root section were made to produce the desired pressure distribution. Modifications to reduce the shock strength, increase lift, smooth the airfoil, and position the shock were also required. A 10% chord active control secondary flap is used to provide pressure gradient and shock position control.

Because the Bailey-Ballhaus Transonic Wing Program (TWP) uses inviscid theory, the Transonic Airfoil Program (TAP) was used to calculate boundary layer thicknesses at the design cruise point for the root, break, and tip sections. These boundary layer thicknesses were added to the appropriate sections to produce fluid sections, which were factored to streamwise ordinates. The fluid airfoils computed at the root, break station, and tip were subsequently lofted to obtain a fluid wing. By examination of previous data and additional estimations of secondary flap effectiveness, a final wing definition was developed. The resultant twist schedule is given in Figure 10. A new spanwise schedule for secondary flap deflection to tailor the span load distribution is shown in Figure 11. Figures 12 through 14 illustrate span loading, span lift coefficient and pressure distribution results from TWP for the fluid wing. The results indicate that the changes in secondary flap schedule and twist schedule are effective in altering span load distribution, shock strength, and shock location.

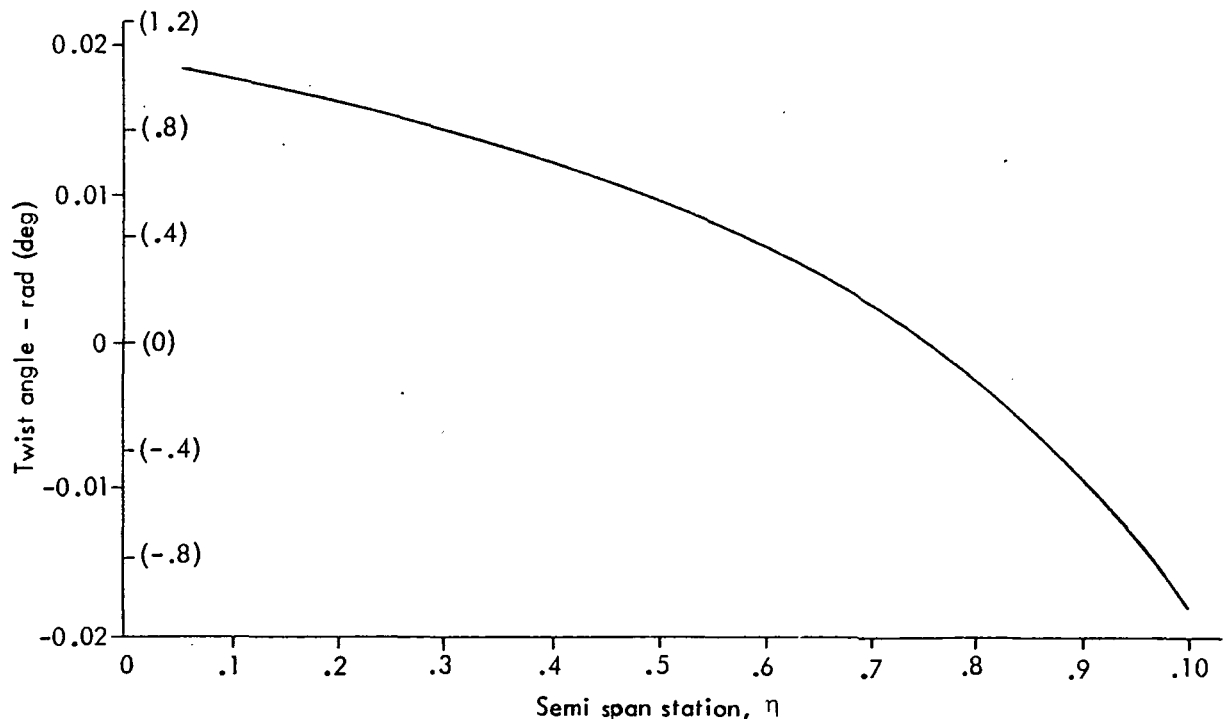


Figure 10. LFC baseline wing twist schedule

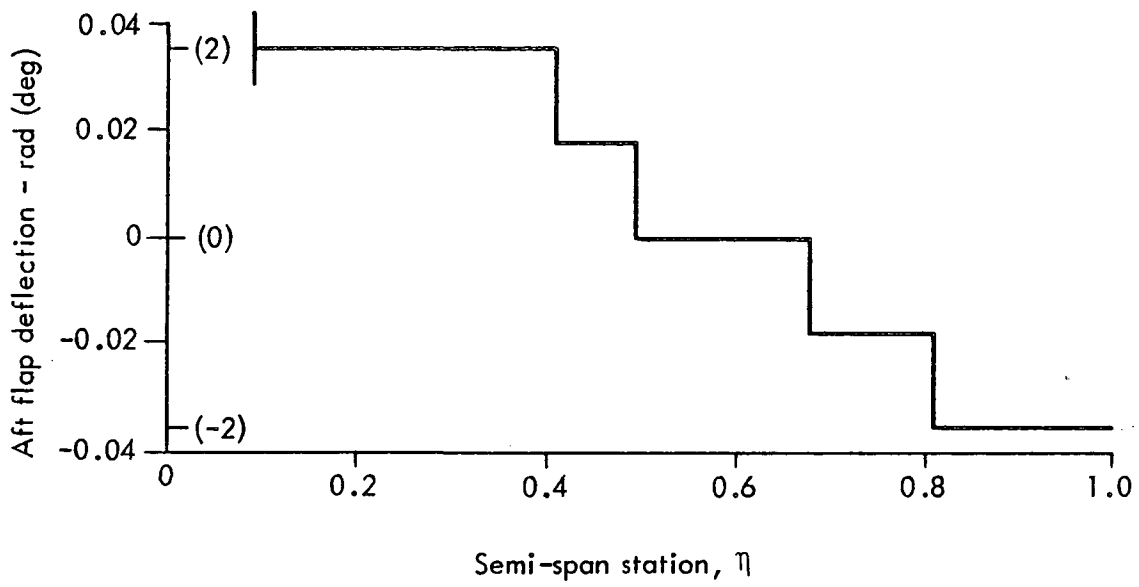


Figure 11. Aft flap deflection schedule

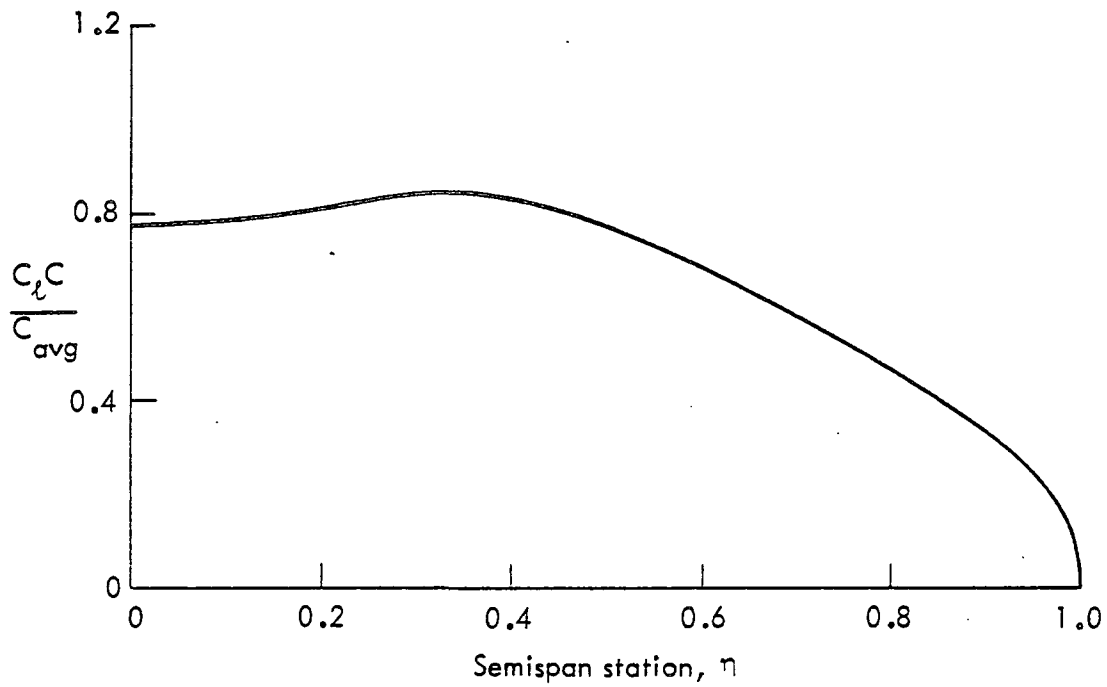


Figure 12. Span loading distribution

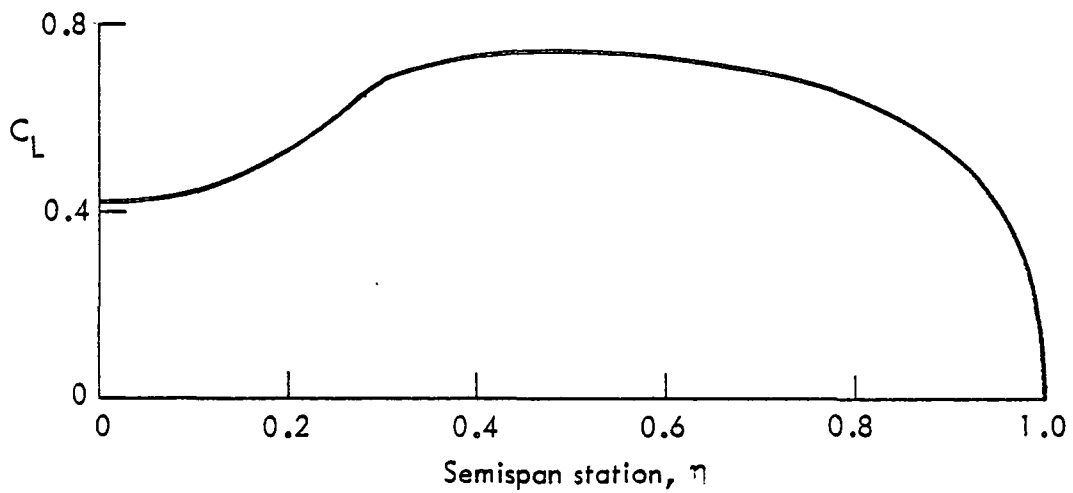


Figure 13. Spanwise variation of lift coefficient

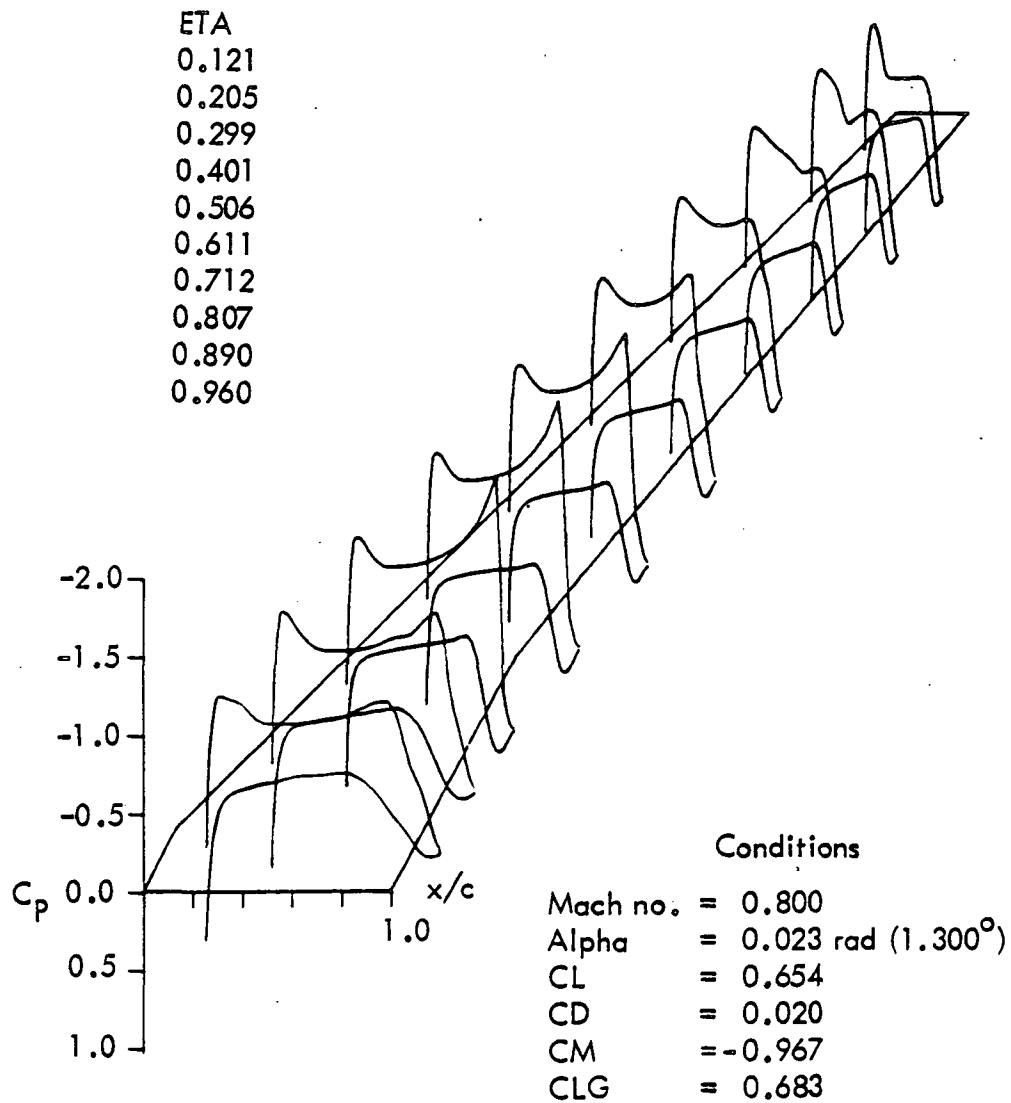


Figure 14. 3-D isometric pressure distribution

5.1.4 High-Lift System Development

The baseline high-lift system was analyzed to:

- (1) Verify that parametric program aerodynamic characteristics estimates for the high-lift system were sufficiently accurate for baseline configuration optimizations.
- (2) Provide data for baseline configuration optimization corrections.
- (3) Define the scheduling of deflections of the high-lift devices which best satisfies both performance and stability and control requirements.

The analyses of the baseline takeoff and landing high-lift system verified the predicted levels of the parametric sizing program. As a consequence, it was verified that the baseline airplane can operate from a 3048 m (10 000 ft) field without a leading-edge device.

The span load distributions for the operational lift levels at lift-off and approach conditions are given in Figure 15. Predicted vortex drag efficiency factors, "e", are also indicated. $C_{L_{Max}}$ and drag predictions for these configurations verify that initial predictions for a high-lift system with no leading-edge devices can be achieved with the baseline high-lift system. Further study of the baseline high-lift system performance or stability and control characteristics would be justified only when an experimental development program is initiated.

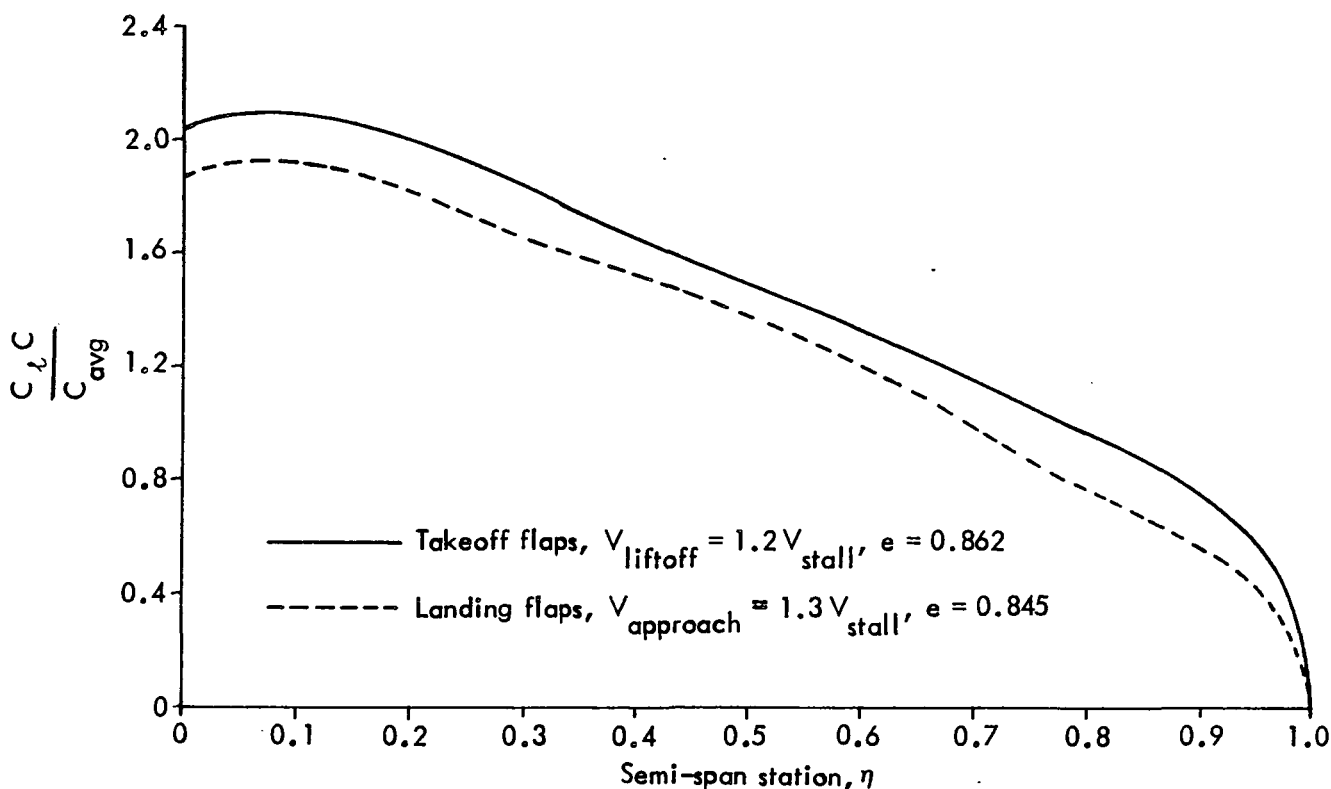


Figure 15. Span load distribution - lift off and approach conditions

5.1.5 Stability and Control

Stability and control for the LFC aircraft was evaluated to ensure that technical problems peculiar to the use of LFC will be amenable to solution using technology available by 1990. In deriving the basic design concept for both the LFC baseline and the comparative turbulent baseline, the full predicted 1990 technology level for flight controls was assumed, as outlined in Section 3.5.2.

Satisfactory longitudinal stability and control was provided by sizing the horizontal tail and control surfaces to provide stability levels and control response consistent with aircraft of the L-1011 class. The aircraft sizing program automatically defines a sufficient horizontal tail area matched to the aircraft size. The comparative turbulent aircraft horizontal tail and controls are sized consistent with a low-tail effectiveness and the same controls technology level employed for the LFC baseline. For both aircraft baselines an unusually small horizontal tail provides adequate stability and control.

As in the longitudinal case, lateral/directional stability and control was provided through parametric sizing. Differences in vertical tail sizing because of engine placement and the LFC baseline T-tail configuration were recognized. Stability augmentation permits the small vertical tails used on both baselines. The lateral control system for both baselines provides rates of roll which are comparable to C-5 roll performance.

5.2 STRUCTURES AND MATERIALS

A central problem in the definition of a feasible production configuration for LFC transports is the development of LFC surface designs which satisfy aerodynamic requirements without imposing unacceptable structural weight penalties, manufacturing costs, and operational requirements. Consequently, extensive investigations were conducted in the development of structural concepts for both the wing-box and the leading-edge regions of the wing of the baseline LFC transport. As a part of the development, alternative structural concepts were evaluated, detailed designs were developed for selected concepts, manufacturing procedures were established, and full-scale structural specimens were fabricated and tested.

5.2.1 Design Objectives

The selection of an optimum surface configuration is of primary importance in the development of a production LFC transport. The design objectives pertinent to the development of LFC structure include the following:

- (1) Satisfaction of the stringent requirements for surface smoothness and waviness
- (2) Compatibility with manufacturing procedures adaptable to a production environment
- (3) Compatibility with in-service inspection, maintenance, and repair, while providing a high degree of reliability
- (4) Imposition of minimum weight and cost penalties on the airframe.

5.2.2 LFC Surface Panel Development

5.2.2.1 Concept Evaluation and Selection

The following methods of providing the required surface configuration are available to the designer:

- o Non-structural covers
- o Structural surfaces
- o Combination of the first two methods

The plan for development and evaluation of alternative surfaces is shown in the flow diagram of Figure 16.

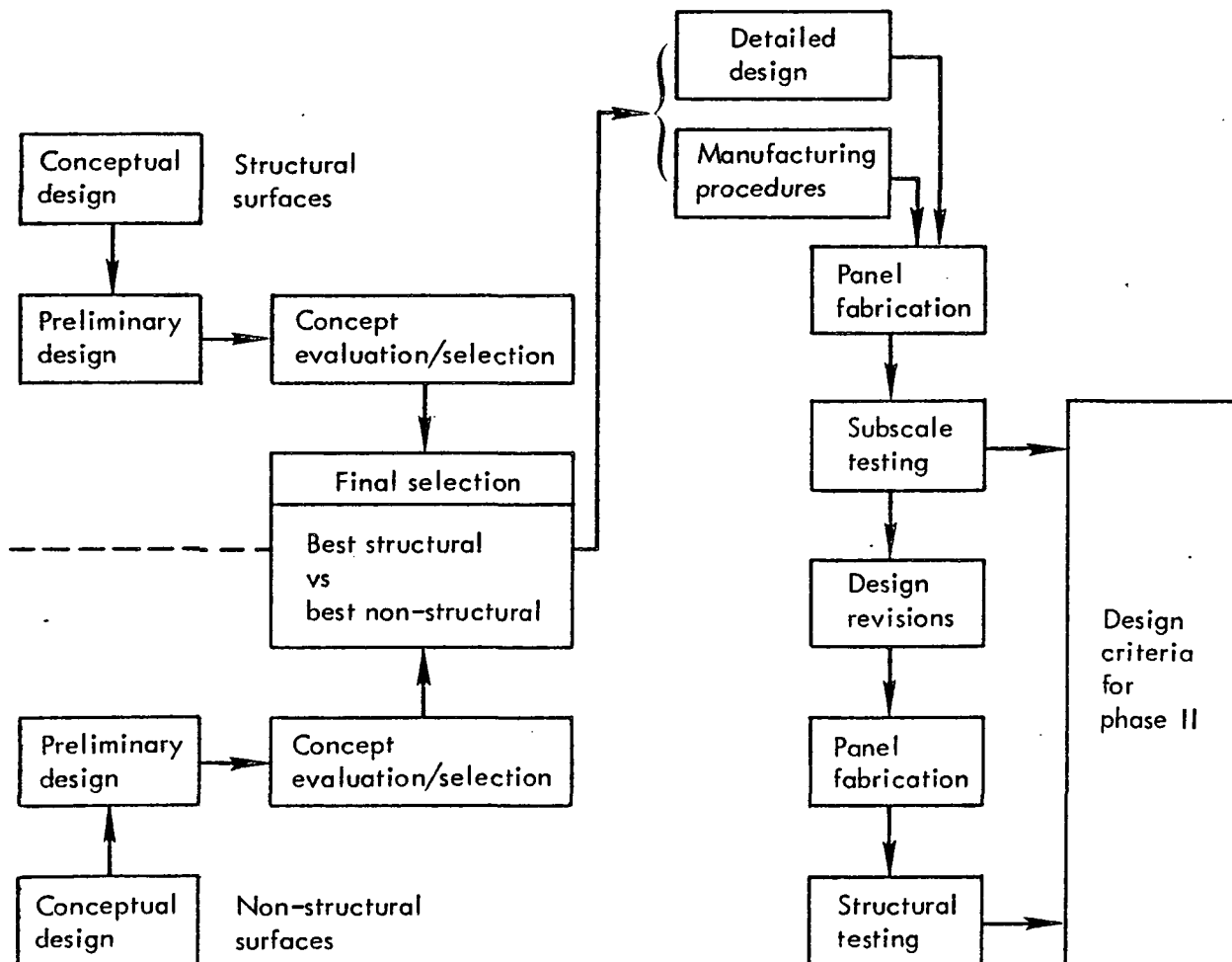


Figure 16. Plan for LFC surface development

Concept design entailed the identification of alternative candidate concepts. The preliminary design effort included the development of consistent weight and cost factors for comparison during the evaluation. To develop weight and cost data, the preliminary design effort included the estimation of loads for the baseline LFC aircraft wing, selection of materials, and the sizing of surface/wing elements. For study purposes, the evaluation was restricted to the portions of the LFC upper and lower surfaces forming the main structural elements between the wing front and rear spars.

In addition to the above, manufacturing procedures were developed, estimates of manufacturing costs were completed, maintainability and reliability were assessed, procedures for repairing damage surfaces were developed, and the compatibility of each surface concept with surface design criteria and other elements of the LFC system was evaluated.

Upon completion of this procedure for each of the candidate concepts, recommended structural, non-structural, and combination concepts were selected. These concepts were subsequently compared to permit selection of a single concept for future development.

On the basis of these evaluations, the hat-section stiffened panel shown in Figure 17 was selected for further development.

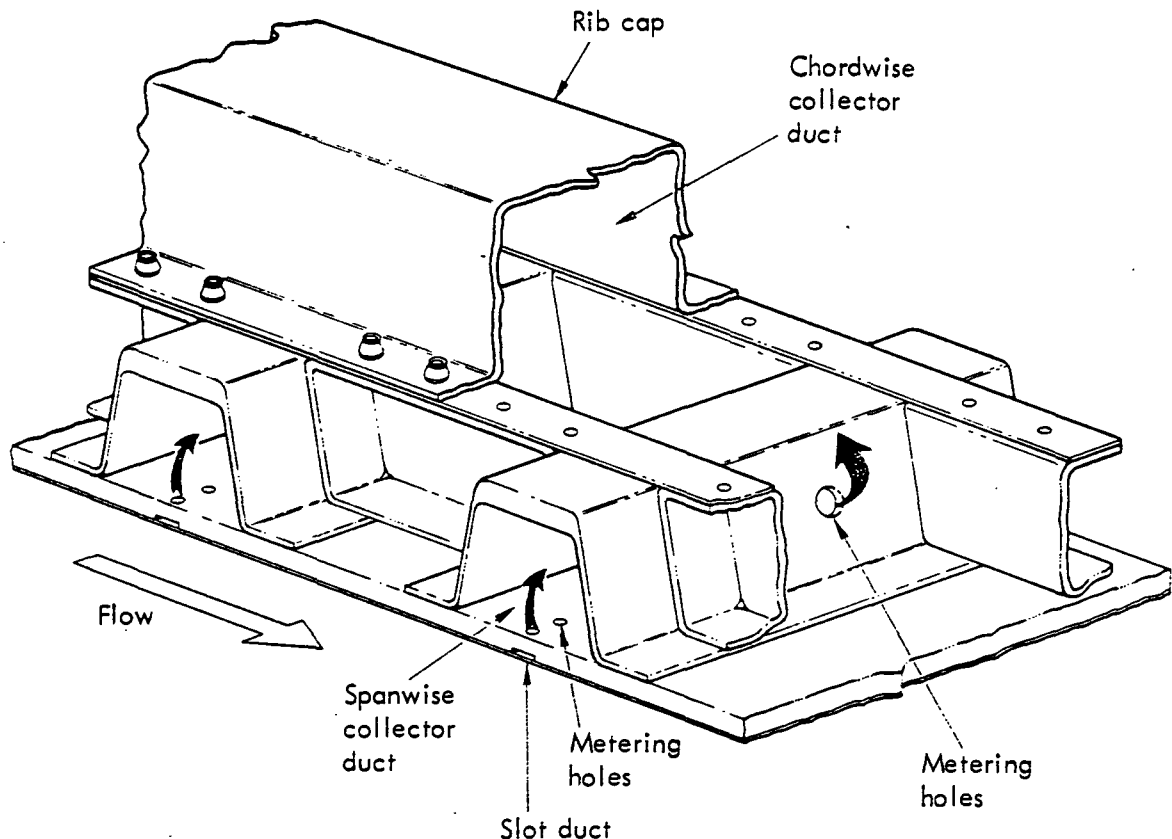


Figure 17. Surface design

5.2.2.2 Design

As shown in Figure 17, boundary layer air is pulled through spanwise surface slots into spanwise capillaries, then through metering holes into structural hat stiffeners. Suction flow is carried spanwise until it reaches the chordwise collector duct formed by hollow rib caps located on alternate ribs.

The LFC surface is constructed of graphite/epoxy. Each element is bonded in place, with mechanical fasteners used at rib caps. The entire surface is covered by a sheet of titanium. The surface is designed to accommodate slot spacings 5.08, 7.62, and 10.15 cm (2, 3, and 4 in) or multiples thereof.

Details of the surface concept, including the selection of materials and number and orientation of the 5208/T300 graphite/epoxy plies, are shown in Figure 18.

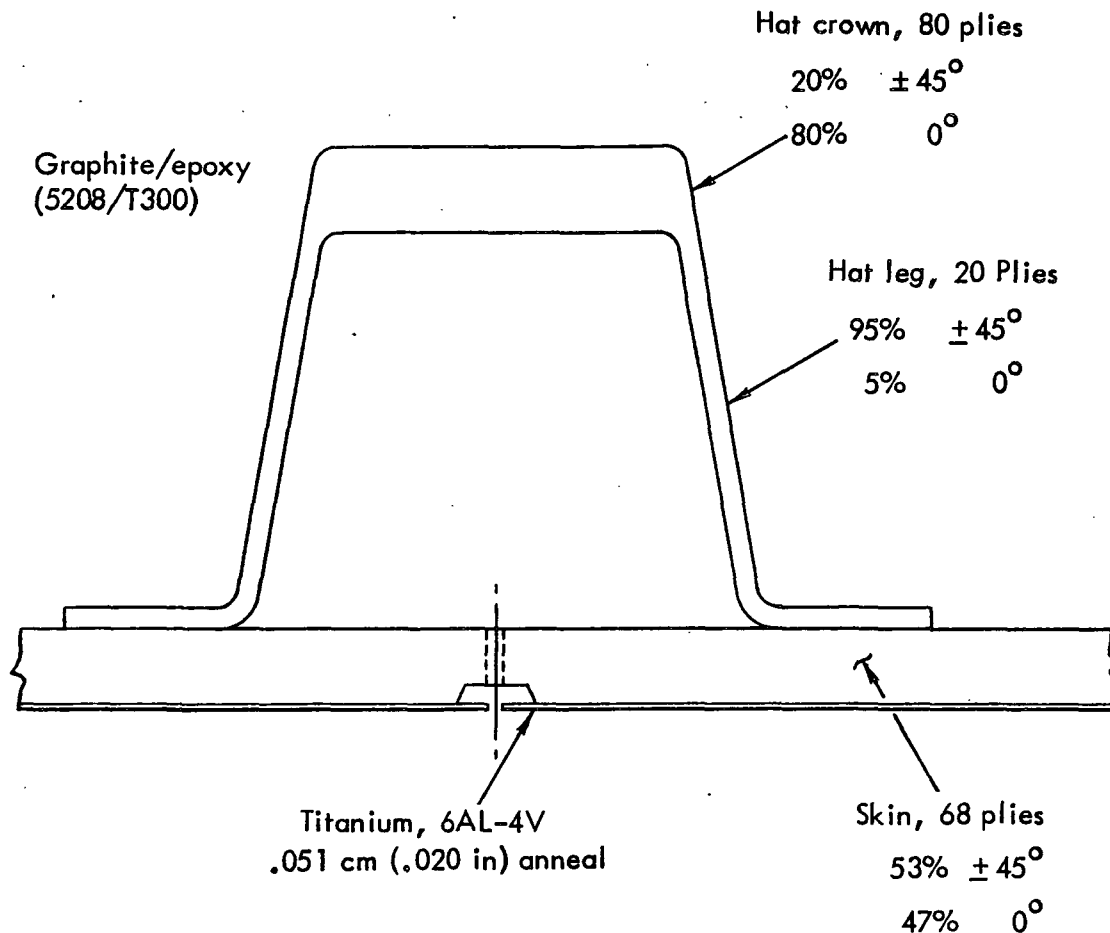


Figure 18. Surface materials & sizing

5.2.2.3 Manufacturing Procedures

The manufacturing procedures evaluated during this phase of the study were directed toward the development of three .91m x 1.52m (3 ft x 5 ft) LFC surface panels to be employed in subscale testing. To permit fabrication of the selected LFC surface design, manufacturing development was required to economically produce acceptable slots in titanium and fabricate basic hat-stiffened wing-box structure from graphite/epoxy composite material in sections thicker than had previously been fabricated. A variety of slotting procedures and graphite/epoxy structure fabrication and assembly procedures were evaluated in the selection of manufacturing procedures providing a high-quality, dimensionally accurate LFC wing panel structure.

The following summarizes the manufacturing procedures developed for fabrication of LFC surface panels:

- (1) The outer skin, inner skin, and hat stiffeners are separately cured and subsequently joined by structural adhesive bonding.
- (2) During the final bonding cycle, the shear clips are integrally molded in place.
- (3) The titanium face sheet is bonded to the outer skin with FM123-4 adhesive.
- (4) The titanium face sheet is slotted using a jeweler's saw.

5.2.2.4 Testing

Subscale testing of LFC surface panels was conducted in the following areas:

- (1) Environmental
 - o Temperature
 - o Icing
 - o Corrosion
 - o Foreign object damage
 - o Repairability
 - o Lightning
- (2) Structural component tests
 - o Rib clip tension
 - o Rib clip shear
 - o Compression

(3) Fatigue

Test specimens were cut from the three .91 m x 1.52 m (3 ft x 5 ft) LFC surface panels described in the preceding section. A photograph of the first surface panel illustrating the allocation of test specimens is presented in Figure 19. The second surface panel was sectioned to acquire the large specimens for the compression tests. The entire third panel was used for the fatigue test. The number and characteristics of test specimens is outlined in Table 3.

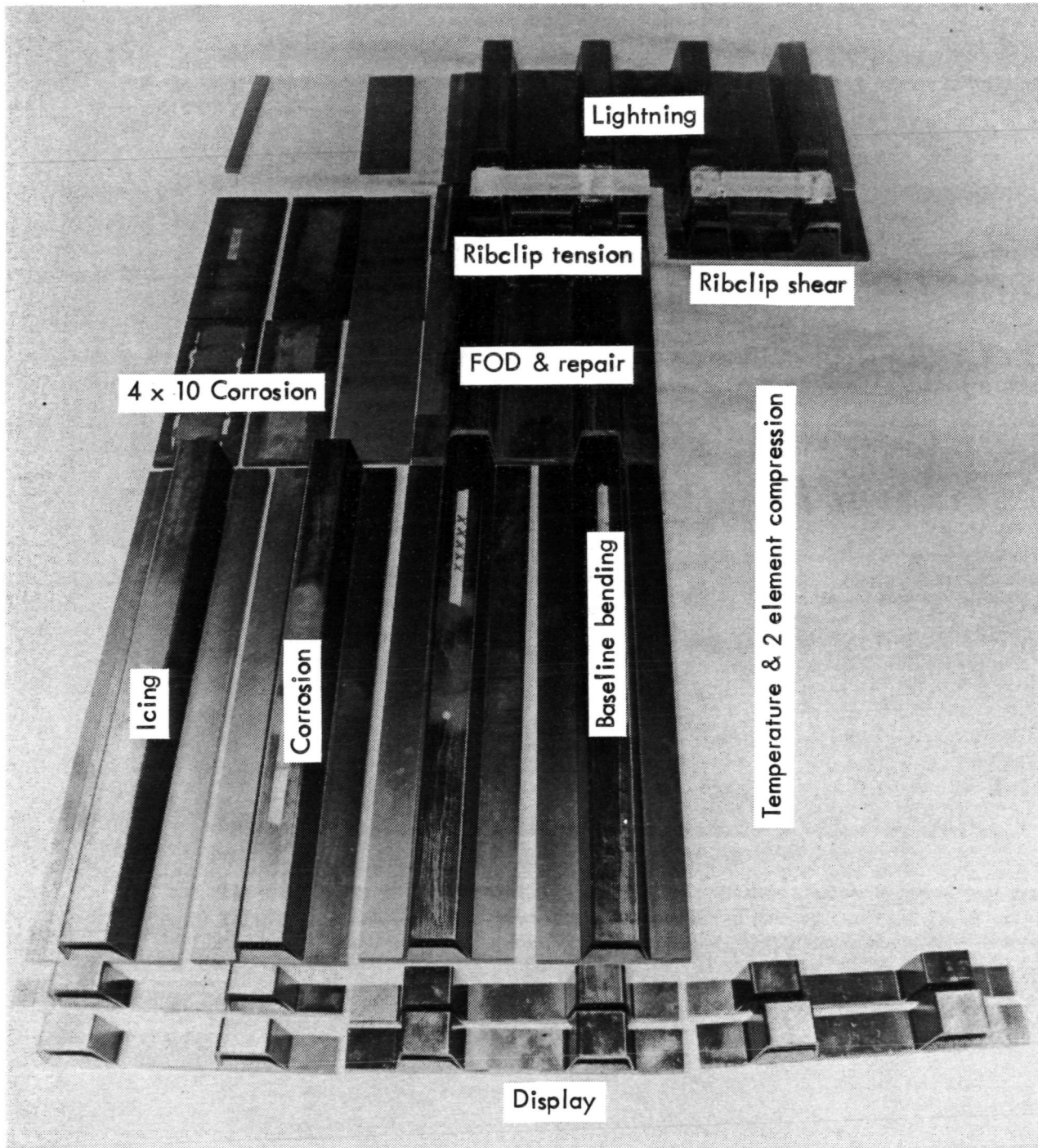


Figure 19. Test specimens - LFC surface panel No. 1

TABLE 3. TEST SPECIMENS

<u>Type of Test</u>	<u>Panel No.</u>	<u>Number of Specimens</u>	<u>Dimensions</u>	
			<u>cm</u>	<u>(in)</u>
Temperature	1	1	30.5 x 91.4	(12 x 36)
Icing	1	1	15.2 x 30.5	(6 x 24)
Corrosion (4 pt bending)				
Skin	1	4	10.2 x 25.4	(4 x 10)
Panel	1	2	15.2 x 61.0	(6 x 24)
Foreign object damage and repairability	1	1	30.5 x 30.5	(12 x 12)
Lightning	1	2	30.5 x 30.5	(12 x 12)
Rib clip				
Tension	1	1	15.2 x 30.5	(6 x 12)
Shear	1	1	15.2 x 30.5	(6 x 12)
Compression				
2 elements	1	1	30.5 x 91.4	(12 x 36)
4 elements	2	1	61.0 x 152	(24 x 60)
Fatigue	3	1	76.2 x 188	(30 x 74)

The narrative which follows summarizes pertinent results of selected tests.

Temperature

Thermal testing was conducted to evaluate the effect of temperature changes on the width of slots in the LFC surface panel and to verify handbook values for the thermal coefficient of expansion for the thick composite structural skin. The thermal test panel and instrumentation are illustrated by Figure 20. Slot width variations were measured through the use of strain gages mounted across the slots. In the temperature range from -50°C (-60°F) to 82°C (180°F), the maximum variation in slot width

ranged between $+6.35$ and -6.10×10^{-4} mm ($+25$ and -24×10^{-6} in). Thus, slot width variations due to temperature changes are considered to be insignificant. An acceptable comparison of measured and handbook values for the coefficient of expansion for the composite structure was obtained.



Figure 20. Temperature test arrangement

Icing

Icing tests were conducted to evaluate the effect of entrapped water in the hat section stiffeners and in the surface ducts and metering holes.

As shown by Figure 21, a specimen was cut from the panel for icing tests and the ends of the hats were closed by clamping aluminum plates with a rubber seal to each end. A stand-pipe was attached to one end and filled with water. The specimen was placed in a low-temperature chamber and frozen at -18°C (0°F). One hat flange separated from the skin. As illustrated by Figure 21, failure was within the composite hat flange. The flange separation emphasizes the need to keep water out of the hat sections during low temperature operation.



Figure 21. Icing test specimen

For the evaluation of icing in the surface ducts and metering holes, the ducts and holes were fileed with water through the skin slots. The specimen was exposed to 15 freeze-thaw cycles, after which there was no visually detectable damage. Removal of the titanium skin did not reveal any hidden damage. A section was cut through a metering hole, and the specimen was mounted and polished. Microscopic examination up to 200X showed no delamination or cracking.

Corrosion

Tests were conducted to evaluate the effect of environments representative of those encountered in airline operations on the bending strength of the LFC surface panel.

Three 10.16x25.40 cm (4 x 10 in) panel specimens were exposed to 30 days of salt fog, 30 days of high humidity, and 30 days of Weather-O-Meter, respectively. In addition, a 15x61 cm (6 x 24 in) specimen was exposed to 30 days in the Weather-O-Meter environment. After exposure, the specimens were static tested in a four-point bending test, as illustrated by Figure 22. The maximum reduction in bending strength was 18% for the specimen subjected to the Weather-O-Meter environment.

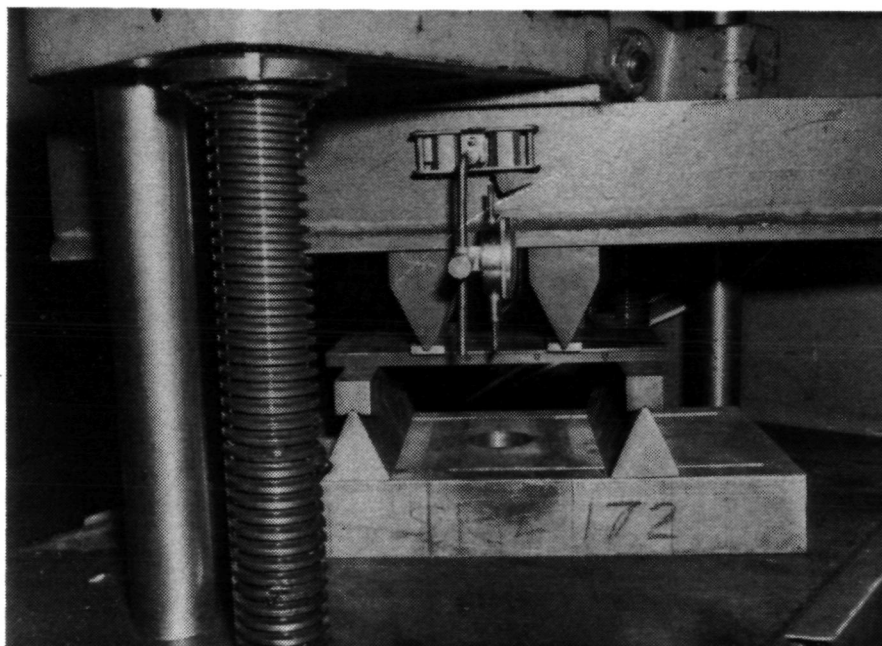


Figure 22. Corrosion/bending test arrangement

Foreign Object Damage

The objective of this test was to determine the resistance of an LFC surface panel to foreign object damage.

Using the experimental arrangement shown in Figure 23, the LFC surface panel was impacted over the slotted surface duct and over the composite-supported titanium at energy levels of 5.76, 11.52, 23.04, 46.08, and 92.16 m-kG (5, 10, 20, 40 and 80 in/lb). the depth of the maximum indentation at

each impact point was measured with a depth micrometer. Figure 24 shows the result of a 92.16 m-kg (80 in/lb) impact over a surface duct. Apparent damage over solid laminate supported titanium was minimal. Removal of the titanium skin revealed little visual damage to the composite over the plenum and none over solid laminate.

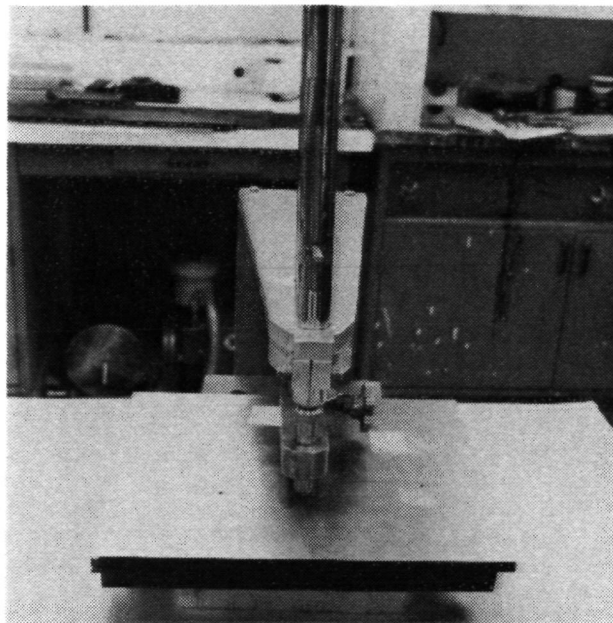


Figure 23. Impact test arrangement

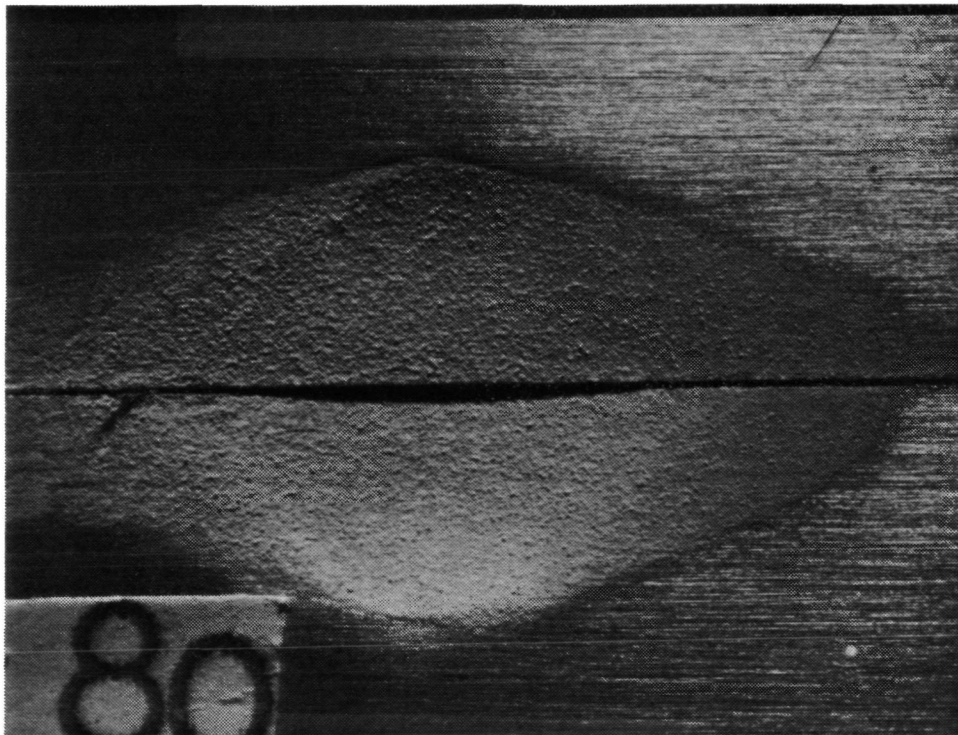


Figure 24. Impact test specimen

Repairability

The objective of this investigation was to demonstrate that typical damage to the slotted titanium LFC surface can be repaired by methods usable in-service by fleet operators.

The LFC surface panel specimen of the foreign object damage test described in the preceding section was used as the test specimen. Repairs were made to the dents produced by the 23.04 m-kg (20 in-lb) to 92.16 m-kg (80 in-lb) impacts in the titanium over the surface ducts.

A counterbore, chucked in a low-speed, hand-held, drill motor was used to remove the damaged area. A patch was prepared from slotted titanium sheet with a connecting tang in the center of the patch, as illustrated by Figure 25. Small strips of shim stock were used to align the slots, light pressure was applied, and the adhesive was allowed to cure at room temperature. The connecting tang was removed using a hand-held jeweler's saw.

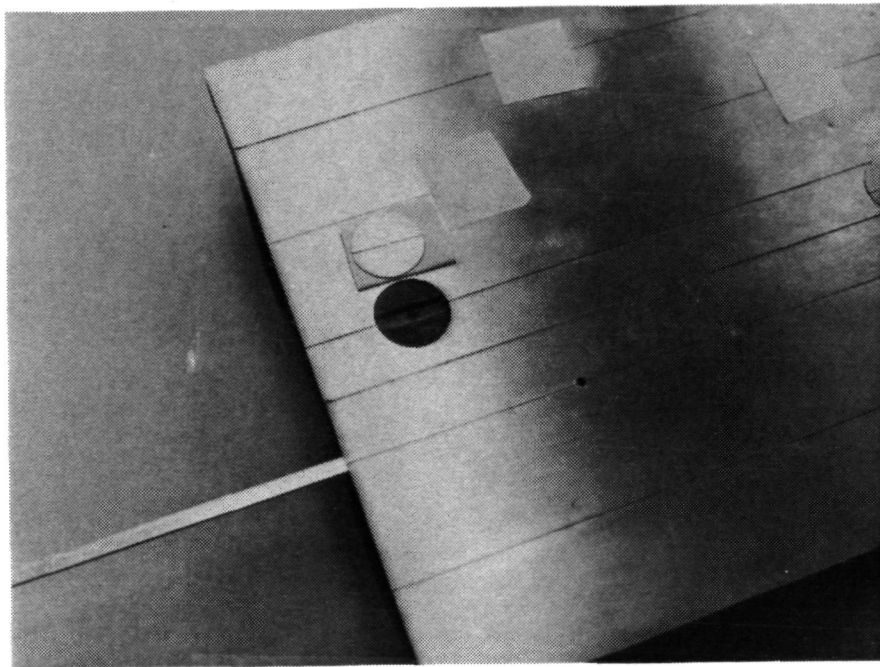


Figure 25. Repairability test specimen

It was demonstrated that a damaged slot can be returned to the original configuration using hand-held tools. While the tests were conducted on a bench, the entire operation could have been conducted either on the upper or lower surface of an aircraft wing. Repairs of this nature could be performed within a time span of four to six hours by using heat lamps to accelerate the adhesive cure.

Lightning

Preliminary tests were performed to ensure that the structural arrangement of the LFC surface panel is resistant to lightning strike. The test specimen shown in Figure 26 was tested by NASA personnel in the NASA LRC lightning strike test facility.

In all tests, the titanium face sheet was effective in preventing the current from penetrating the composite. The panel after four lightning strikes is shown in Figure 26.

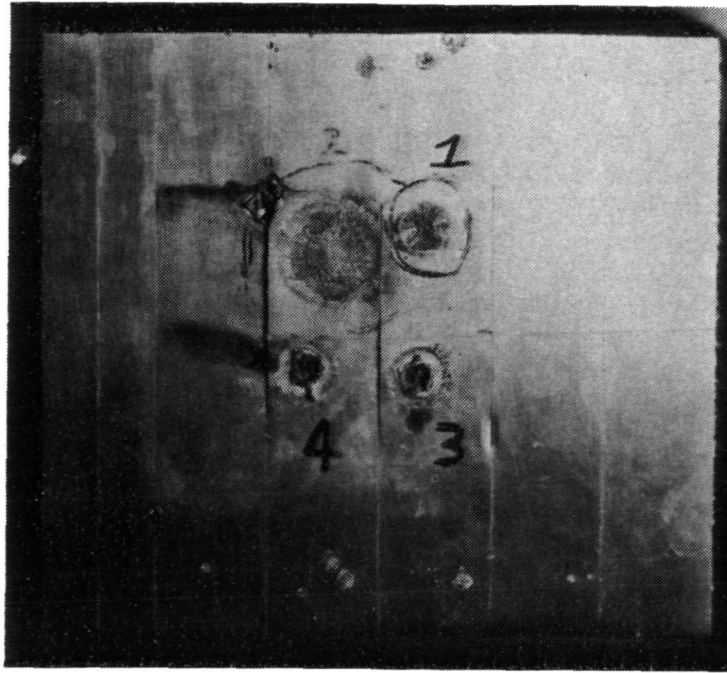


Figure 26. Lightning test specimen

Compression

The objective of the panel compression test was to obtain design data for a four-element compression panel. The acceptable criterion for the compression panel was a design ultimate load of 6.49 MN/m (37.08 kips/in) without failure.

The specimen was loaded in 0.445 MN (1 000 000 lb) increments. While loading between 0.890 MN (200 000 lb) and 1.334 MN (300 000 lb), it was noted that the titanium skin was buckling at the top and the bottom edge of the panel, including areas that had previously been determined to have some disbonding. Loading was continued to 2.224 MN (500 000 lb) and buckling of the titanium strips progressed over the length of the panel. The specimen withstood 3.959 MN (890 000 lb), the design ultimate load, when failure occurred by delamination of the hats and skin, as shown in Figure 27.

Both the environmental testing and the structural testing conducted in this phase of the study provided results demonstrating the compatibility of the selected LFC surface panel design with the anticipated operational environment for future LFC transports.

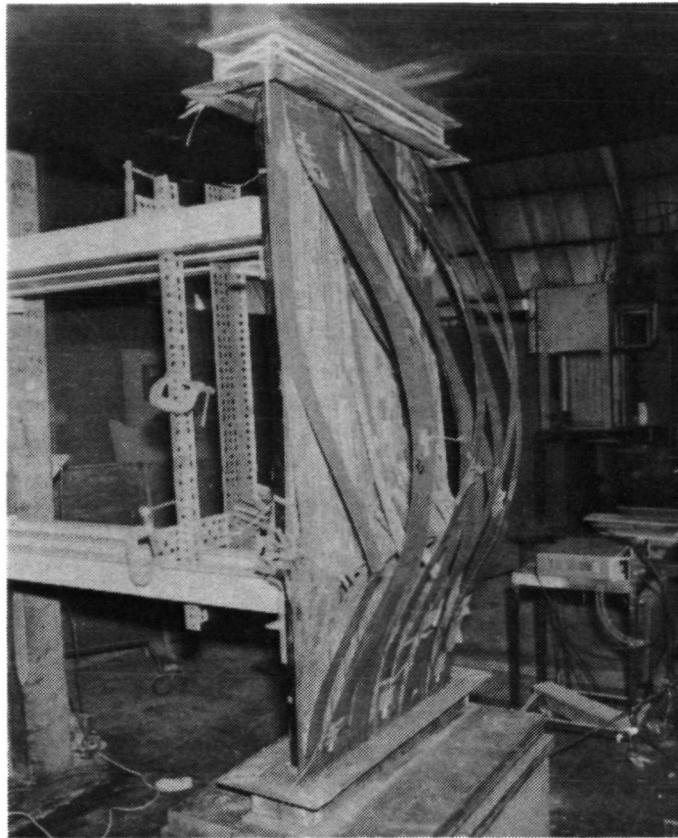


Figure 27. Compression panel test - failure mode

Fatigue

The objective of this test was to investigate the durability of a typical section of the LFC wing panel, including effects of foreign object damage and a large simulated crack. The test specimen was the third LFC surface panel. The panel was instrumented with 50 axial strain gauges. Acoustic emission transducers were mounted on the panel and monitored throughout the test.

After assembly of the panel and end fittings, the panel was exposed for 100 days to 95% relative humidity at 82°C (180°F). This exposure resulted in a moisture level of over 1%. A strain survey showed good load distribution.

Before beginning the fatigue test, the panel was subjected to foreign object damage. The panel was loaded to 2.224 MN (500 000 lb) in tension and impacted with a 1.27-cm (0.5-in) dia aluminum ball travelling at 61 m/sec (200 ft/sec). The test arrangement with the impact gun in place is shown in Figure 28.

The surface panel was subjected to the equivalent of two lifetimes using a loading spectrum based on the L-1011 lower wing surface. Each lifetime includes 18 000 simulated flights applied as flight-by-flight type loading. Each lifetime includes 218 000 cycles with the panel subjected to a maximum of limit load.

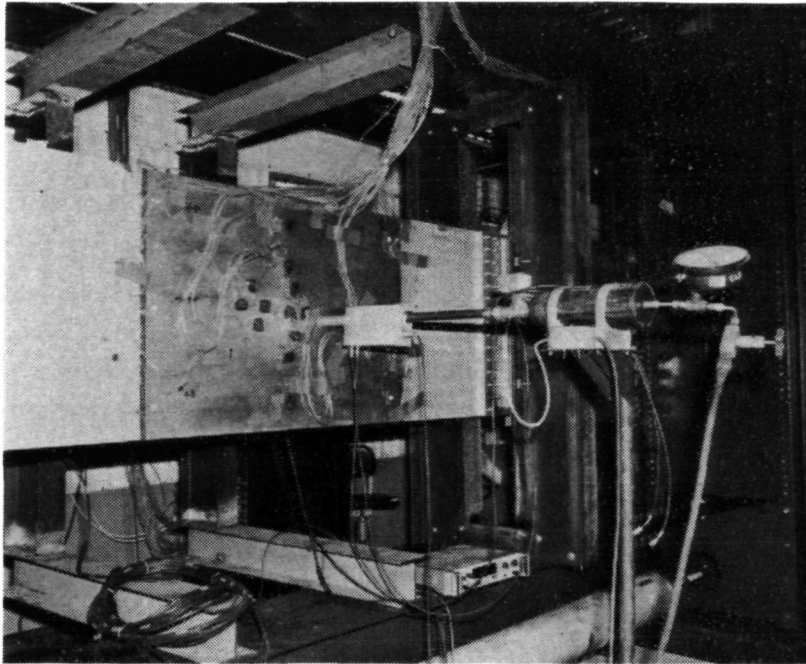


Figure 28. LFC surface panel No. 3 with impact gun

After the second lifetime, a 15.2-cm (6-in) slot perpendicular to the centerline of the hat was cut through the center of the panel to simulate a crack. The panel was fatigue tested for an additional 1440 flights and tested for residual strength.

The residual strength test verified that the crack did arrest, the remaining structure would still possess appreciable load-carrying ability, and that design features such as low-modulus crack-arrestment strips are not necessary for the LFC wing surface design to satisfy FAA damage tolerance criteria.

5.2.3 Leading-Edge Development

There is general concurrence that the design and fabrication of the leading-edge region represents one of the most challenging problems attending the development of operational LFC aircraft. The activities summarized in this section had the dual objectives of:

- (1) Performing the design, manufacturing development, fabrication and test activities required to define procedures for LFC leading-edge development, and
- (2) Providing a fully functional leading-edge test section for subsequent evaluation of cleaning and suction systems in low-speed wind-tunnel tests.

The configuration of the leading-edge selected for development is based on the wing defined for the 1993 LFC transport and described in Section 5.1.

The leading edge is a constant-chord section, representative of the baseline wing at 98% semi-span. The leading-edge chord is 41.4 cm (16.3 in), with an airfoil thickness at the front spar of 25.4 cm (10 in).

5.2.3.1 Design

A concept evaluation and selection procedure similar to that described in Section 5.2.2 was employed to select a preferred structural concept for development.

Figure 29 is a drawing of the selected structural arrangement of the leading-edge section and the method of attachment to the front spar. The section is fabricated in two panels, a fixed upper/nose panel and a hinged lower panel which provides access for maintenance and adjustment of the suction and washing systems. The substructure consists of two full-length diaphragms. These members provide support for the covers and form the boundaries of the upper and lower surface trunk ducts. All leading-edge components are of sandwich construction with graphite/epoxy face sheets and corrosion resistant aluminum honeycomb core. A thin gauge titanium skin, bonded to the surface panel outer face sheet, contains the required suction slots and provides an environmental protection for the composite structure.

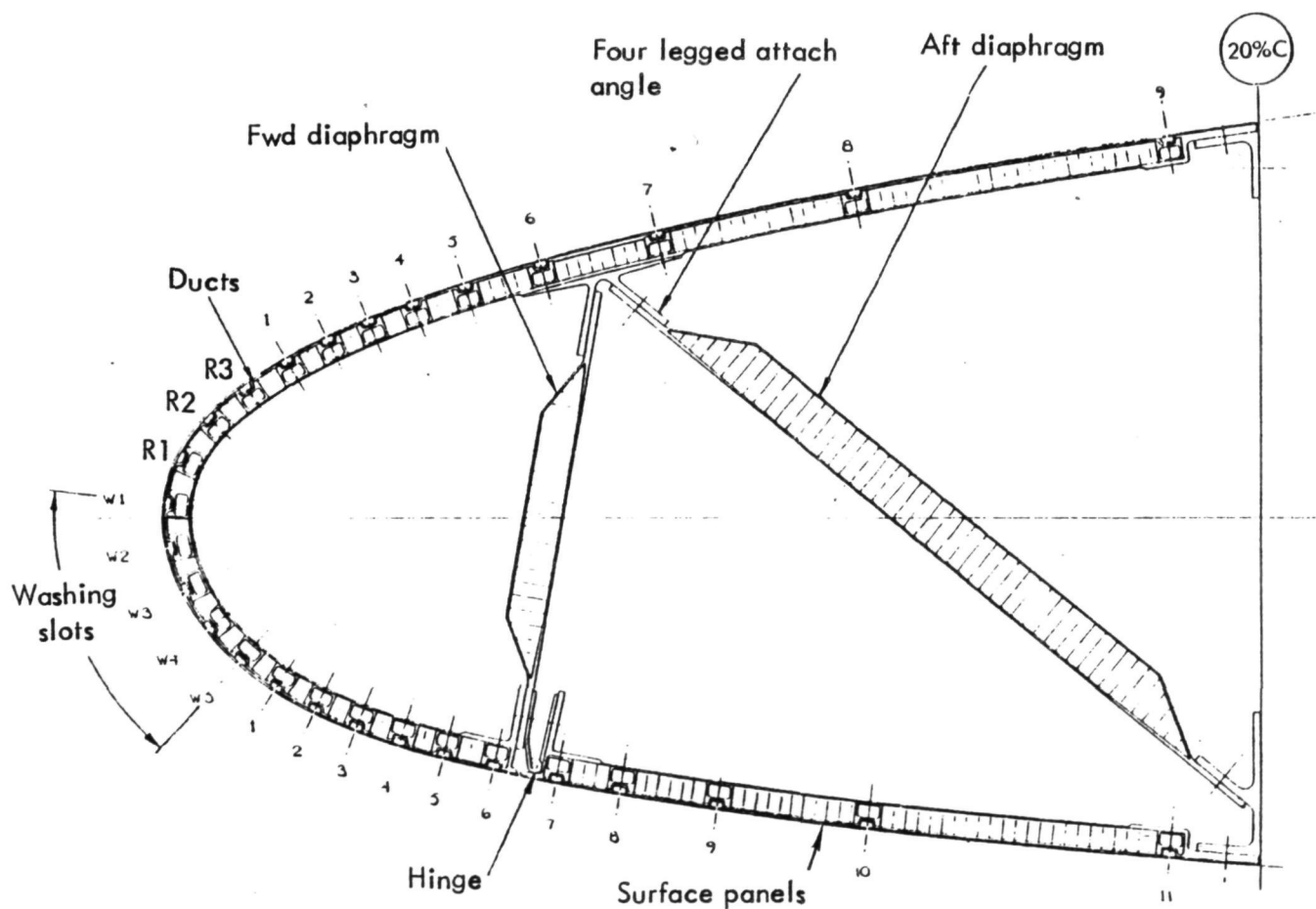


Figure 29. Leading edge structure

5.2.3.2 Manufacturing Procedures

Figure 29 identifies the following structural components of the leading-edge section:

- (1) Collector ducts
- (2) Upper/nose and lower surface panels
- (3) Forward and aft diaphragms
- (4) Diaphragm attachment fitting.

The following summarizes the manufacturing procedures developed for fabrication of the leading-edge test section:

- (1) The collector ducts and outer panel skin are cured separately.
- (2) The outer skin, collector ducts, honeycomb core, and inner skin are laid up in the contour tool and cocured.
- (3) The diaphragms and diaphragm attachment fittings are cured separately.
- (4) Metering holes are drilled in the slot ducts, the diaphragms are installed, and the titanium face sheet is bonded to the surface panel.
- (5) The titanium face sheet is slotted using a jeweler's saw.

The final phases of the manufacturing sequence are illustrated by Figures 30 and 31.

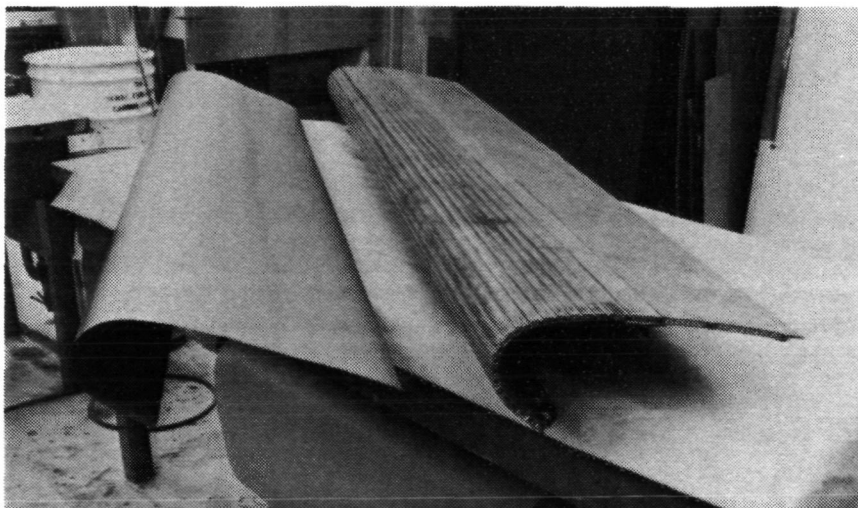


Figure 30. Leading edge structure and formed titanium skin ready for bonding

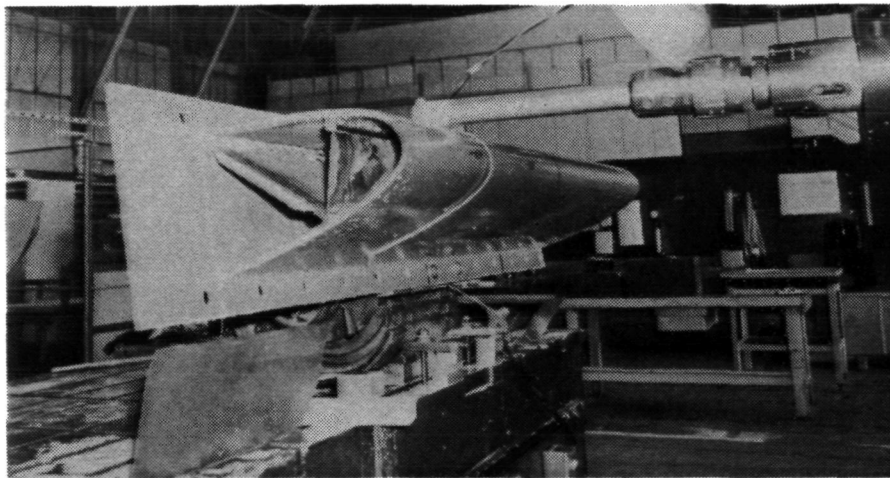


Figure 31. Slotting of leading edge test article

5.2.3.3 Testing

Component Testing

As a part of the development of the leading-edge test section, component tests were conducted as required to verify selected elements of the design.

Hinge Angle Shear Test - A portion of a tool-trial specimen of the lower surface panel of the leading-edge test section was tested in shear. Failure occurred by buckling of the honeycomb core at the edge of the tie down support. The failure load of 245 kg₂ (542 lb) is equivalent to a surface pressure load of over $2.14 \times 10^5 \text{ N/m}^2$ (31₄ lb/in₂²), compared to the maximum lower surface design pressure of $1.38 \times 10^4 \text{ N/m}^2$ (2 lb/in₂²).

Hinge Angle Tension Test - A portion of a tool-trial specimen of the lower surface panel was tested in tension. the test objective was to verify the structural capability of the hinge angle and panel joint. Failure occurred at 488 kg (1075 lb) by buckling of the honeycomb core below the first duct. The failure load was approximately eight times the maximum design load.

Four-Leg Attach Angle Test - The four-leg attach angle fitting used to attach the upper surface of the leading-edge test section to internal diaphragms was tested in tension. The objectives of this test were to determine the structural integrity of the fitting and the tension strength of the bond between the fitting and the upper surface panel. The four-leg angle withstood more load than the upper surface panel can apply. The failure load of 572 kg (1260 lb) is equivalent to an upper surface pressure loading of $6.21 \times 10^5 \text{ N/m}^2$ (90 lb/in₂²).

Leading-Edge Proof Test

The leading-edge section was loaded to simulate upper and lower surface pressures three times greater than the maximum expected during wind-tunnel testing. The test arrangement is illustrated by Figure 32. No damage was detected during or after loading.

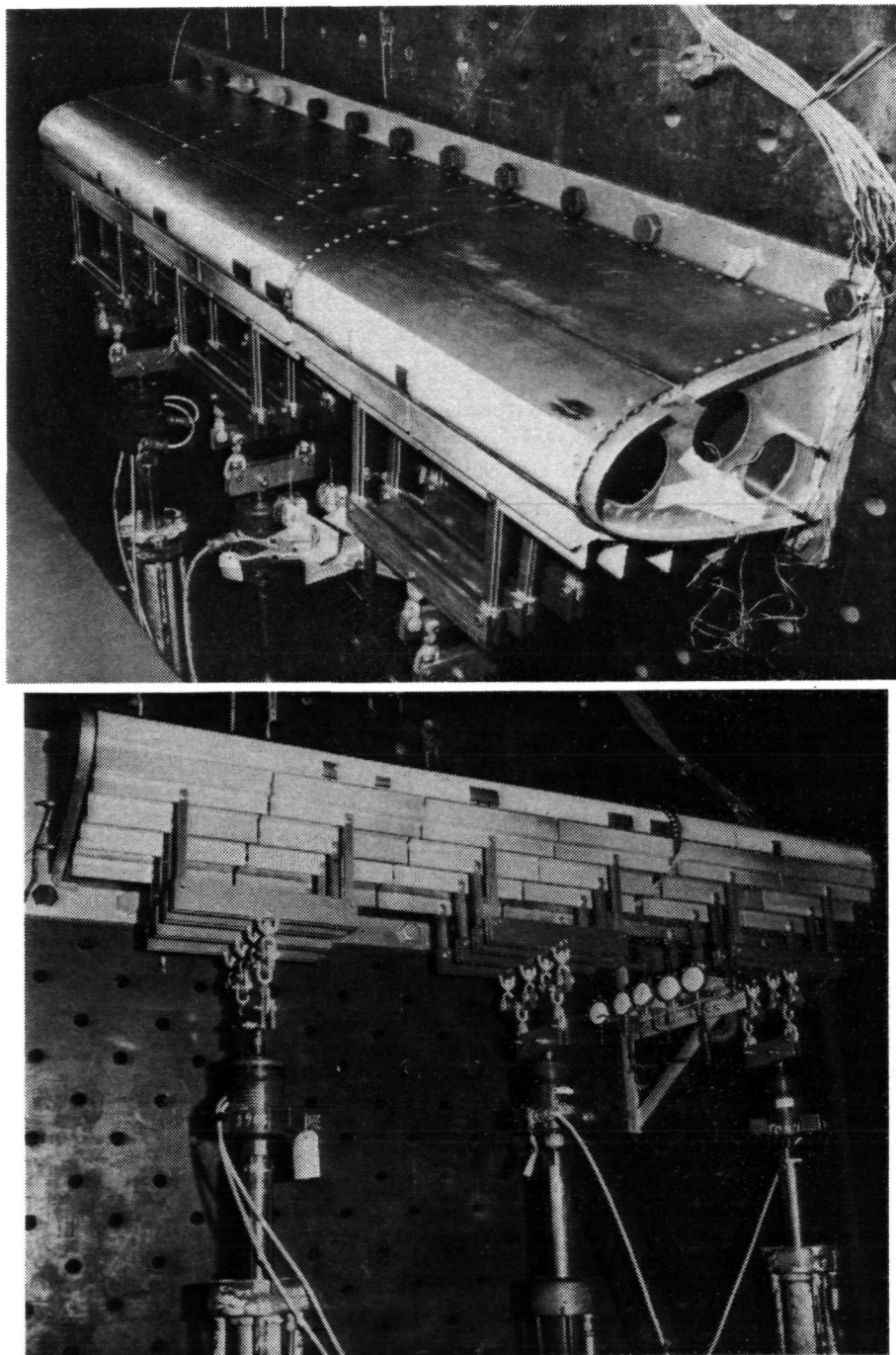


Figure 32. Loading arrangement details

5.3 LFC SUCTION SYSTEM

5.3.1 Design Objectives

The primary objective of the suction system design is to achieve efficient removal of the low-energy boundary-layer air from the airfoil surfaces as required to maintain laminar flow over the surface. A secondary, but equally important, objective is to design a system which is compatible with the structural design, manufacturing techniques and capabilities, low

manufacturing cost, high reliability, and good maintainability. Accomplishment of the primary objective is dependent on removal of boundary-layer air in a selective manner to prevent boundary-layer transition. The required inflow of suction air is not uniform over the surface and the variation in local pressure over the airfoil surface necessitates various levels of suction. These constraints dictate that the suction surface and internal ducting be the subject of a careful design analysis to achieve the primary objective while maintaining compatibility with the secondary objective.

5.3.2 Surface Configuration

5.3.2.1 Design Criteria

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. The slot design must also be economically manufacturable and relatively insensitive to realistic production tolerances and contamination. They must be sized and located on the airfoil surfaces to match the suction flow distribution requirements and local flow levels. The following 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 7:

$$\begin{aligned}\beta_w &\geq 0.075 \\ 1.0 &\leq w/z \leq 1.4 \\ C_{ps} &\geq 0.02 \\ U_z/U_e &\leq 0.30 \\ R_w &\leq 100\end{aligned}$$

Unfortunately, supporting data for these criteria and limits 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 the criteria and limits.

5.3.2.2 Design Envelope Derivation

As a result of the complexities and interactive effects of the design criteria and the possibility of aircraft operation at other than design cruise conditions, a surface configuration sensitivity study was conducted to permit development of a design that would allow for off-design conditions. The basic approach adopted for this effort was to determine a design based on commonality of slot spacing and slot width over as much of the wing span as possible without violating any of the design criteria at off-design conditions.

An analytical evaluation of the governing equations for the β , w/z , C_{ps} and U_z/U_e slot design criteria showed that they may all be expressed in terms of slot Reynolds number, R_w , and slot width, w , for given airfoil surface boundary layer and airflow conditions and distributed suction flow requirements. Similarly, the slot spacing, ΔC_n , is defined solely by slot Reynolds number, R_w , at these same surface aerodynamic conditions. An upper limit of R_w may, in turn, be defined by the upper limit of the boundary layer sucked height velocity ratio U_z/U_e and the local boundary layer conditions. Thus, for a given location z on an airfoil surface with defined surface aerodynamic conditions and suction rate, specific limiting value lines may be plotted for each of the slot design criteria as a function of R_w vs w , or, in the case of slot spacing, simply as a function of R_w . An example of such a plot is shown on Figure 33.

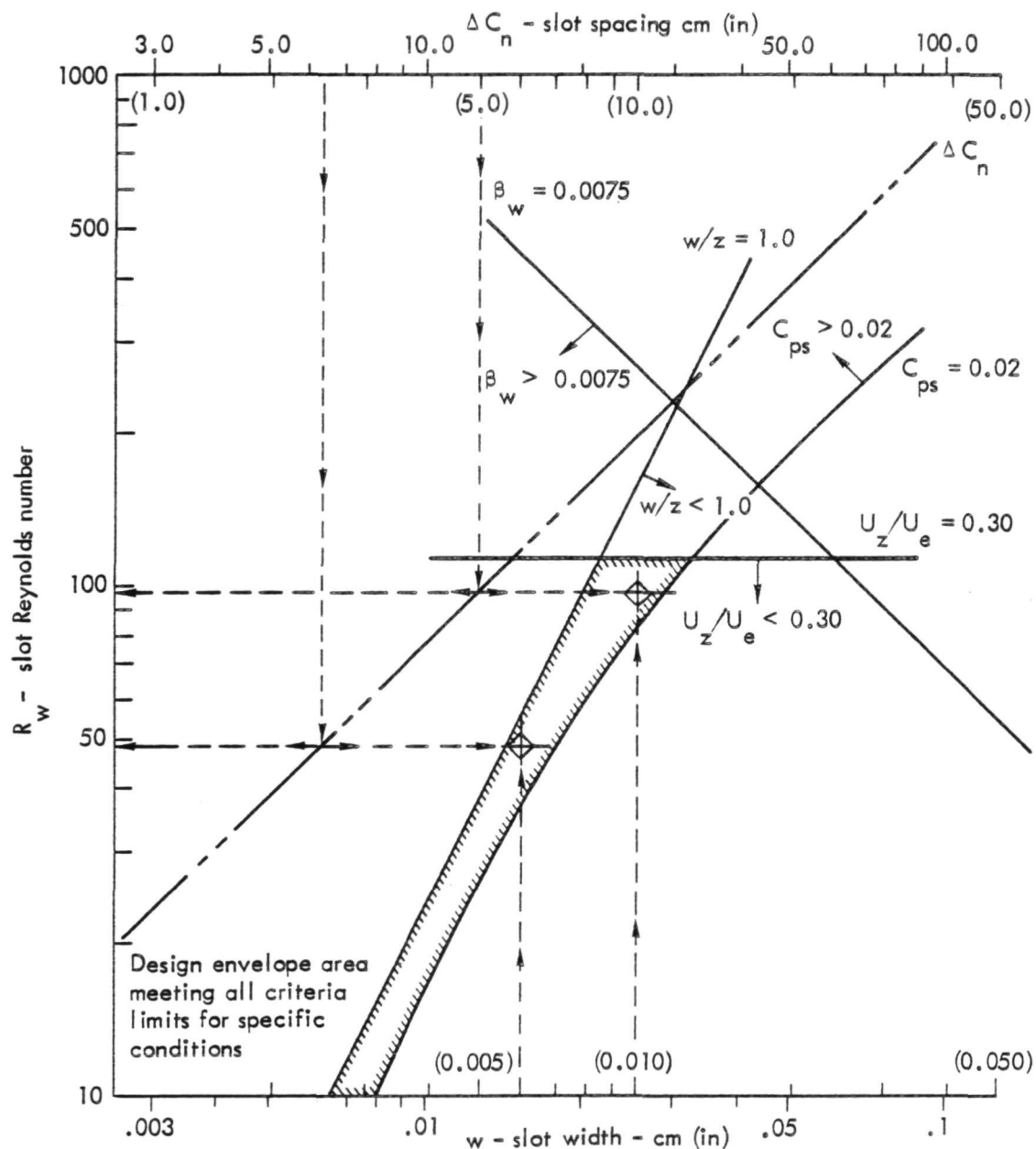


Figure 33. Typical criteria limit envelope

The limiting values of design criteria in terms of R_w as a function of w are shown as solid lines with the direction of acceptable criteria variations indicated by arrows. The intersection of the areas of acceptable criteria values is indicated by heavier lines and cross hatching on the figures. This area is referred to as a "Design Envelope" and is defined as the area on a criteria limit plot, or design chart, within whose boundaries all the criteria limits are satisfied for a specific surface location, airfoil geometry, flight condition, and distributed suction rate. The relationship between ΔC_n and R_w for these same specific conditions is shown as a phantom line on the figure.

The design chart may be used to select a design configuration by choosing a point within the design envelope based on a compromise of the design criteria limits or, as is more likely, by choosing a slot spacing or a slot width that is compatible with structural or manufacturing requirements. If the former method is used, the resulting slot width and/or spacing may prove to be inconvenient or impossible to manufacture. The latter method allows selection of a convenient slot width or spacing or possibly both.

5.3.2.3 Surface Design

Through the use of appropriate surface design charts, Figure 34 was developed to graphically illustrate the selected surface design for a production aircraft. This figure illustrates the mid-semispan chord location with a chord length of 6.96 m (22.813 ft). The chordwise design region for both the upper and lower wing surfaces start at the first slot aft of the leading-edge cleaning/deicing system region located at $x/c = 0.01$. The design region terminates on the upper and lower surfaces at about $x/c = 0.70$ due to the standing shock wave and adverse pressure gradients located in this vicinity.

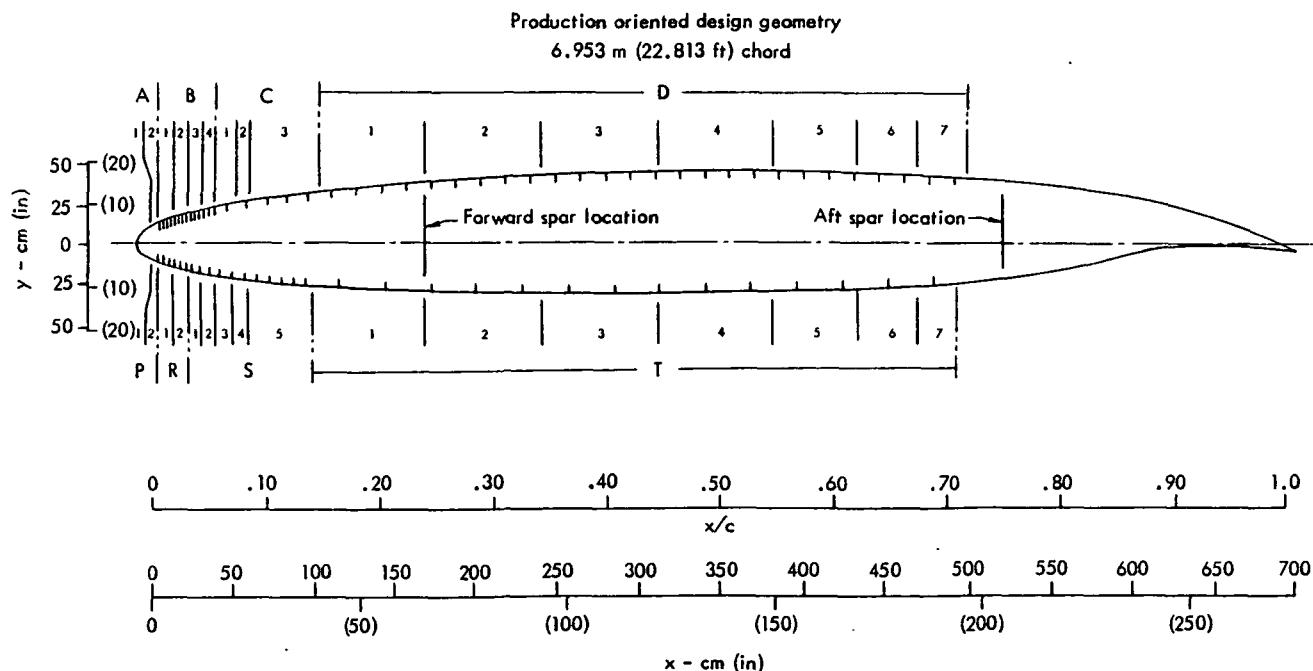


Figure 34. Production oriented wing surface design

The design illustrated by Figure 34 shows the outline of the airfoil shape as a function of both x/c and chord distance x . The suction slots are represented by marks internal to the airfoil outline. The external divisions signify different zones, an alpha character describing a major zone distinguished by a constant slot width throughout, and a numeric character describing a sub-zone region of each major zone. The combined alpha-numeric zone corresponds to a single line of slot performance data in the associated tables which follow. Each line of slot performance data in these tables corresponds to a specific x/c location, while the alpha-numeric zone represents a range of x/c locations. For analysis purposes, it was assumed that all slots located in a zone performed in a manner such that the table values reflect the average slot performance for that zone. Slot locations are not shown in Zones A and P due to very small spacing in those regions. Table 4 lists both the geometry and performance of the upper surfaces for the 12 192 m (40 000 ft), 0.80-Mach-number cruise condition. The column headings correspond to an alpha-numeric zone location (ZONE), chordwise (X/C) location, slot width (W) in inches, slot spacing (ΔCN) 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). The lower surface geometry and performance are listed for the design cruise condition on Table 5.

TABLE 4. UPPER SURFACE PRODUCTION DESIGN DATA

Altitude = 12 192 m (40 000 ft)			Mach No. = 0.80			Chord = 6.953 m (22.813 ft)		
ZONE	X/C	W	CN	RW	W/Z	UZ/UE	BETA	CPS
A1	.1200-01	.3500-02	.6200+00	.3393+02	.1351+01	.2830+00	.1684+00	.6069-01
A2	.1800-01	.3500-02	.6200+00	.3074+02	.1328+01	.2583+00	.1859+00	.5821-01
B1	.2700-01	.5000-02	.1120+01	.4847+02	.1295+01	.2839+00	.8252-01	.4537-01
B2	.3700-01	.5000-02	.1250+01	.4480+02	.1204+01	.2452+00	.8929-01	.4100-01
B3	.4800-01	.5000-02	.1250+01	.3979+02	.1180+01	.2133+00	.1005+00	.3456-01
B4	.6200-01	.5000-02	.1750+01	.3386+02	.1165+01	.1790+00	.1181+00	.2750-01
C1	.7600-01	.1000-01	.5000+01	.9675+02	.1270+01	.2783+00	.2067-01	.2772-01
C2	.9200-01	.1000-01	.5000+01	.9675+02	.1226+01	.2678+00	.2067-01	.2756-01
C3	.1000+00	.1000-01	.5000+01	.9675+02	.1202+01	.2624+00	.2067-01	.2752-01
D1	.2000+00	.1300-01	.6000+01	.1161+03	.1249+01	.2480+00	.1325-01	.2105-01
D2	.3000+00	.1300-01	.6000+01	.1161+03	.1213+01	.2404+00	.1325-01	.2108-01
D3	.4000+00	.1300-01	.6000+01	.1161+03	.1195+01	.2364+00	.1325-01	.2129-01
D4	.5000+00	.1300-01	.6000+01	.1161+03	.1168+01	.2318+00	.1325-01	.2166-01
D5	.6000+00	.1300-01	.6000+01	.1161+03	.1170+01	.2331+00	.1325-01	.2202-01
D6	.6500+00	.1300-01	.6000+01	.1161+03	.1188+01	.2385+00	.1325-01	.2250-01
D7	.7000+00	.1300-01	.6000+01	.1161+03	.1183+01	.2397+00	.1325-01	.2299-01

TABLE 5. LOWER SURFACE PRODUCTION DESIGN DATA

Altitude = 12 192 m
(40 000 ft)

Mach No. = 0.80

Chord = 6.953 m
(22.813 ft)

ZONE	X/C	W	CN	RW	W/Z	UZ/UE	BETA	CPS
P1	.1106-01	.3000-02	.8750+00	.2555+02	.1363+01	.2925+00	.2610+00	.4233-01
P2	.1760-01	.3000-02	.9200+00	.2560+02	.1215+01	.2393+00	.2604+00	.4546-01
R1	.2560-01	.4000-02	.1500+01	.3916+02	.1296+01	.2803+00	.1277+00	.3832-01
R2	.3510-01	.4000-02	.1500+01	.3607+02	.1109+01	.2185+00	.1386+00	.3502-01
S1	.4640-01	.6000-02	.2300+01	.4977+02	.1352+01	.2436+00	.6697-01	.1994-01
S2	.5910-01	.6000-02	.2650+01	.5006+02	.1249+01	.2249+00	.6658-01	.2047-01
S3	.7340-01	.6000-02	.3250+01	.5135+02	.1186+01	.2178+00	.6491-01	.2159-01
S4	.8910-01	.6000-02	.3250+01	.4875+02	.1107+01	.1925+00	.6838-01	.2007-01
S5	.1000+00	.6000-02	.3250+01	.4875+02	.1077+01	.1871+00	.6838-01	.2008-01
T1	.2000+00	.1500-01	.1100+02	.1650+03	.1198+01	.2799+00	.8081-02	.2145-01
T2	.3000+00	.1500-01	.1100+02	.1650+03	.1186+01	.2752+00	.8081-02	.2153-01
T3	.4000+00	.1500-01	.1100+02	.1650+03	.1094+01	.2526+00	.8081-02	.2155-01
T4	.5000+00	.1500-01	.1100+02	.1650+03	.1092+01	.2507+00	.8081-02	.2158-01
T5	.6000+00	.1500-01	.1100+02	.1650+03	.1056+01	.2411+00	.8081-02	.2163-01
T6	.6500+00	.1500-01	.1100+02	.1650+03	.1076+01	.2449+00	.8081-02	.2168-01
T7	.7000+00	.1500-01	.1100+02	.1650+03	.1141+01	.2465+00	.8081-02	.2087-01

5.3.3 Suction Ducting System

The suction ducting system is composed of a matrix of ducts to meter, collect, and transport the suction flow from each surface slot to the suction pump. Desired distribution of suction flow over the wing surfaces is primarily controlled by the metering system contained within the airfoil surface structure. Further metering is included in collector ducting integral with the structural members of the wing, with final collection occurring in the trunk ducts formed by the wing leading-edge cavity. Trunk ducts convey the suction flow to the wing root, where additional ducting features provide necessary suction pump control capability.

5.3.3.1 Ducting Concept

The ducting system for the baseline airplane has evolved over the course of this study based on both LFC system requirements and structural considerations. The resulting system concepts are compatible with both disciplines with relatively few compromises to either. The requirements of both disciplines divide naturally into leading-edge requirements and wing-box requirements. Somewhat different, although conceptually similar, configurations were developed for the mutual benefit of both disciplines.

5.3.3.2 Leading-Edge Ducting

The suction surface of the leading-edge region provides the entire metering system for the suction flow, as illustrated in Figure 35. The surface, described in Section 5.2.3, consists of a slotted titanium skin bonded to a contoured continuous graphite composite structural skin with inner slot ducts pre-formed into the surface, the closing side of the duct

being formed by the titanium skin. A pre-formed fiberglass collector duct is bonded to the underside of the graphite and another continuous graphite sheet forms the inner skin.

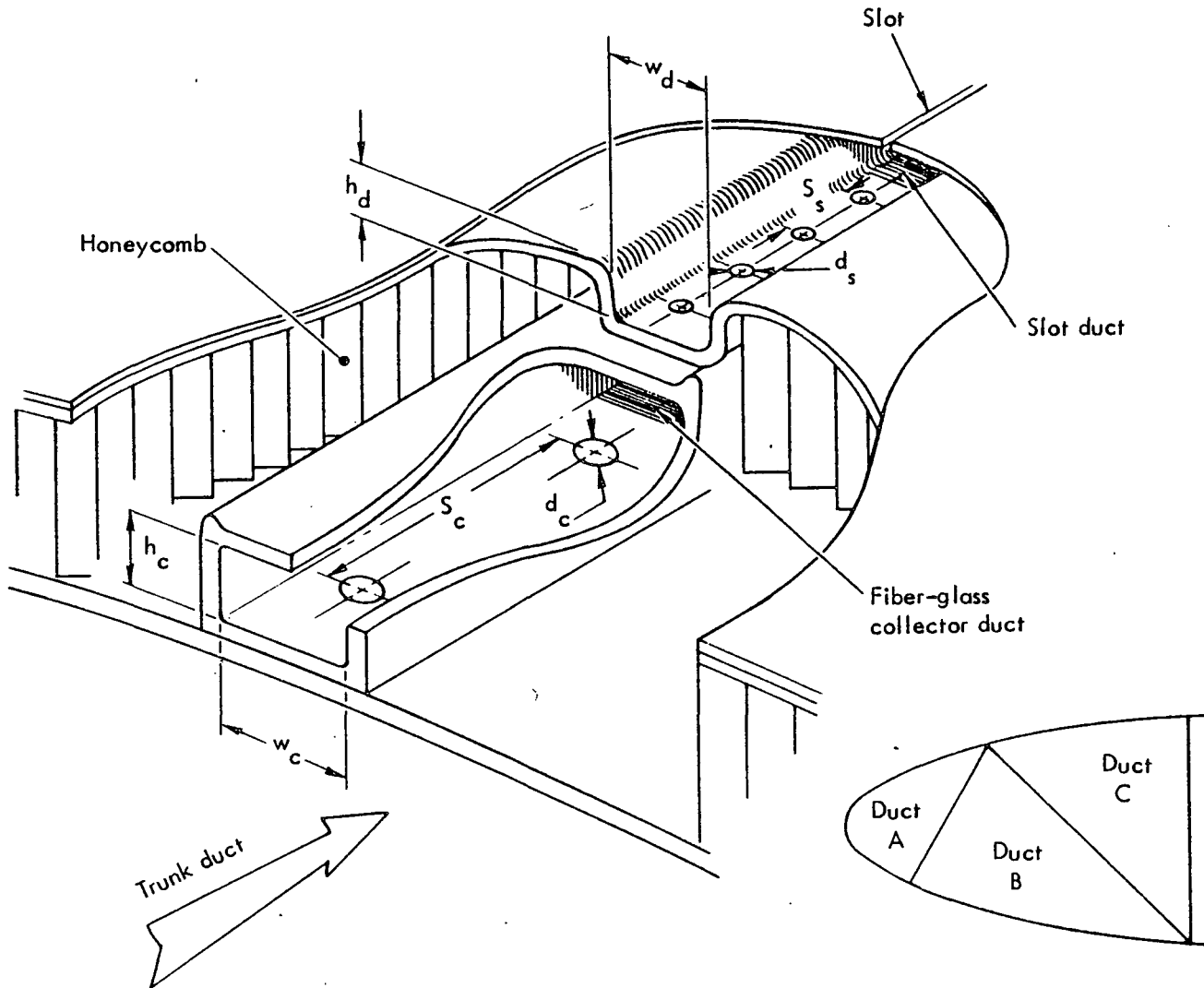


Figure 35. Leading edge ducting and metering schematic

Metering holes connect the slot duct to the collector duct and serve to distribute the slot flow uniformly along the slot. This metering prevents excessive slot flow variations that might otherwise occur as a result of slot width manufacturing tolerances and variations in external aerodynamic parameters. The diameter, d_s , and spacing, S_s , of these metering holes must be selected to provide suction flow pressure losses approximating those of the slots. They must provide stable flow and controlled pressure distribution in the slot duct that will limit slot flow variations to less than 1% across the slot lengths between metering holes.

A second and final level of leading-edge suction metering is provided by metering holes from the collector duct to the leading-edge trunk duct immediately inside the skin, as illustrated schematically by the inset in Figure 35. This metering is provided to meet two requirements: the collector cavity pressure must be maintained at a uniform level to provide

the proper discharge environment for the upstream slot metering holes, and proper flow metering must be provided downstream to match the local pressures within the respective trunk ducts.

5.3.3.3 Wing-Box Ducting

The slot suction metering concept in the wing-box region is essentially the same as that of the leading-edge region, although the actual configuration differs in several respects. For this surface, discussed in detail in Section 5.2.2, the titanium skin is bonded directly to a graphite composite structural skin. The structural requirements for this skin are such that the skin is relatively thick and therefore does not incorporate collector ducts in the same manner as the leading edge. The slot ducts are formed into the surface, as shown in Figure 36, and the structural hat members bonded to the inner surface of the skin serve as slot collector ducts. The relatively large cross-sectional area contained within the hat-section cavity serves as a duct to carry the flow spanwise to a rib location, where the flow is metered through orifices into chordwise ducts which are integral with the wing rib caps. These chordwise ducts are located at intervals along the wing. The hat ducts flow either inboard or outboard to the nearest chordwise duct as shown in Figure 37. The chordwise ducts convey the suction flow forward to a trunk duct, where the flows are metered to match the pressure existing locally in the appropriate trunk duct.

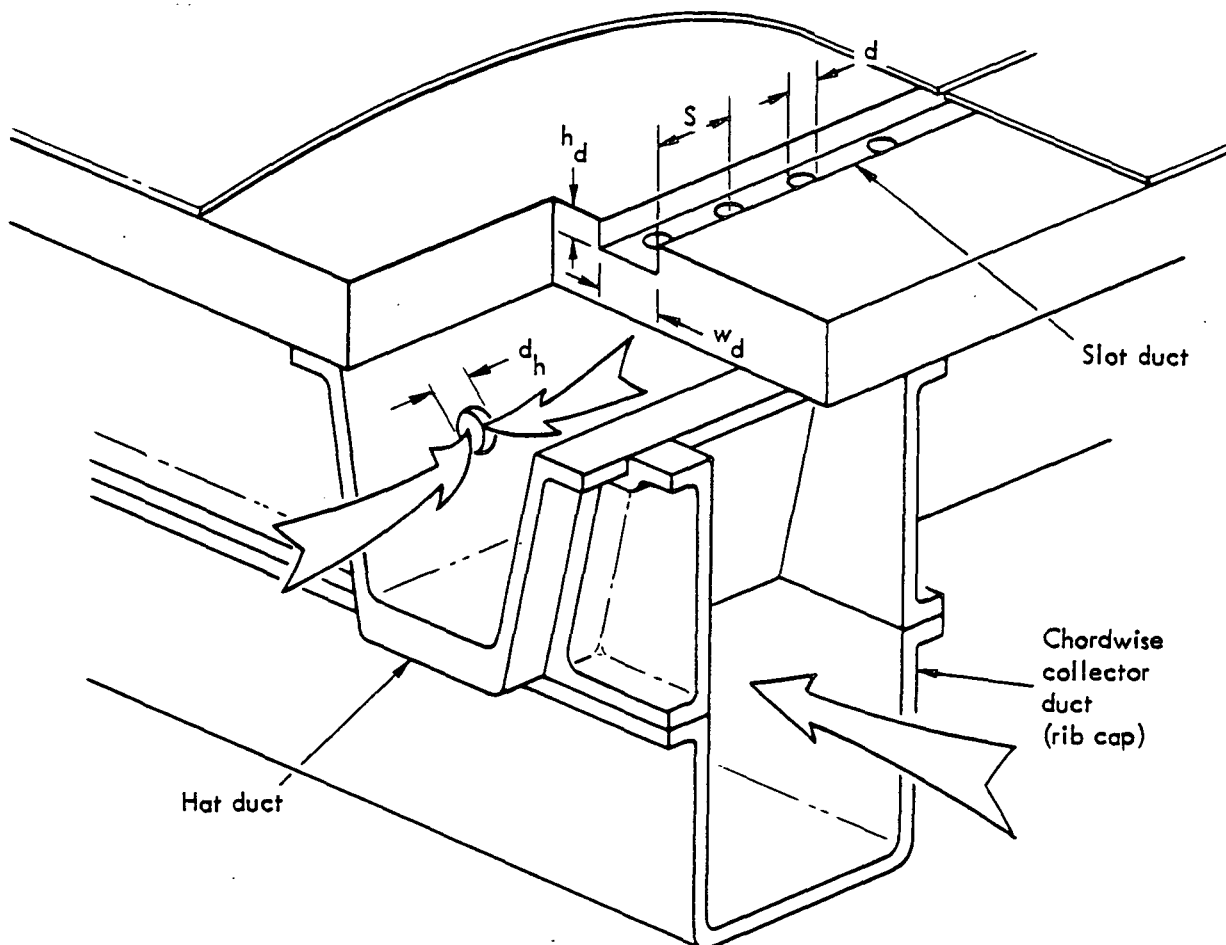


Figure 36. Wing box ducting and metering schematic

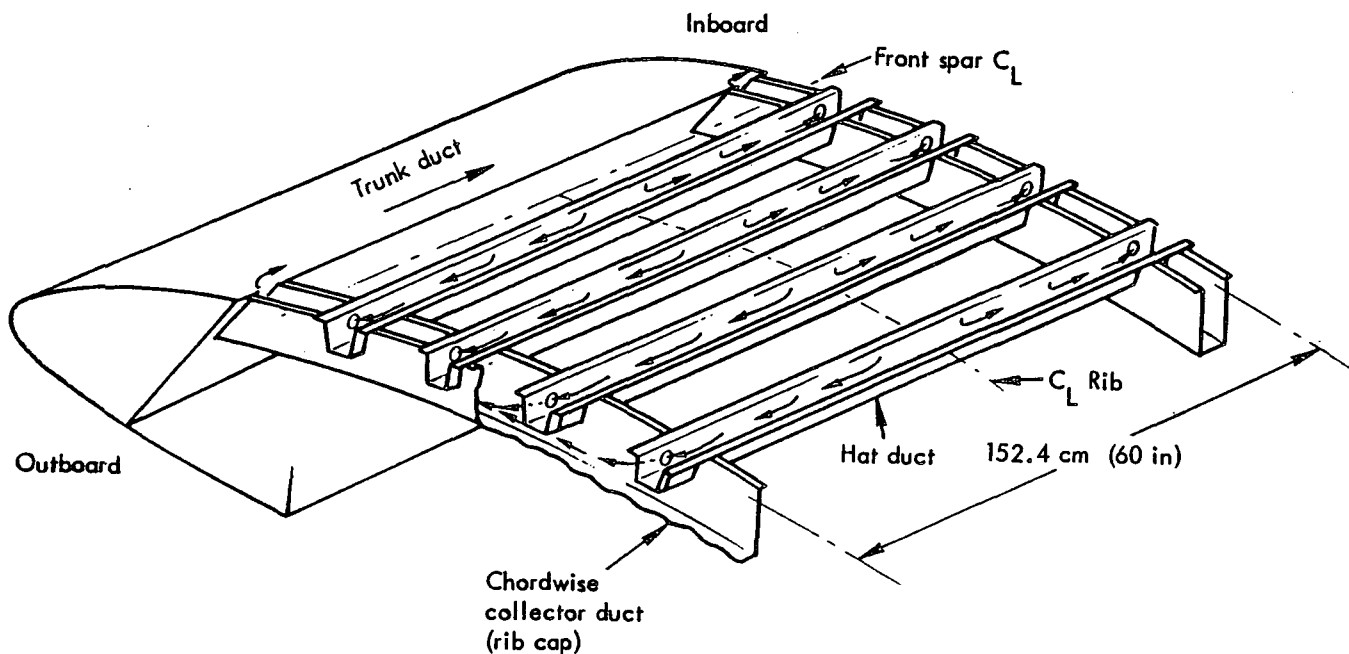


Figure 37. Wing box ducting system

Metering holes are drilled from the slot ducts into the hat-section collector ducts through the structural skin and serve the same function as those in the leading-edge region. Orifices through the forward leg of the hat section meter the flow from the hat duct into the chordwise ducts integral with the rib caps. These metering holes serve to regulate the flow from spanwise segment of the upper or lower box surface. Separate chordwise ducts are included for the upper and lower surfaces, permitting different pressures in the two chordwise ducts at any wing station. Metering of the hat-duct flow into the chordwise duct for either the upper or lower surface is thus independent of the significant pressure differentials that exist between the two surfaces.

The final level of wing-box suction flow metering is provided at the junction of the chordwise collector ducts with the leading-edge trunk ducts. Metering at this point maintains additional spanwise control and matching of upper and lower surface flows with the leading-edge flows. However, the primary requirements for the metering is to match the suction flow and the pressure within the collector duct to the pressures existing in the trunk ducts. Upper surface air flows into trunk duct C, shown schematically on Figure 35, while lower surface air flows into trunk duct B. The pressures within these trunk ducts are dictated by the requirements of the lowest-pressure suction flows entering them. The upper-surface leading-edge flows are metered directly into the trunk ducts. The surface pressures over the leading-edge region, therefore, dictate the pressures in these trunk ducts.

5.3.4 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 0.8 at 12 192 m (40 000 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.

5.3.4.1 Suction Requirements

The suction requirements and external aerodynamics of the wing airfoil are consistent with the airfoil evolved in Section 5.1. 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	346 m ² (3726 ft ²)
Wing lower	319 m ² (3430 ft ²)
Horizontal tail - each surface	33 m ² (351 ft ²)
Vertical tail - total	81 m ² (874 ft ²)

The laminarized wing areas are the total for the airplane and include adjustments for 75% nominal chord laminarization, airfoil surface curvature, allowance for flap hinge fairings on the wing lower surface, and an adjustment to the wing surfaces to recognize the inclusion of leading-edge suction with the upper surface suction. Empennage areas include adjustments for 65% nominal suction and airfoil surface curvature.

These areas, together with the C_p and distributed suction mass ratios were employed to define the total airplane suction profile shown in Figure 38. This figure illustrates the total suction flow and associated compression requirements arranged in the order of decreasing suction pump pressure ratio. The most stringent suction C_p values were taken for each surface and an allowance for 10% suction duct pressure loss was used in determining the required suction pressure ratios. The figure shows that 100% of the total flow must be compressed through a ratio of 1.92:1 or more, while 63.2% of the flow must be compressed through a ratio of at least 2.32:1, and 50.7% must be compressed through a ratio of 2.84:1.

5.3.4.2 Suction Unit Description

The suction unit selected to satisfy the requirements of the study aircraft is shown in Figure 39. 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 diffuser. The forward frame serves as the attachment for the aircraft suction system low-pressure duct and houses the boost element variable inlet guide vanes. These vanes provide a control for matching the boost element flow and pressure ratio with the high-pressure element inlet flow conditions under varying flight suction requirements. The two-stage boost element is sized to meet the low-pressure suction flow and pressure ratio requirements. The two stages

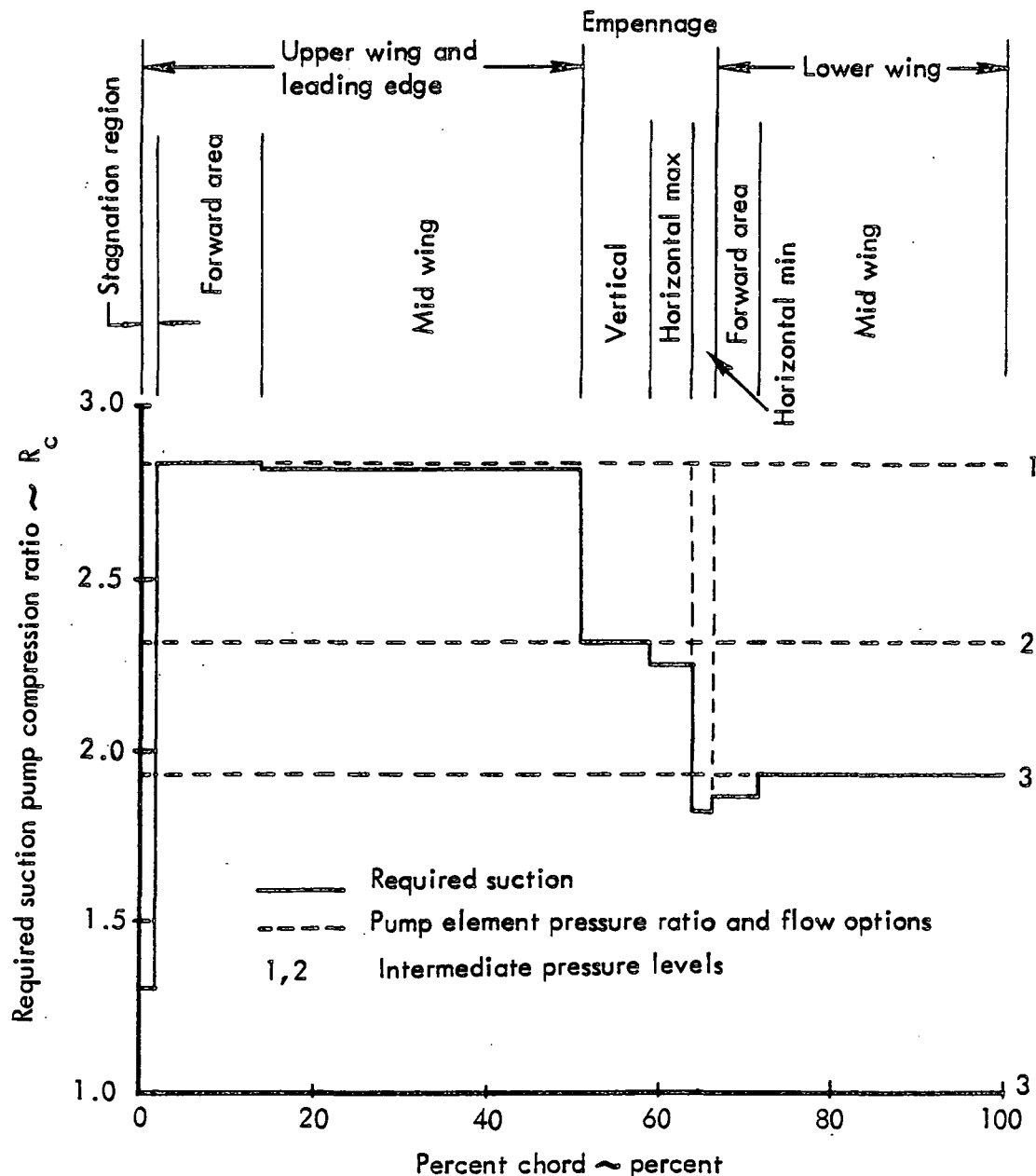


Figure 38. Suction requirements profile

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 shown 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. Both the boost and high-pressure elements are configured to operate on a common shaft.

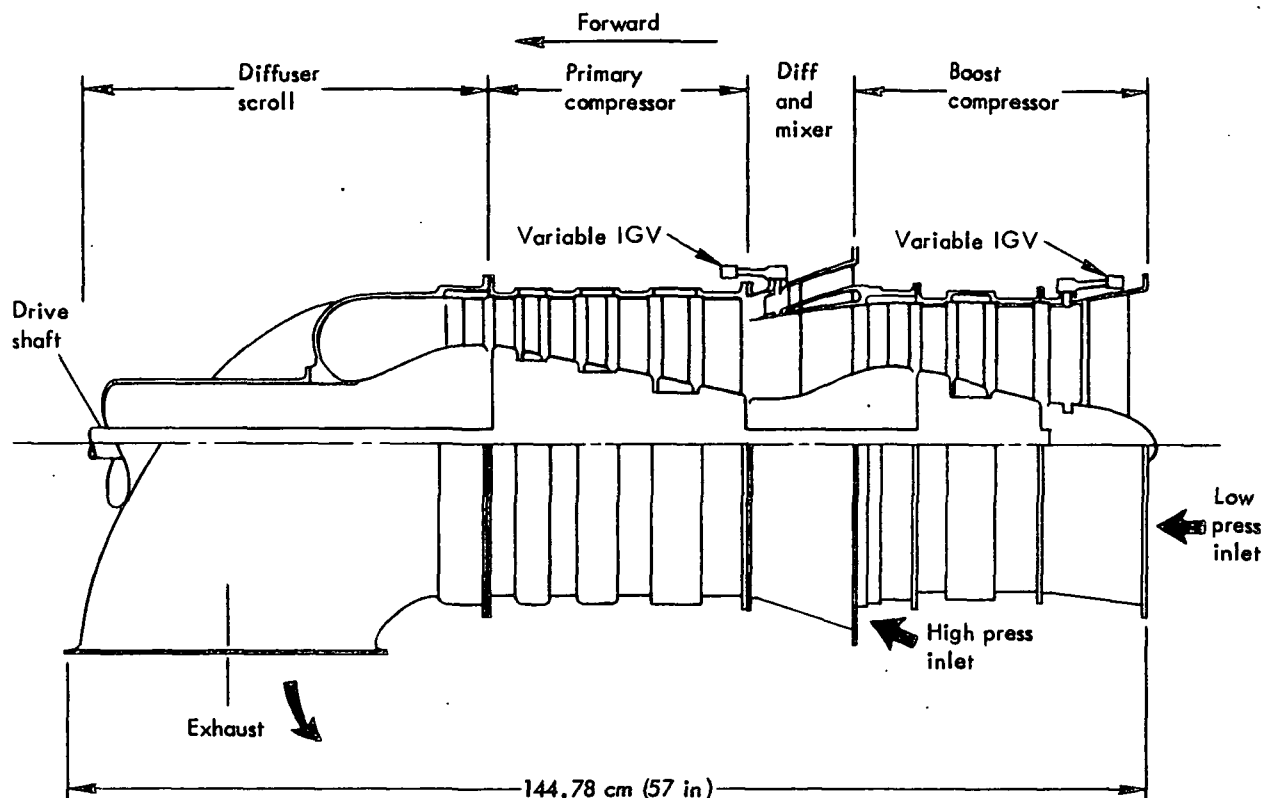


Figure 39. Suction pump

The exhaust diffuser is configured to collect the discharge flow of the suction pump and turn it through 1.571 rad (90°), while reducing the flow velocity to $M = 0.3$ 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 diffuser/scroll also provides for a 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 a ram inlet and exhaust discharge at essentially freestream velocity. The independent drive was adopted because it has no impact on the primary propulsion unit and can therefore be independently sized. A conventional advanced technology shaft engine was adopted for this study. The suction pump weight was evaluated at 95.7 kg (211 lb) and the power unit weight was evaluated at 196.4 kg (433 lb), resulting in a total suction unit weight of 292.1 kg (644 lb).

5.3.5 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 effects of production tolerances and deterioration, in addition to the variable flight conditions.

The major problem in controlling the suction flow is that of matching the 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. In the selected pump configuration, variable inlet guide vanes were used in both the low-pressure and high-pressure inlets, as shown in Figure 39. These vanes are adequate to 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. This does not provide discrete control to accommodate the change in the chordwise C_p distributions. The suction system may be designed to maintain sensitivity to this change at the expense of increased suction system pressure losses. The suction pump variable inlet guide vanes are also capable of accommodating changes in suction system deterioration within limits. The variable vanes may be controlled automatically on the basis of low-pressure and high-pressure suction flows and pressures which will be monitored in the ducting system. Marginal ability to control these parameters according to a prescribed schedule would be an inflight indication of the requirement for system maintenance or cleaning. In the cruise mode, the suction power unit would also be controlled automatically to these same suction flow and pressure parameters to drive the pump at a speed commensurate with meeting the prescribed suction requirements.

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 shut-down 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. 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 40. 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.

In the event of an inflight suction unit failure, instrumentation at the suction pump inlet and discharge will 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-pressure and high-pressure suction trunk ducts near the wing mid-semispan, shown in Figure 40, will also close, allowing only in-board wing suction. The empennage isolation valve will close simultaneously, eliminating empennage suction.

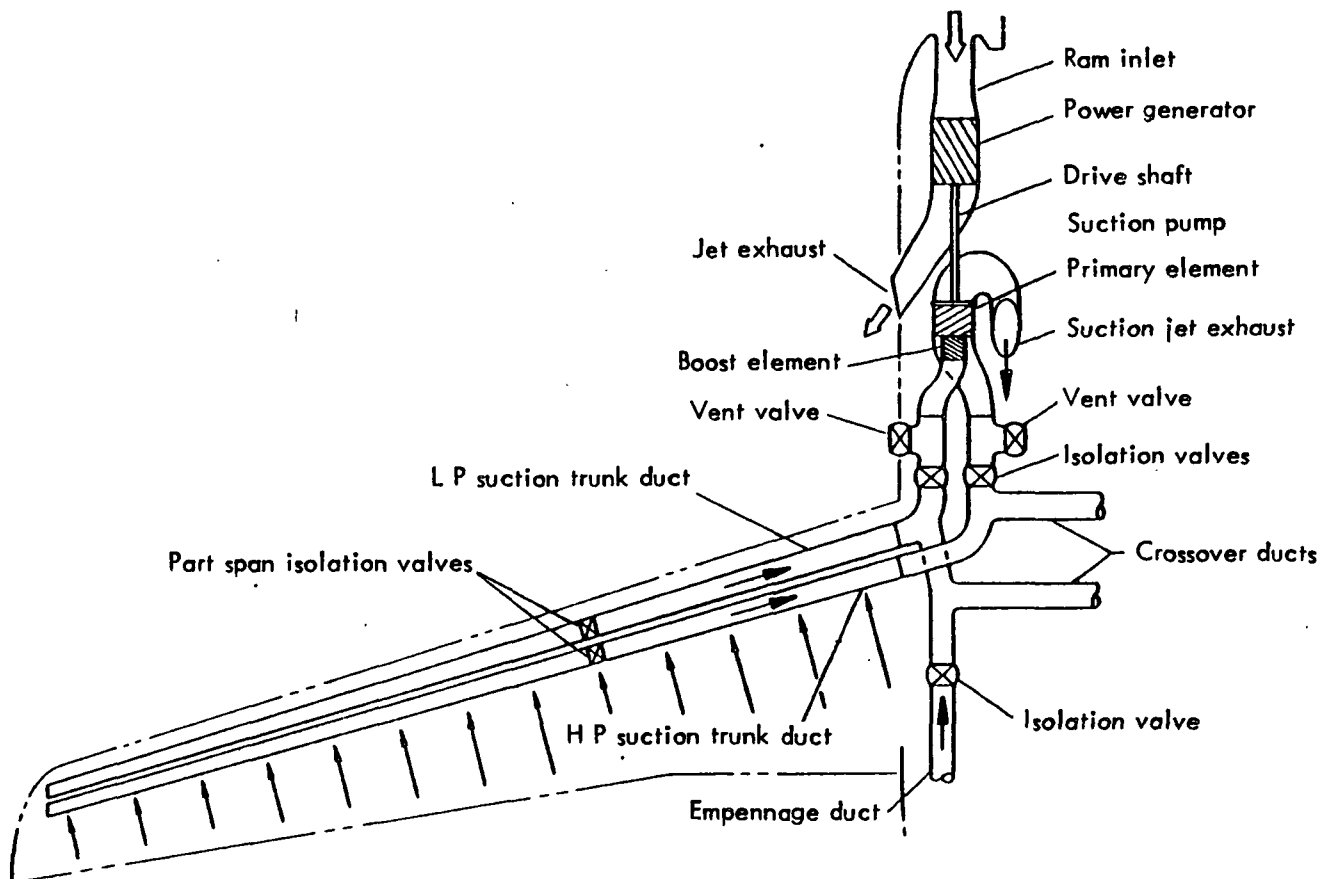


Figure 40. Schematic of suction system

Incidence of rain and ice crystals in the cruise mode that would prevent laminarization may necessitate immediate shut down of the suction system 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 suction unit shut down.

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. Suction system pressures and flows, pump pressure ratio and pump and power unit operational parameters would be compared to prescribed limits. It is expected that this ground check may be accomplished in a total time of less than 4 min.

Automation of these control systems does not appear to present any major problems and final selection of the level of automation would be at the discretion of the customer.

5.4 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 have been of continuing concern. While an appreciable amount of analytical effort has been expended and some wind-tunnel and flight testing of candidate concepts has been conducted, the effectiveness of a cleaning system compatible with the requirements of an operational LFC aircraft has not been demonstrated.

As a part of this study, the evaluation of candidate concepts resulted in the selection of a fluid dispersal system integrated into the leading edge to counter potential insect contamination and provide icing protection for LFC aircraft proposed for the 1990 period. Wind-tunnel testing of a subscale leading-edge section was conducted to evaluate alternative configurations for fluid dispersal and the effectiveness of the fluid film in preventing insect accretion. This testing facilitated the selection of a conceptual design for the leading-edge section and demonstrated the effectiveness of the concept in preventing insect accretion at low speeds. Based on the results of this testing, a full-scale leading-edge section, sized for the mid-semispan region of aircraft in the JetStar/DC-9-10 class, was designed. This test section, incorporating functional cleaning and suction systems, was tested in the Lockheed-Georgia Company low-speed wind tunnel and demonstrated the effectiveness of the cleaning system design in preventing leading-edge contamination at speeds representative of the takeoff/climb profile for LFC aircraft.

5.4.1 Design Objectives

Throughout the evaluation, selection, and design of candidate leading-edge cleaning systems, the following requirements were placed on system design:

- (1) The system must be effective in preventing insect contamination of the leading-edge region at the highest anticipated insect densities.
- (2) The system must not prevent laminarization of the boundary layer.
- (3) The weight and cost penalties attending incorporation of the system should be minimized.
- (4) The system should involve no unusual maintenance procedures or requirements.

5.4.2 Concept Evaluation

A data search of previously recorded work (Ref. 10-18) was accomplished to identify concepts worthy of consideration in the current study. To this list were added concepts developed during the course of the study.

Following is a listing of concepts subjected to initial evaluations:

- (1) Natural erosion
- (2) Permanent coatings
- (3) Temporary coatings
 - o Soluble films
 - o Quasi-static liquid films
 - o Subliming materials
 - o Ice coatings
- (4) Continuously-flowing fluids
- (5) Protective systems
- (6) Incineration systems
- (7) Mechanical systems
 - o Armstrong-Whitworth wire scraper
 - o Armstrong-Whitworth moistened pad scraper
 - o Handley-Page discardable scraper
 - o Coleman's deflector plate
 - o Rotating leading-edge devices
 - o High-lift leading-edge devices
- (8) Restoration of laminar boundary layer

After a preliminary screening to eliminate infeasible concepts, detail design studies were accomplished for each of the promising concepts listed above. These design studies were carried to the depth required to develop component size and weight data required to determine the system weight penalty for incorporation in the LFC baseline airplane.

Based on this weight comparison plus evaluation of each system from a maintenance standpoint and the availability of actual test data, the continuously-flowing liquid system was selected for use in the study aircraft.

5.4.3 Testing

Two series of wind-tunnel tests were conducted to obtain design data necessary for the integration of an efficient leading-edge cleaning/de-icing system into an operational LFC transport. Subscale testing was conducted to obtain preliminary system and surface design data, followed by a full-scale test to validate the concept under simulated flight conditions.

5.4.3.1 Subscale Wind-Tunnel Testing

A subscale exploratory test was conducted to evaluate various cleaning liquids, liquid injection surface configurations, governing characteristics of liquid distribution over the surface, and provide a preliminary evaluation of system capabilities for preventing insect accretion. The results of this testing were used in the design of the leading-edge test article described in Section 5.2.3, which was subsequently used in full-scale testing.

5.4.3.2 Full-Scale Wind-Tunnel Testing

The objectives of the full-scale wind-tunnel test program included the validation of the selected leading-edge cleaning system for the control of insect accretion and the determination of cleaning system effects on suction slot characteristics.

Test Configuration

The test article for the full-scale testing was the leading-edge section designed and fabricated in Section 5.2.3. Integration of the test article and surface instrumentation into the afterbody and end-plate assembly is shown in Figure 41.

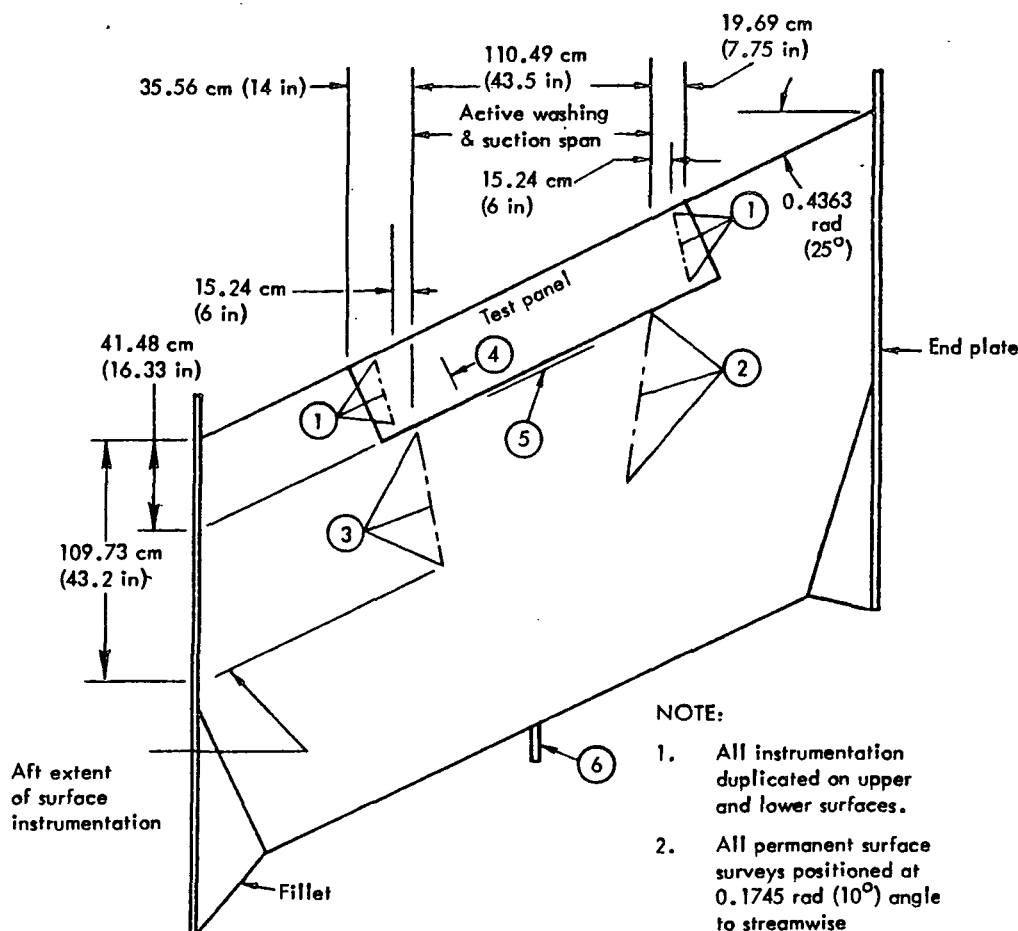


Figure 41. Model assembly

Figure 42 is a schematic illustration of the suction system for one slot, showing system controls and instrumentation. Segment control valves, a slot flow venturi, and a slot control valve for each slot were mounted on a master suction control panel located in the control room. Suction lines from all slots were connected through a single shut-off valve to a Roots blower suction pump system equipped with an automatically controlled inlet vent to prevent pump stalling.

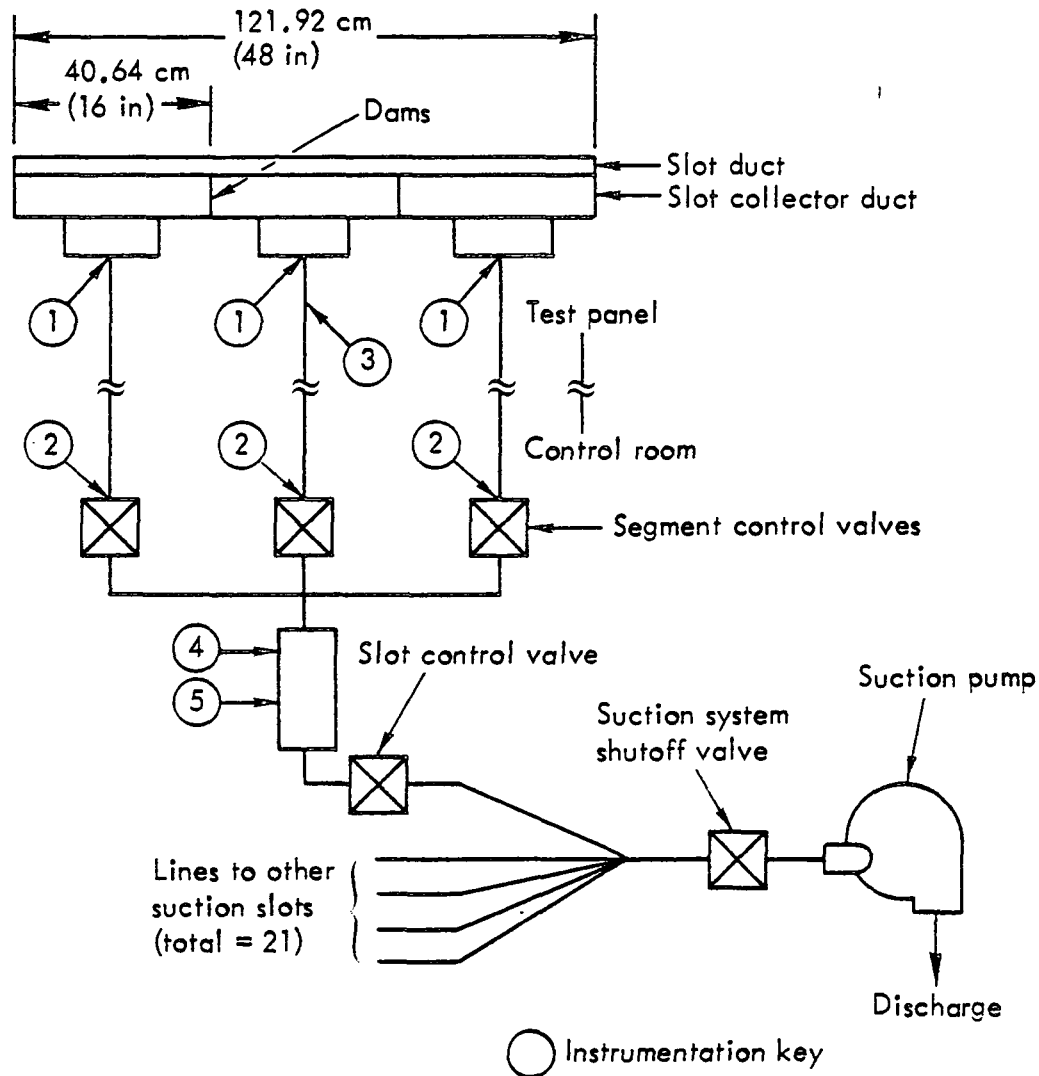


Figure 42. Slot suction system schematic

Cleaning system controls and instrumentation are illustrated schematically in Figure 43. At high pitch angles, there is a tendency for the liquid in the slot and slot manifold ducts to flow toward the low end of the slot, resulting in excessive flow at the lower end of the slot and flow starvation at the upper end. A similar characteristic results during airplane acceleration, with the excessive flow occurring at the most aft portions of the slot. To prevent this, dams were located at 20.3-cm (8-in) intervals in both the slot and metering ducts. Each slot system was connected through a venturi meter and slot control valve. All slot lines were connected through a venturi meter and slot control valve. All slot

lines were connected to a liquid reservoir through a common shutoff valve. The reservoir was pressurized by a compressed gas source through a regulator valve.

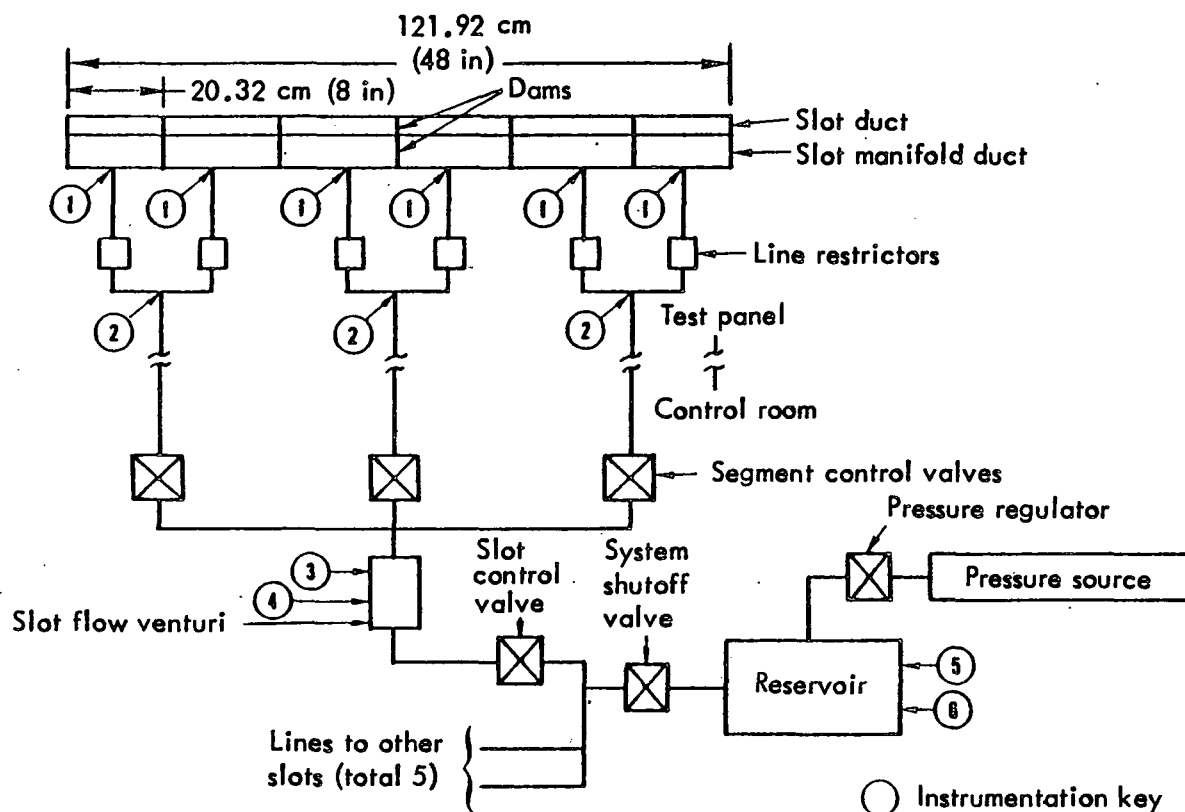


Figure 43. Slot cleaning system schematic

The test article and afterbody assembly were mounted in the Lockheed low-speed wind tunnel on three pylons, as shown in Figure 44. As the model was pitched up to high angles of attack, the leading-edge slope approximated that of a 0.436 rad (25°) swept wing rotated to the same attitude.

Figure 45 shows the insect injector suspended on a system of cables between the top and bottom of the wind tunnel about 4.57 m (15 ft) upstream of the model. The injector consisted of two 7.62-cm (3-in) flow-through tubes 50.8-cm (20-in) long mounted on 12.7-cm (5-in) centers. Toward the upstream end of each, a 2.54-cm (1-in) tube penetrated the 7.62-cm (3-in) tube at a 0.785 rad (45°) angle, pointing downstream and extending slightly into the larger tube. From these 2.54-cm (1-in) tubes, flexible tubes led to hoppers located above the wind tunnel. During the testing, insects were manually dropped into the hoppers at prescribed rates. The insects were sucked into the 7.62-cm (3-in) tube where they accelerated to tunnel velocity.

The Lockheed low-speed wind tunnel has a 7.12 m (23.36 ft) by 4.95 m (16.24 ft) test section with a continuously variable velocity range from $q = 191.5$ to 3830 N/m^2 (4 to 80 lb/ft^2) or approximately 14 to 285 km/hr (7.7 to 154 kn). The tunnel is equipped for automatic data recording and on-line data reduction.

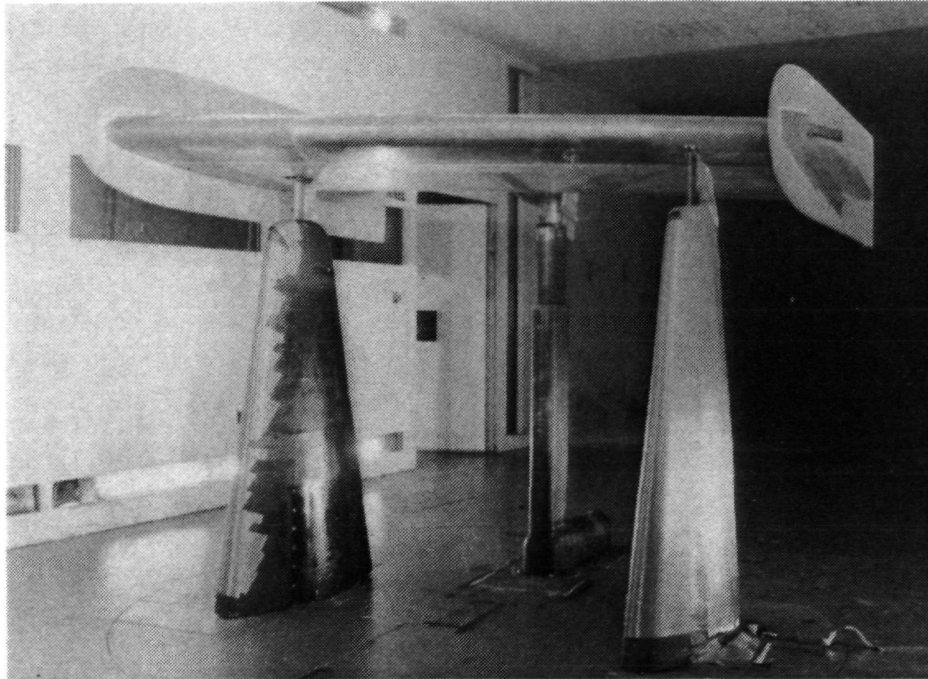


Figure 44. Installed wind tunnel model

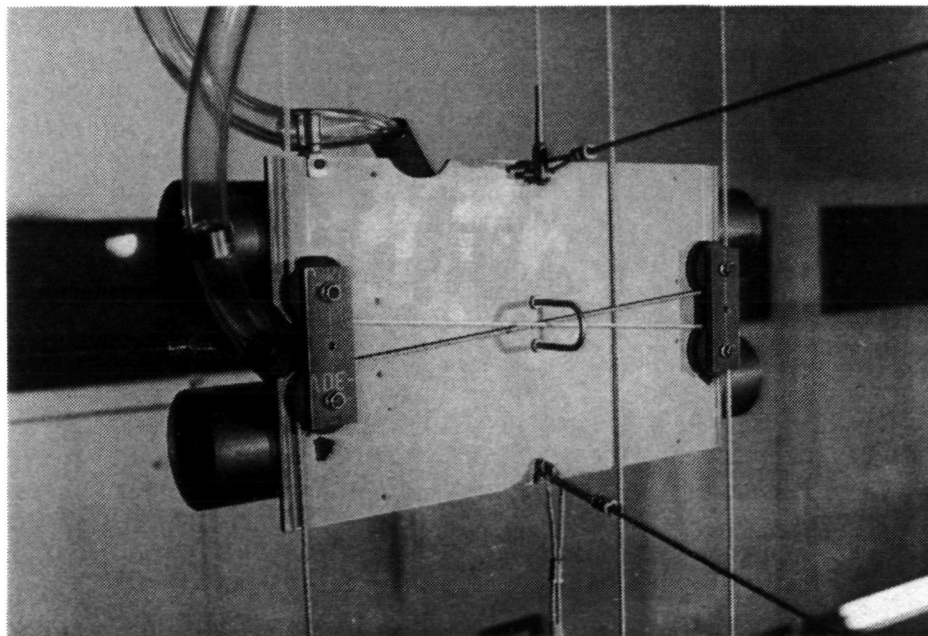


Figure 45. Insect injector

Preliminary Testing

Prior to initiating wind-on testing, baseline data were recorded for the cleaning test. The suction system slot segment valves were adjusted to provide equal flow across the span of a slot. The slot flow control valves were adjusted to produce the nominal suction flow distribution level. Suction flow and pressure data were recorded.

C distribution and stagnation line location data were recorded for a range^p of tunnel velocities up to the maximum and airfoil pitch angles for 0° up to approximately 0.262 rad (15°). A tunnel transient test routine was established to best represent airplane takeoff and climbout within the wind tunnel limitations. The tunnel velocity was accelerated from approximately 65 to 259 km/hr (35 to 140 kn) in 75 sec at an airfoil angle of attack of 0° to simulate takeoff ground roll. The tunnel velocity was held constant while the airfoil angle of attack was increased to 0.262 rad (15°) in 15 sec to simulate rotation and the tunnel velocity was then increased to 285 km/hr (154 kn) to simulate climbout. This sequence was used for subsequent transient tests.

The LFC suction testing was conducted at this point in the program to preclude possible contamination from insect accretion or cleaning fluid.

Insect Accretion Pattern

The highest insect distribution rate found in the literature was assumed. This was reported in the 1939 research of P.A. Glick (Ref. 19). The weight of airborne insects was assumed to follow the frequencies shown in Reference 20 that were reported by J. A. Freeman in 1945. These assumptions, together with the assumed airplane takeoff and climbout profile, were used to determine a representative insect injection rate for test simulation. It was found that this would require a total of less than 10 insects in the dispersion pattern to simulate a complete airplane takeoff and climbout. Further, only one of these insects would be as large as a housefly. The mass of a housefly is nearly seven times the average mass of a Freeman distribution. The previous subscale testing indicated that the greatest demands on the cleaning system would be imposed by the impact of larger insects such as blowflies, which weigh more than seven times as much as a housefly and would represent the majority of moths that might be encountered at night. Consequently, the houseflies and blowflies were selected for the test.

Figure 46 illustrates the insect accretion of blowflies injected continuously during a simulated takeoff and climbout schedule on a dry surface. The blowfly injection frequency rate was 16 times that determined from the preceding analysis to be required for a representative airplane takeoff and climbout. The blowflies injected in this test approached 800 times a representative weight. Insect accretion on the lower surface occurred during the portion of the run at 0.262 rad (15°) angle of attack and may be seen to extend back to 35% chord. Figure 47 shows a closeup of upper surface accretion for this same run. Evidence of insect accretion may be seen as far back as 5% chord on the upper surface. The extremely high concentration of impacts may be clearly seen in the stagnation region.

Other insect accretion runs were made on a clean dry leading edge and an insect injection frequency 8 times that required for a typical takeoff and climbout was selected as providing a good demonstration without needlessly overloading the surface with insects. When blowflies were injected, this rate impacted approximately 400 times the mass of insects that would be representative of a typical takeoff. The injection frequency 8 times the typical rate was used for all further testing.

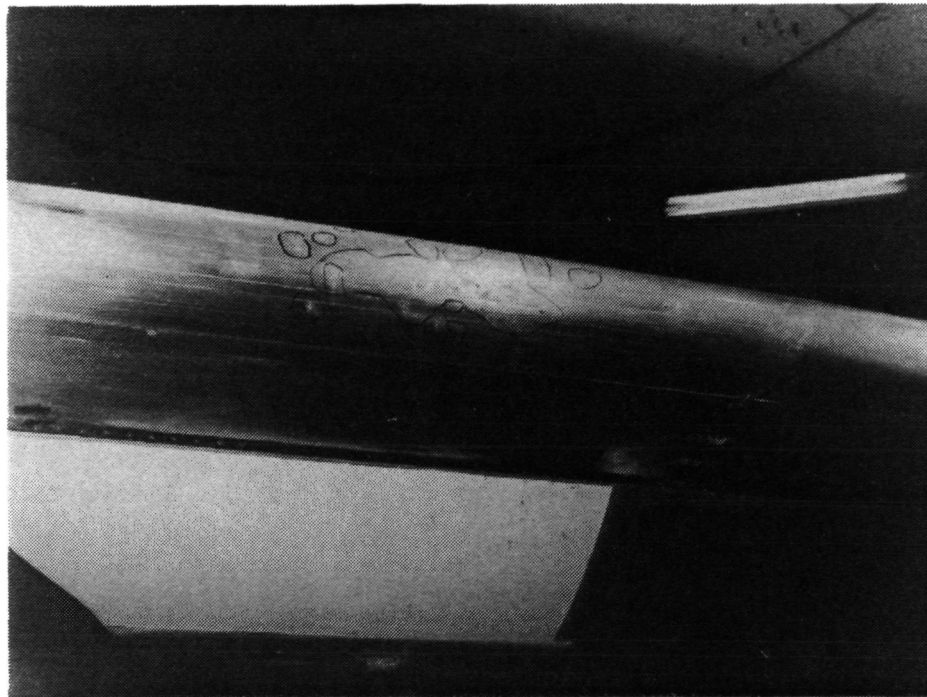


Figure 46. Dry leading edge accretion



Figure 47. Dry leading edge accretion closeup

Cleaning System Demonstration

Initial tests were run to adjust the cleaning system and determine the liquid film coverage for a representative takeoff and climb profile. A combination of difficulties precluded achieving design fluid film coverage of the lower surface. Consequently, testing at higher angles was limited.

By setting the airfoil to -0.026 rad (-1.5°), good liquid film coverage of both the upper and lower surface was obtained. Figure 48 illustrates a run in which this angle was held constant while the tunnel velocity was increased from 18 km/hr (10 kn) to 285 km/hr (154 kn) with approximately design cleaning flow rate. Blowflies were injected continuously throughout the run at a frequency rate 8 times the representative level. Both upper and lower surface film coverages were good throughout the test run. The fluid film remained attached to the lower surfaces even at 18 km/hr (10 kn) and at the -0.026 rad (-1.5°) angle of attack. In no case throughout the test was the liquid seen to prematurely separate from the lower surface when the tunnel was turned on.

Approximately 80 blowflies had been injected at the time the Figure 48 photograph was taken. Two insect impacts can be seen in the original color photograph but are indistinguishable from leading-edge polish marks in the figure. These impacts were totally contained on the surface between two slots in an area that had no liquid film coverage during the run. These were the only evidence of residual accretion found during close inspection following the run, even though insect mass flow rate had been extremely high. Numerous other runs were made at various flow rates for airfoil angles up to 0.105 rad (6°). In no case was residual accretion found on any surface protected by design levels of cleaning fluid flow.

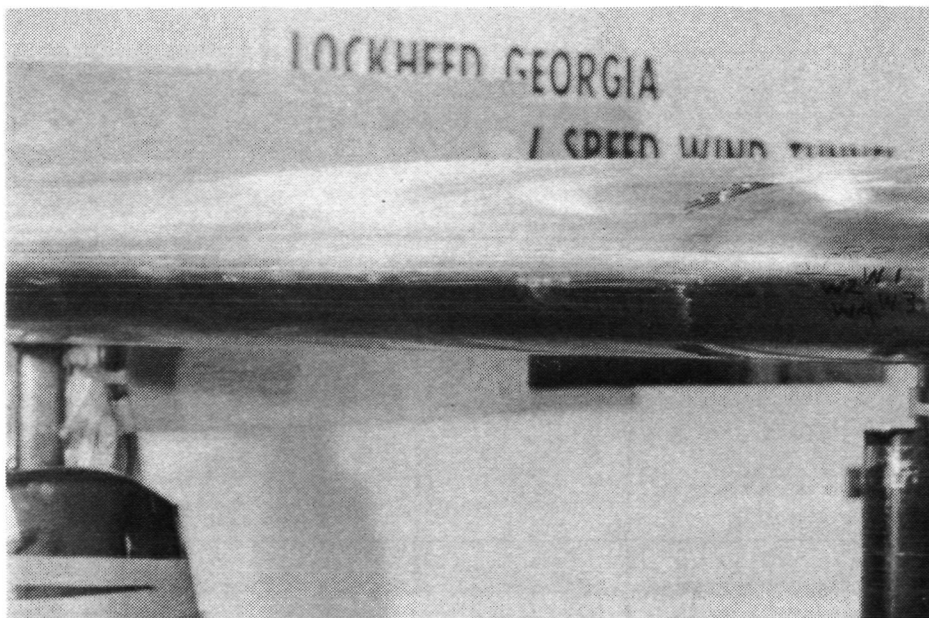


Figure 48. Insect accretion with fluid flow

Checks of the suction system following the cleaning liquid demonstration disclosed that residual liquid partially blocked the slots. It was also found that much of the suction system internal pressure instrumentation had cleaning liquid in the lines. It was apparent that the slots must be either artificially purged or given sufficient time to dry from the external airflow. It was also apparent that the suction system internal pressure instrumentation required artificial purging. This might be extended to include all surface pressure instrumentation in a flight test program where it cannot be protected during the cleaning tests as it was in the wind tunnel.

5.5 AUXILIARY SYSTEMS INTEGRATION

The two unique systems required for an LFC airplane are the suction system and the leading-edge system to prevent insect accretion. There would be obvious advantages from integrating either of these systems with any of the normal airplane auxiliary systems or using these systems to perform some additional functions. The suction system includes a suction pump or compressor and power unit and involves a significant amount of airflow. The possibilities of integrating all or some part of this system with the airplane environmental control system (ECS) or auxiliary power unit (APU) system are both obvious and enticing. Several variations of integrating these systems were considered. In each case, basic mismatches or complexities appear to outweigh any advantages.

Integration of the leading-edge system to prevent insect accretion presented a more encouraging possibility for integration. The system for preventing insect accretion was found to be compatible with de-icing requirements and is similar to a system that has been successfully employed on operational airplanes for over twenty years. This integration was planned for the airplane and it was found that no basic modifications to the system were required for the de-icing function. The selected method of injecting the liquid film onto the surface provides another integration possibility. With very slight modification to the system, suction may be applied to the cleaning slots so that they can double as suction slots if this should prove beneficial for laminarization.

6.0 CONFIGURATION SELECTION AND ASSESSMENT

The ultimate objective of this study is the integration of selected system concepts into the baseline configuration to form a final LFC transport configuration, and the subsequent comparison of this aircraft with a similarly-optimized turbulent transport. This section summarizes the operational considerations which must be included in the selection of design options and describes the selected LFC configuration and supporting systems. The characteristics of an advanced technology turbulent transport are summarized and the two aircraft are compared on the basis of weight, cost, and fuel efficiency.

6.1 OPERATIONAL CONSIDERATIONS

6.1.1 Airline Recommendations

During the course of this contract, Lockheed carried on a dialogue with Delta Air Lines to ensure that practical operational considerations were accommodated in the 1993 LFC transport. To the extent possible, their recommendations relative to design options, maintainability requirements, and ground and flight operational procedures were implemented in the selection of system concepts for the final study aircraft.

6.1.2 Ground Operations

Airline users will expect to maintain LFC aircraft within the framework of existing maintenance programs. While varying in details, airline maintenance programs are comprised of the following schedule inspections and intervals:

- o Post-flight/pre-flight - Each flight
- o A Check - Each 50 flight hours
- o C Check - Each 1000 flight hours
- o D Check - Each 8000 flight hours
- o Unscheduled - As required

Assimilation of LFC transports into fleet service will impact each of the above areas of maintenance. Table 6 presents examples of LFC maintenance items which fall into these general categories. Elements of an LFC system can be categorized in two major areas: functional systems and surfaces and ducting. The functional systems, which include suction pumps, valves, and controls, are similar to systems currently being maintained by the airline users and thus present to unusual maintenance requirements.

The LFC surfaces with integral slots and ducting present unique maintenance requirements which airline operators have not previously encountered. These requirements result from the criticality of surface smoothness and cleanliness. New maintenance procedures for titanium covered, composite structure must be developed. Of particular importance are leading-edge

TABLE 6. LFC MAINTENANCE REQUIREMENTS

Periodic Maintenance (A, C, D Checks)

- o Inspection and testing of LFC ducting system - surfaces slots, metering holes and ducts--for proper flow, cleanliness, and smoothness.
- o Inspection of pump installations for integrity of mounting, connections, and leakage
- o Operational check of safety items, such as the duct-installed sniffers to detect fuel leaks
- o Inspection and check-out of leading-edge cleaning system for proper flow characteristics
- o Inspection/verification of LFC monitoring system

Unscheduled Maintenance (as required)

- o Repair of damaged slots and slot ducts
- o Repair of trunk ducts
- o Repair/replacement of pumps and controls
- o Repair/replacement of cleaning system components
- o Repair/restoration of wing surfaces for smoothness and cleanliness

Servicing - Post-flight/Pre-flight

- o Inspection/cleaning of leading edge
- o Replenishment of leading-edge cleaning fluid
- o Replenishment of suction pump lubricant
- o Flushing/purging of suction system ducting

panels which are more fragile than main box surfaces. Leading edges incur frequent, often unreported damage in current operations, but for LFC operations these surfaces will require immediate attention.

With proper procedural planning and training, it is expected that required LFC maintenance can be successfully folded into normal airline maintenance programs.

6.1.3 Flight Operations

Throughout the development of LFC transport aircraft, it is imperative that the minimization of operational differences between LFC and current turbulent transports be maintained as a continuing objective. Consequently, the investigations of this study have been directed toward the development of an aircraft for which flight operations differ little from those of the current airline fleet.

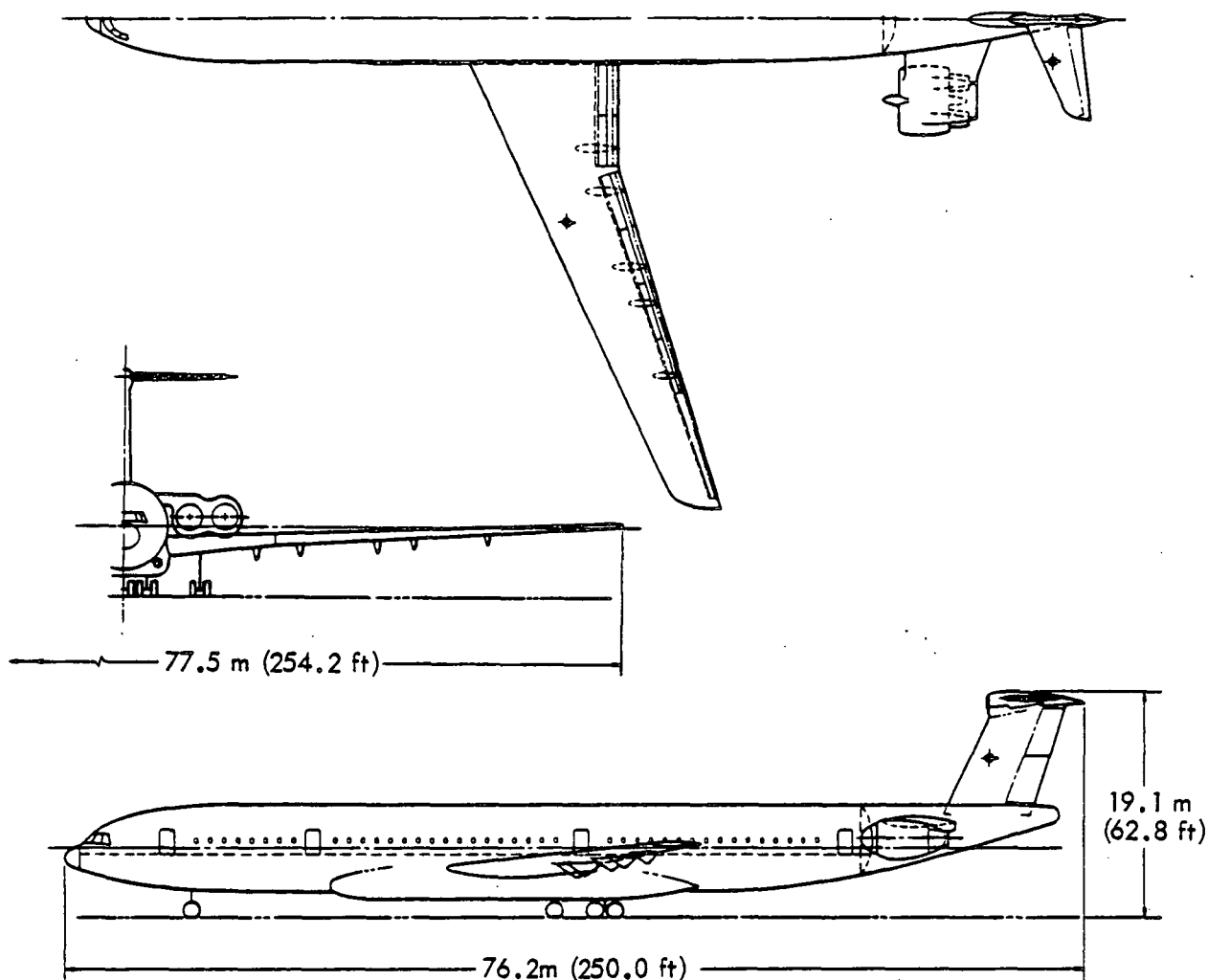
The LFC aircraft of this study are compatible with the air traffic control systems and the general operating environment envisioned for the post-1990 period. The aircraft are compatible with the international mission profile discussed in Section 4.1 and are capable of operating under pertinent FAA rules.

6.2 CONFIGURATION DEVELOPMENT

In section 4.3, a baseline LFC passage transport for the 1993 time frame was defined to satisfy the requirements of the selected mission. Subsequent evaluation of alternative concepts and design options provided no justification for major changes in the baseline configuration. Therefore, the final airplane is identical in general arrangement to the previously described baseline. Variations are limited to detail design refinements, a wing area change, operational procedure changes, various items affecting aircraft weight, and the addition of a leading-edge cleaning/de-icing system.

6.2.1 Configuration Definition

The selected LFC configuration is shown in Figure 49. This airplane is a wide-body configuration designed to carry 402 passengers and baggage over an intercontinental range of 12 038 km (6500 n mi) at $M = 0.80$ with adequate fuel to account for adverse winds, intermittent LFC disruption due to atmospheric conditions at cruise altitude, and normal international fuel reserves. A typical cabin arrangement, shown in Figure 50, was developed for the basic purpose of sizing the fuselage. This arrangement accommodates a 10/90 passenger mix, with 40 in first class and 362 in tourist class cabins. Space allowances are made for galleys, lavatories, closets, cabin crew provisions, as well as rest areas for flight crew as dictated by FAR Part 121.485 for flights of more than 12 hours duration. Space for LD-3 cargo containers is provided forward of the wing box and aft of the main landing gear bay. A bulk cargo bay is also provided at the rear of the pressurized belly. These cargo bays will accommodate 16 874 kg (37 200 lb) of cargo.



	Area	AR	Sweep	Taper
Wing (base)	491.7 m ² (5293.0 ft ²)	11.60	L.E. .436 rad (25°)	.350
Horizontal	50.2 m ² (540.3 ft ²)	5.00	1/4 Ch .349 rad (20°)	.400
Vertical	62.5 m ² (672.6 ft ²)	1.50	1/4 Ch .436 rad (25°)	.800
TOGW	268 624 kg (592 205 lb)			
Engine	149 kN (33 540 lb)			

Figure 49. General arrangement

As shown in Figure 49, the baseline airplane is a low-wing T-tail monoplane with four aft-fuselage mounted propulsion engines. An independently-driven LFC suction unit is located in a fairing under each wing root as shown in Figures 51 and 52. The airplane and its power plants are designed to meet NPRM 75-37c proposed revisions to FAR Part 36. Fuel is carried in the wing including the wing center-section box.

The wing has a moderate sweep of 0.436 rad (25°) at the leading edge with an aspect ratio of 11.6. Full-span flaps, including drooped ailerons, provide the required airport performance. Leading-edge high-lift devices

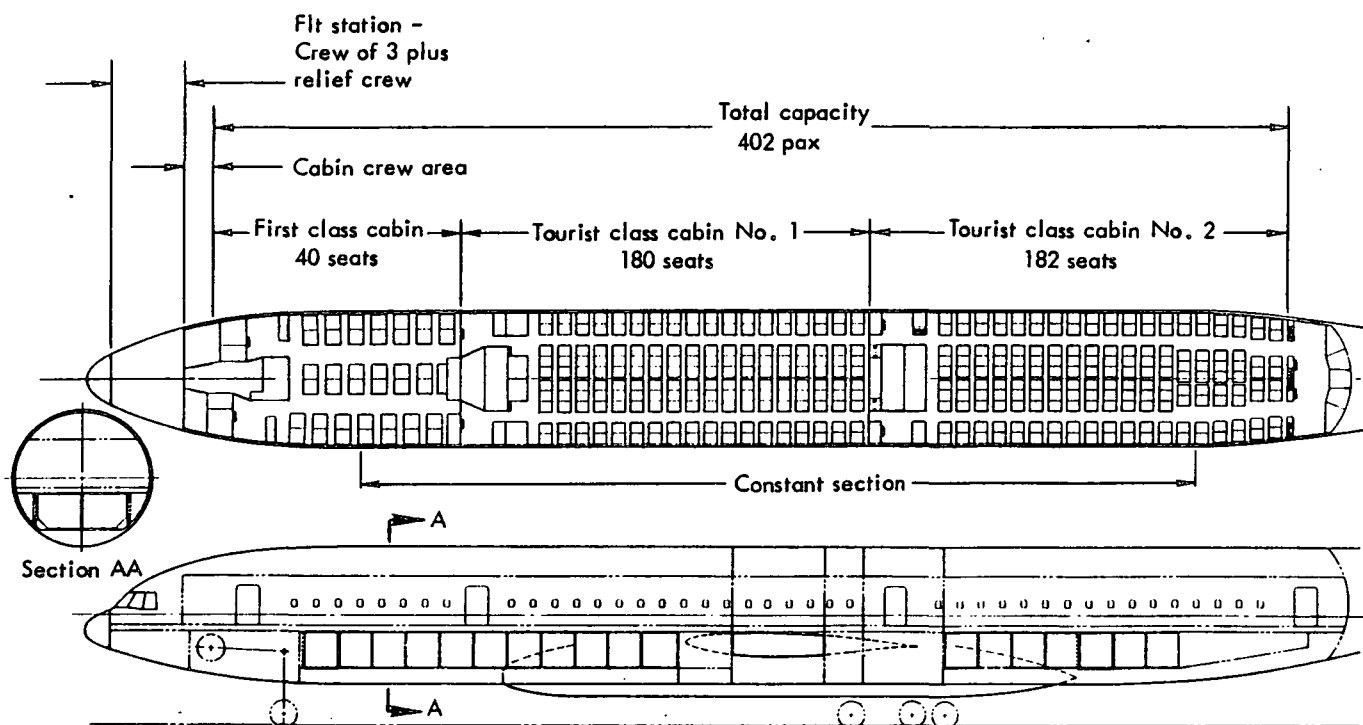


Figure 50. Inboard profile

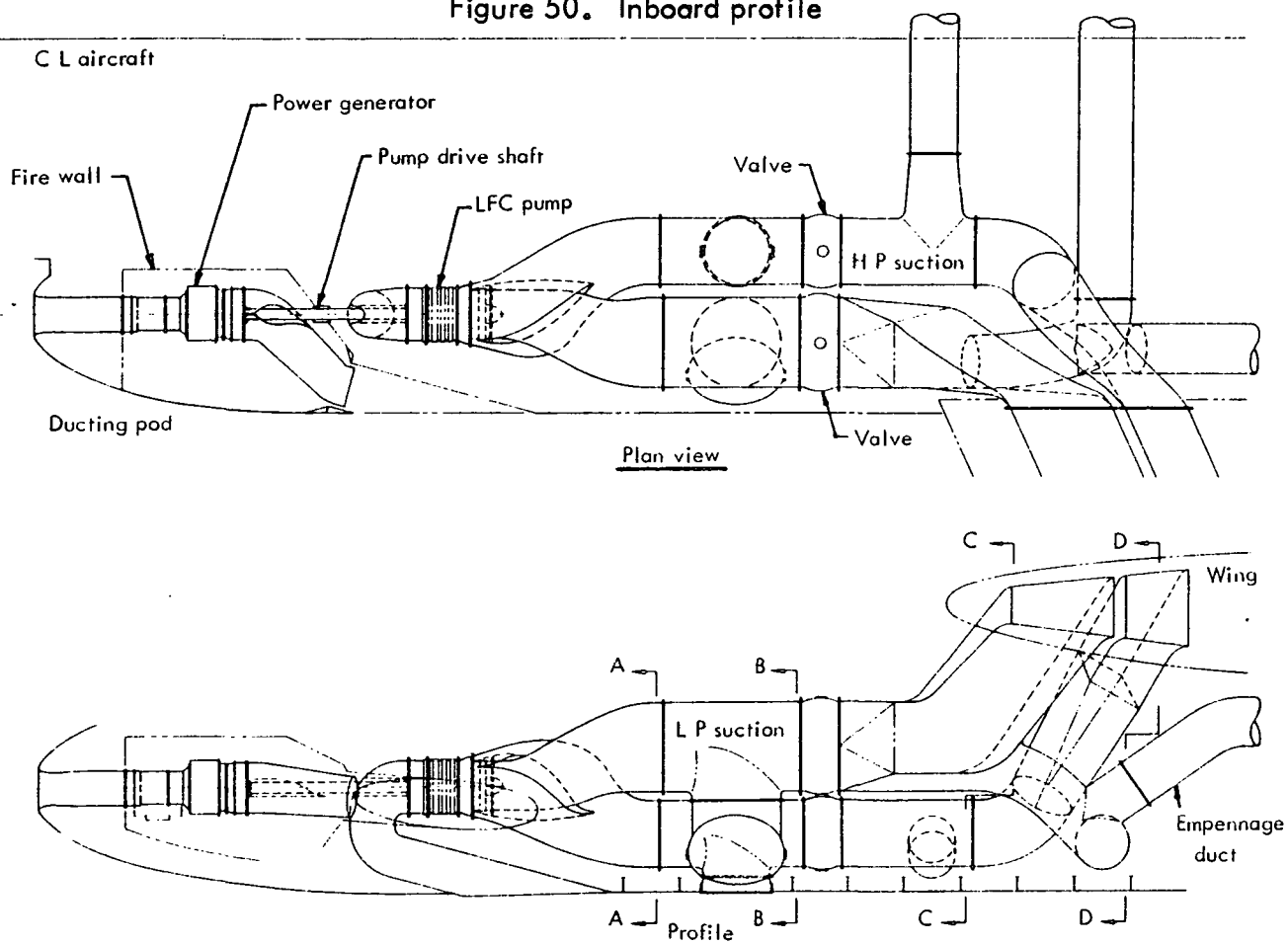


Figure 51. Ducting arrangement for fuselage - mounted LFC suction units

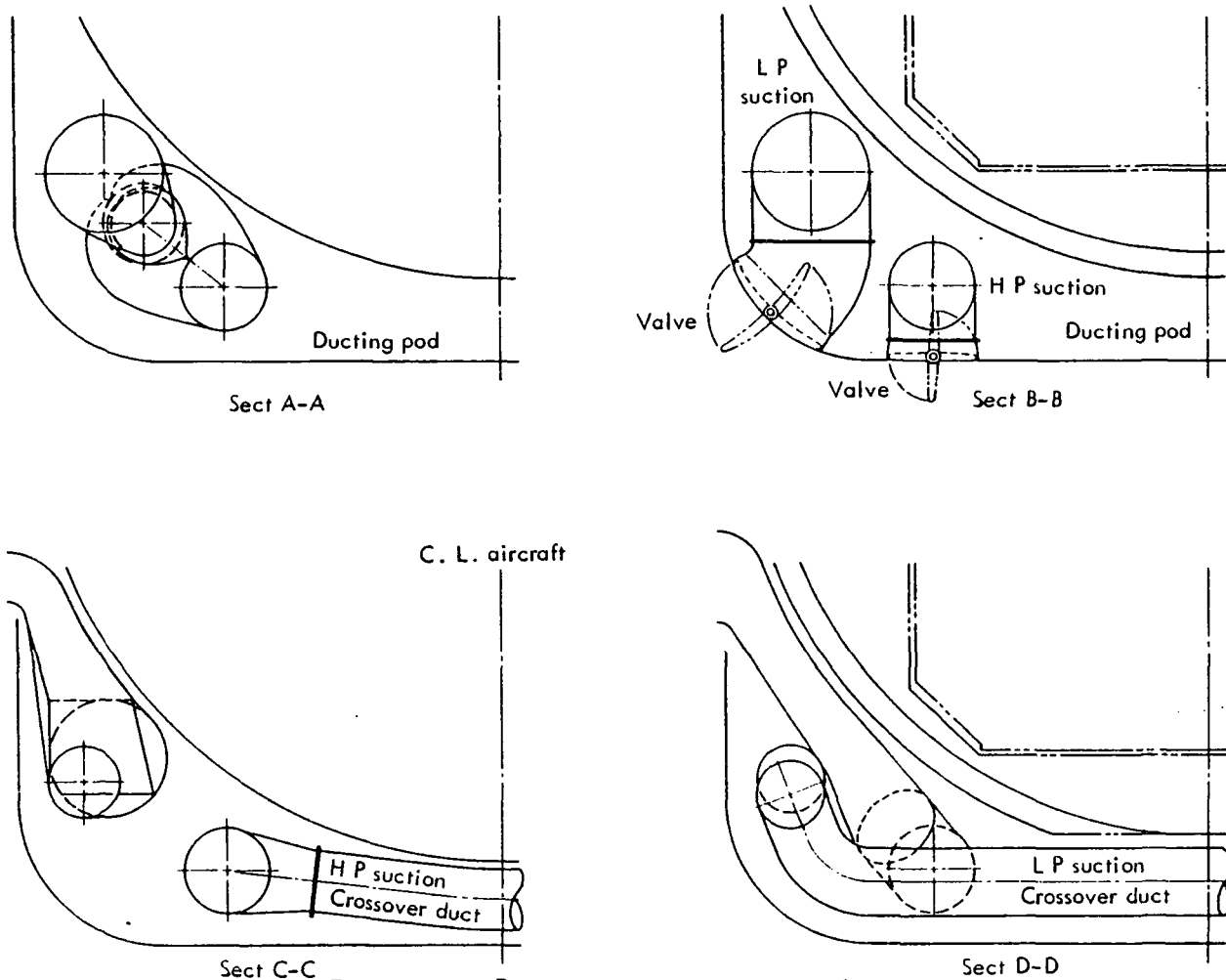


Figure 52. Ducting arrangement section cuts

are not required. Partial span spoilers are incorporated as required. A structural arrangement of the wing is shown schematically in Figure 53. Small-chord secondary flaps are incorporated into the main flaps to provide upper surface pressure gradient and shock position control for off-design operation as well as serving as active controls to minimize structural requirements.

LFC suction capability is provided on both wing surfaces from 0 to 75% chord. A combination de-icing, cleaning system is incorporated in the leading-edge region. Empennage components are similar to the wing elements. LFC suction capability is provided on all four empennage surfaces from 0 to 65% chord. A liquid dispersal system for surface cleaning, similar to that for the wing, is incorporated in both vertical and horizontal tail leading edges.

6.2.2 Configuration Performance

Aircraft payload/range capabilities are summarized in Figure 54 for cruise at the design Mach number of 0.80 and altitude of 11 582 m (38 000 ft). Several mission points in the payload/range envelope were examined for comparison with the basic design point and are indicated by the circles labeled 1 through 6. Significant data for these missions are compared with the design point in Table 7.

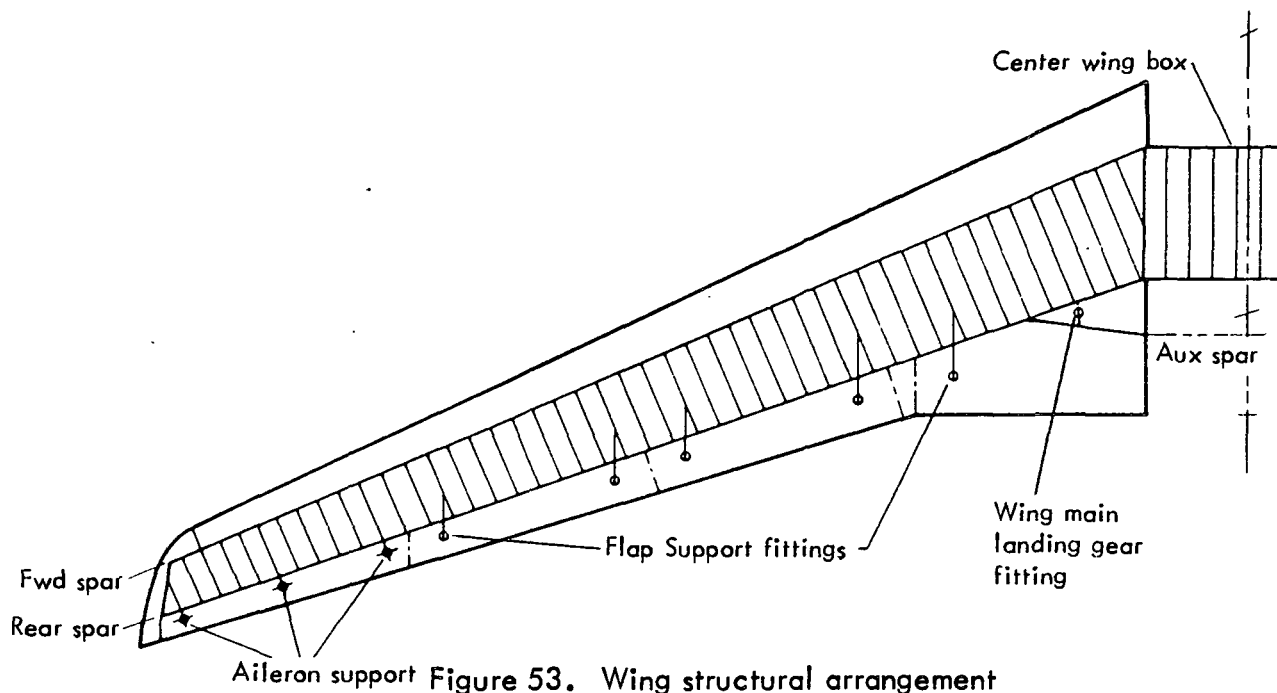


Figure 53. Wing structural arrangement

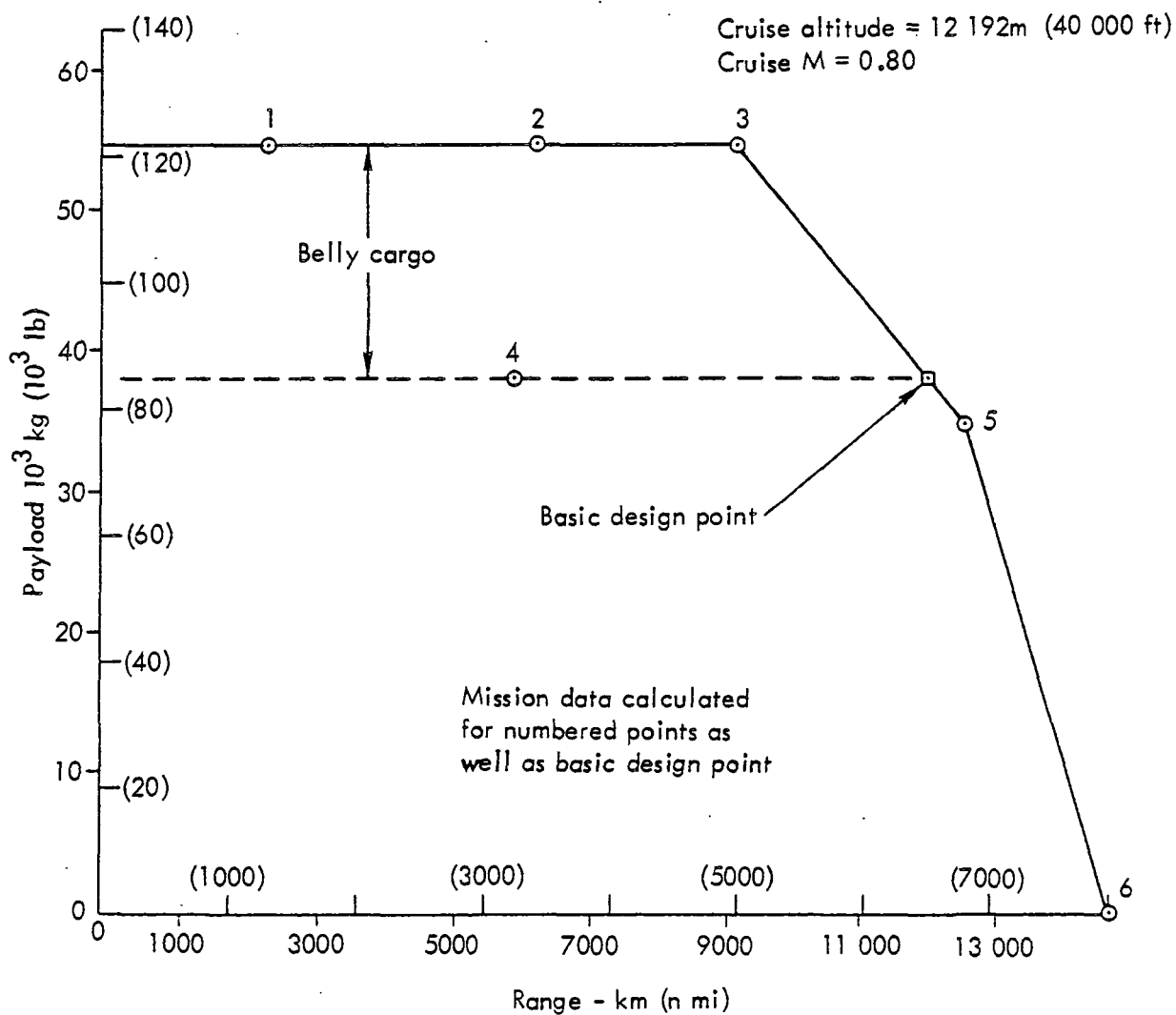


Figure 54. Payload/range

TABLE 7. PERFORMANCE FOR TYPICAL MISSIONS - LFC TRANSPORT

Cruise Altitude = 11 582 m (38 000 ft)

Cruise M = 0.80

Fuel Weight = .80 kg/l (6.70 lb/gal)

Mission No.	No. Passengers	Belly Cargo kg (lb)	Block Range km (n mi)	Block Time (hr)	Ramp Weight kg (lb)	Takeoff Distance m (ft)	Cruise Fuel Efficiency skm/l (smn/gal)	Average Fuel Efficiency skm/l (smn/gal)
*	400	0	12 049 (6 506)	16.20	268 624 (592 205)	3 050 (10 008)	50.3 (102.8)	47.1 (96.3)
1	400	16 874 (37 200)	2 445 (1 320)	3.50	216 435 (477 149)	1 615 (5 300)	55.0 (112.5)	44.1 (90.1)
2	400	16 874 (37 200)	6 312 (3 408)	8.62	244 764 (539 603)	2 323 (7 620)	51.3 (104.8)	46.2 (94.5)
3	400	16 874 (37 200)	9 277 (5 009)	12.54	268 624 (592 205)	3 050 (10 008)	49.0 (100.2)	45.2 (92.3)
4	400	0	6 026 (3 254)	8.23	232 162 (489 776)	2 045 (6 710)	54.8 (112.0)	49.6 (101.4)
5	366	0	12 601 (6 804)	16.93	268 204 (592 205)	3 050 (10 008)	46.2 (94.5)	43.4 (88.8)
6	0	0	14 716 (7 946)	19.71	235 038 (518 140)	2 054 (6 740)		

Sensitivity of range to intermittent loss of LFC was determined for the basic design point takeoff weight, payload, cruise speed and cruise altitude. With no intermittent loss of LFC, a range of 12 137 km (6550 n mi) may be attained. With LFC fuel flow continued, a range of 9630 km (5200 n mi) may be attained if the LFC system is lost for the entire mission.

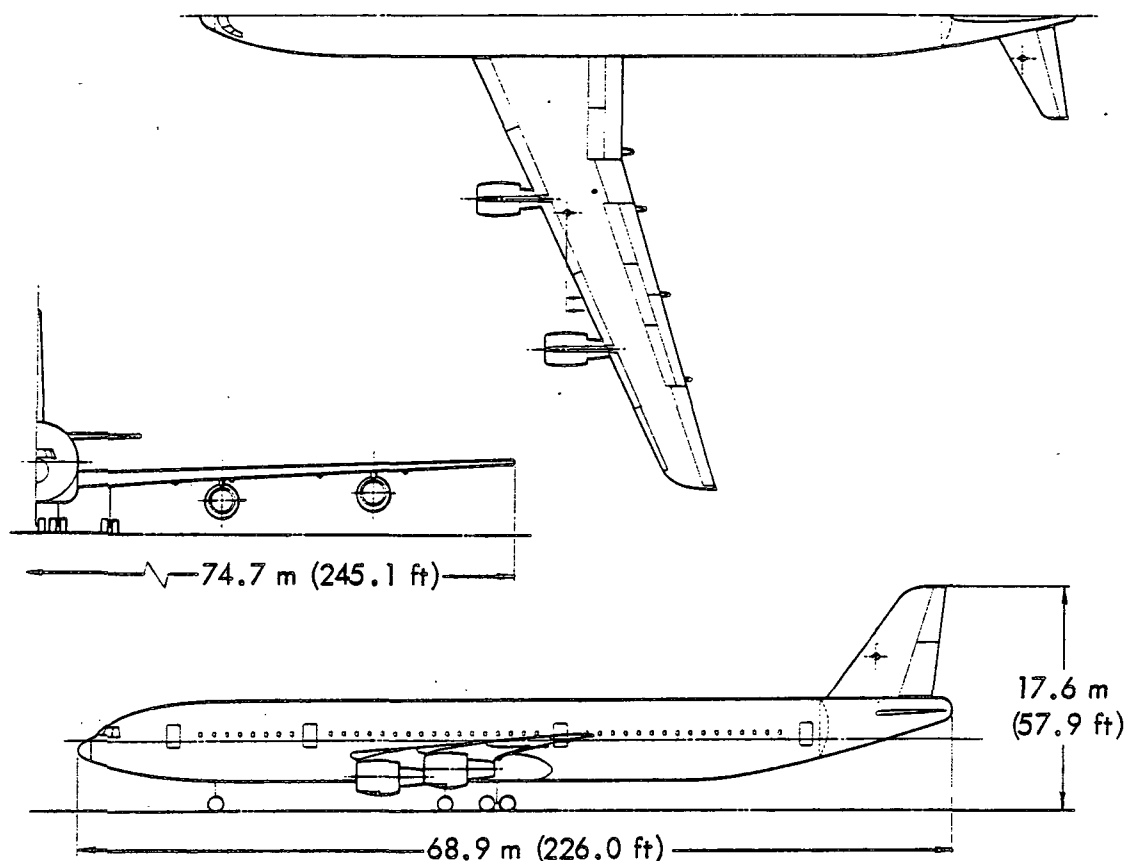
A 50% loss of LFC would be similar to complete loss of LFC at the mid-point of the mission if no prior intermittent loss of LFC had been suffered. In this case, a range of 10 742 km (5800 n mi) is possible. By using the diversion distance fuel allowance, the remaining distance of only 1296 km (700 n mi) could be recovered through use of part of the normal 10% fuel reserves allowance to reach the original destination. Because more than 1482 km (800 n mi) range would be available through use of fuel reserves, some flexibility exists in establishing a revised flight plan.

6.3 TURBULENT CONFIGURATION

A turbulent transport for the 1990 time period was developed to serve as a basis for comparison of the relative merits of LFC.

6.3.1 Configuration Definition

Figure 55 shows a near-optimum turbulent transport configuration which incorporates a technology level identical to that assumed for the LFC configuration. Parametric analysis of operational and geometrical parameters indicated a cruise altitude of 11 582 m (38 000 ft) and a cruise speed of M = 0.80 to be near optimum for the specified mission.



	Area	AR	Sweep	Taper
Wing (base)	507.3 m ² (5461 ft ²)	11.00	L.E. .436 rad (25°)	.35
Horizontal	56.9 m ² (613 ft ²)	4.50	1/4 Ch .436 rad (25°)	.35
Vertical	55.8 m ² (600.6 ft ²)	1.60	1/4 Ch .524 rad (30°)	.35
TOGW	292 605 kg (645 073 lb)			
Engine	163 kN (33 799 lb) thrust ea			

Figure 55. Turbulent transport

The turbulent airplane is a wide-body, low-wing, low-horizontal-tail configuration with four wing-mounted engines. The wing has an aspect ratio of 11.0 and is swept 0.436 rad (25°) at the leading edge. The high-lift system includes leading-edge slats and Fowler trailing-edge flaps. The interior of the fuselage is identical to that described in Section 6.2.3 for the LFC transport.

6.3.2 Configuration Performance

Aircraft payload/range capabilities are summarized in Figure 56 for cruise at the design Mach number of 0.80 and altitude of 11 582 m (38 000 ft). Several mission points in the payload/range envelope were examined for comparison with the basic design point and are indicated by the circles labeled 1 through 6. Significant data for these missions are compared with the design point in Table 8.

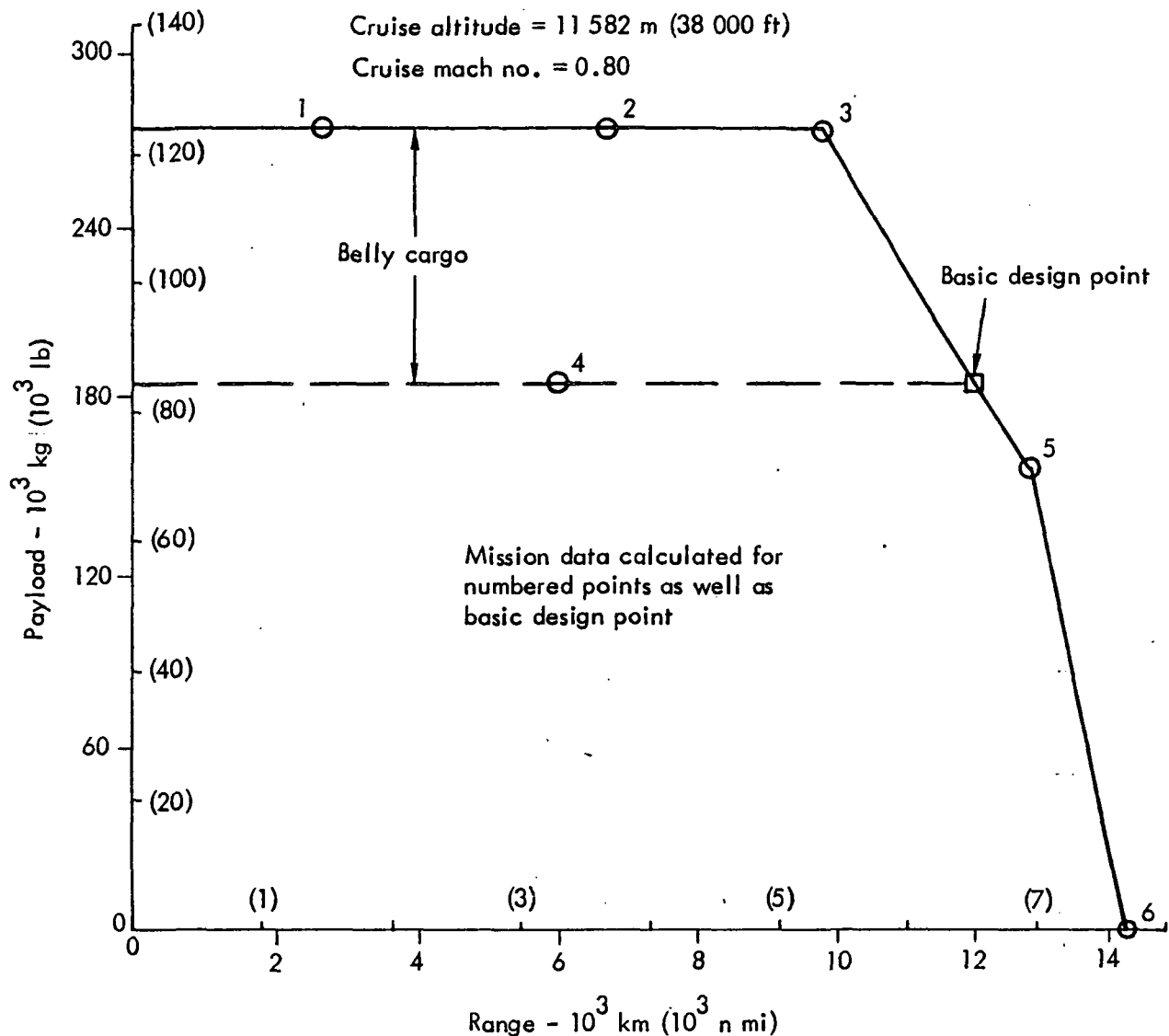


Figure 56. Turbulent baseline payload/range

6.4 CONFIGURATION COMPARISON

Both the LFC and turbulent aircraft developed in this study represent near-optimum configurations for the defined mission. Thus, a valid comparison of the benefits provided by LFC is possible. As shown in Figure 57, there are several readily apparent configurational differences. The turbulent airplane is configured in the traditional form of current passenger transports with wing-mounted engines and a low horizontal tail. High-lift devices for the turbulent airplane include leading-edge slats and modified Fowler trailing-edge flaps.

To provide a clean wing for maximum LFC efficiency, engines on the LFC configurations are mounted on the aft fuselage and the horizontal tail is in a T configuration. There are no leading-edge devices included on this configuration to minimize wing surface discontinuities. LFC suction pumps are housed in pods beneath and extending forward of the wing roots. The aft fuselage of the LFC configuration is extended by 4.27 m (14 ft) to structurally accommodate the pylons which support the propulsion engines.

TABLE 8. PERFORMANCE FOR TYPICAL MISSIONS - TURBULENT TRANSPORT

Cruise Altitude = 11 582 m (38 000 ft)

Cruise M = 0.80

Fuel Weight = .80 kg/l (6.70 lb/gal)

Mission No.	No. Passengers	Belly Cargo kg (lb)	Block Range km (n mi)	Block Time (hr)	Ramp Weight kg (lb)	Takeoff Distance m (ft)	Cruise Fuel Efficiency skm/l (snm/gal)	Average Fuel Efficiency skm/l (snm/gal)
*	400	0	12 038 (6 500)	16.20	292 605 (645 073)	3 051 (10 011)	38.5 (78.7)	36.9 (75.4)
1	400	16 874 (37 200)	2 719 (1 486)	3.91	222 863 (491 320)	1 417 (4 650)	41.6 (85.1)	36.5 (74.5)
2	400	16 874 (37 200)	6 784 (3 663)	9.24	260 607 (574 530)	2 210 (7 250)	39.4 (80.6)	36.9 (75.5)
3	400	16 874 (37 200)	9 864 (5 326)	13.32	292 605 (645 073)	3 051 (10 011)	37.6 (76.8)	35.8 (73.1)
4	400	0	6 088 (3 287)	8.32	233 298 (514 325)	1 945 (6 380)	42.0 (85.9)	39.3 (80.3)
5	335	0	12 864 (6 946)	17.29	292 605 (645 073)	3 051 (10 011)	32.5 (66.5)	31.3 (63.9)
6	0	0	14 246 (7 692)	19.10	260 358 (573 981)	1 954 (6 410)		

6.4.1 General Characteristics

Both airplanes are designed to meet identical performance requirements, including cruise at M = 0.80, a maximum FAA takeoff field length of 3048 m (10 000 ft) and a maximum approach speed of 259 km/hr (140 kn). A comparison of the general characteristics of the two airplanes is shown in Table 9.

6.4.2 Weight

Table 10 provides a weight comparison of the LFC and turbulent airplanes. It is significant to note that a savings of 21.7% in total fuel, block plus reserves, accrues to the laminar flow airplane, while the gross weight of the LFC airplane is 8.2% less than that of the turbulent configuration. Other items of interest tabulated in the weight comparison table illustrate the relatively small penalties imposed by LFC, such as the surface penalty of 2.4% of empty weight. The total weight of the entire LFC system, pumps, valves, ducts and surfaces, represents 4.4% of empty weight.

6.4.3 Economics

Table 11 shows that the DOC of the LFC and turbulent aircraft are so close as to fall within the scatter of the computational methods.

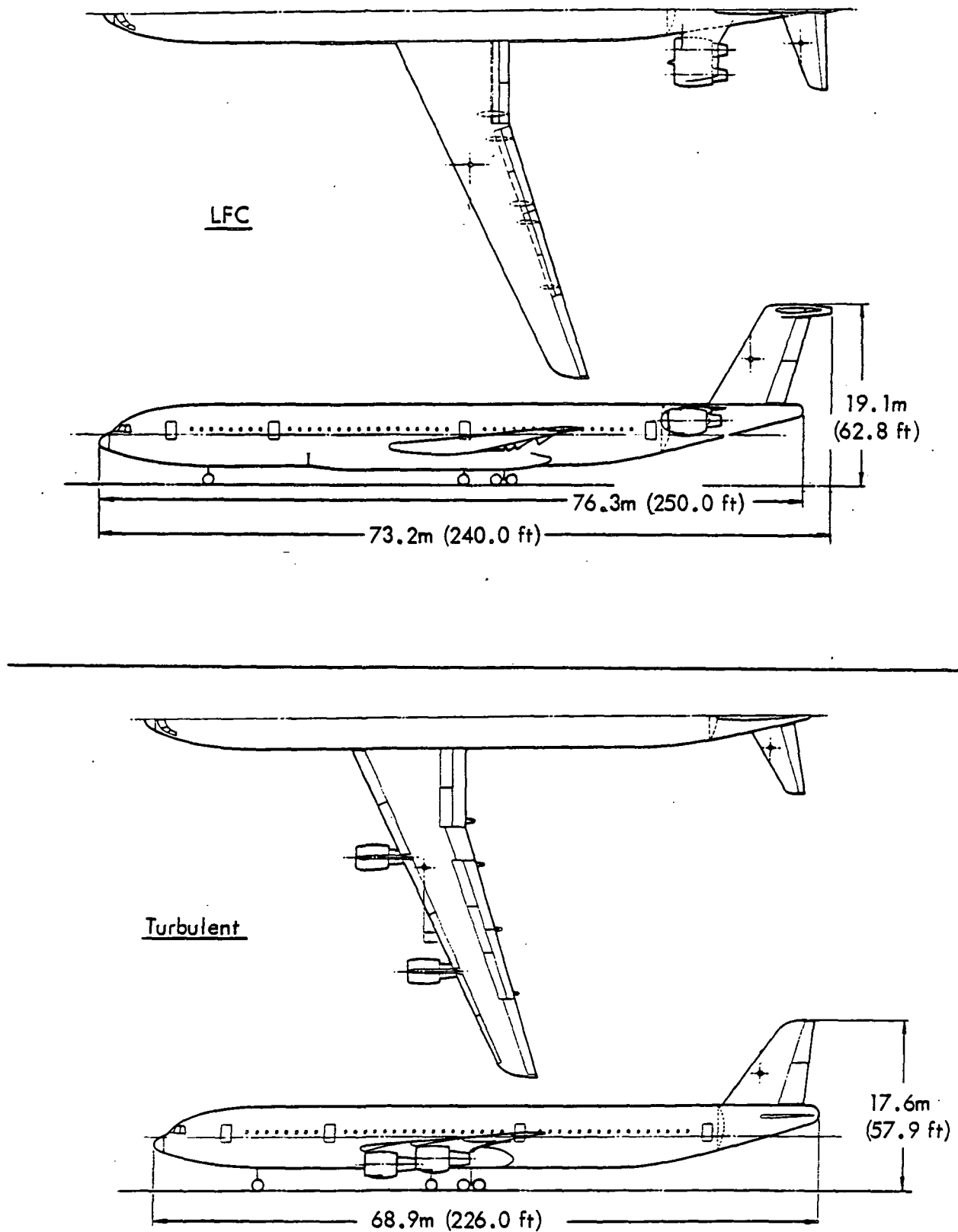


Figure 57. Configuration comparison

TABLE 9. GENERAL CHARACTERISTICS COMPARISON

	<u>LFC</u>		<u>Turbulent</u>	
Basic Wing Area, m^2 (ft^2)	491.7	(5 293)	507.3	(5 461)
AR		11.6		11.0
Sweep at L.E., rad (deg)	0.436	(25)	0.436	(25)
c/c		0.1128		0.0988
Wing Loading, kg/m^2 (lb/ft^2)	532.1	(109.0)	563.9	(115.5)
TOFL, m (ft)	3 050	(10 008)	3 051	(10 011)
Approach Speed, km/hr (kn)	253	(136.5)	249	(134.3)
Sea Level Static Thrust Each Engine, kN (lb)	149.2	(33 540)	163.6	(36 790)
Ramp Weight, kg (lb)	268 624	(592 205)	292 605	(645 073)
Block Fuel, kg (lb)	82 080	(180 953)	104 755	(230 942)
Maximum Ferry Range, km (n mi)	14 715	(7 946)	14 246	(7 692)
Total Suction, m^2 (ft^2)	811.2	(8 733)		

For the LFC airplane, the 21.7% block fuel advantage offsets a 13% maintenance advantage and a 2% advantage in depreciation accruing to the turbulent airplane for a 6112 km (3300 n mi) flight. Similar cost computations for a 12 038 km (6500 n mi) flight shift the comparison in favor of the LFC aircraft, reflecting the growing advantage of LFC with increasing range.

During this period of high inflation, all cost elements are increasing. However, fuel costs are rising more rapidly than other elements of the DOC formula. The current average carrier price for jet fuel is almost 26.4 cents per liter (\$1.00 per gallon). At this price, LFC provides a 4% DOC advantage. If fuel costs rise to 52.8 cents per liter (\$2.00 per gallon), a DOC advantage of 10% results from the application of LFC.

TABLE 10. WEIGHT COMPARISON

	LFC		Turbulent	
	kg	lb	kg	lb
Structure	69 611	153 465	68 070	150 066
LFC Surfaces	(2 820)	(6 218)		
Propulsion System	15 581	34 350	15 079	33 243
LFC Pumps	(597)	(1 318)		
LFC Ducts, etc.	(1 392)	(3 070)		
Systems & Equipment	30 745	67 779	31 375	69 170
LE Cleaning System	(325)	(716)		
Weight Empty	115 937	255 594	114 524	252 479
Operating Equipment	15 028	33 131	15 028	33 631
Operating Weight	130 965	288 725	129 552	286 110
Passenger Payload	38 465	84 800	38 465	84 800
Zero Fuel Weight	169 430	373 525	168 018	370 910
Fuel	97 392	214 711	124 360	274 163
LE Cleaning Fluid	1 800	3 968		
Gross Weight	268 622	592 204	292 378	645 073

LFC Surfaces = 2.4% of empty weight

LFC Total System = 4.4% of empty weight

LFC Surface = 3.47 kg/m^2 (0.71 lb/ft^2) for laminarized area

6.4.4 Fuel Efficiency

Figure 58 illustrates the potential advantages for LFC in terms of fuel efficiency. Based on the data of Reference 21, the family of curves on the lower left represents the efficiencies of first- and second-generation jet transports in current service. The two circles represent current wide-body transports which are capable of long-range operations, and which are expected to be in operation well into the 1990's.

TABLE 11. ECONOMIC COMPARISON

	<u>LFC</u>	<u>Turbulent</u>	<u>$\Delta\%$</u>
Flying Operations	10 695	11 885	-21.7
Direct Maintenance	8 994	7 932	+13.0
Depreciation	9 887	9 698	+ 2.0
Total DOC/Flight	29 566	29 515	+ 0.1
DOC			
¢/s km (¢/ssm)			
6112 km (3300 n mi)			
stage length	1.065 (1.973)	1.053 (1.950)	+ 0.1
DOC			
¢/s km (¢/ssm)			
12 038 km (6500 n mi)			
stage length	1.161 (2.150)	1.166 (2.160)	- 0.5

Fuel price = 11.8¢/l (45¢/gal)

Costs in Jan. 1979 dollars

At the average stage length of 6114 km (3800 s mi), the LFC transport demonstrates an advantage in fuel efficiency of 91% and 28%, respectively, compared to the best of the current transports and the advanced technology turbulent aircraft. At 10 459 km (6500 s mi), the fuel efficiency of the LFC transport is greater than that of current transports by 255%. These data illustrate the dramatic potential offered by a fleet of LFC transports as we approach the 1990 time period.

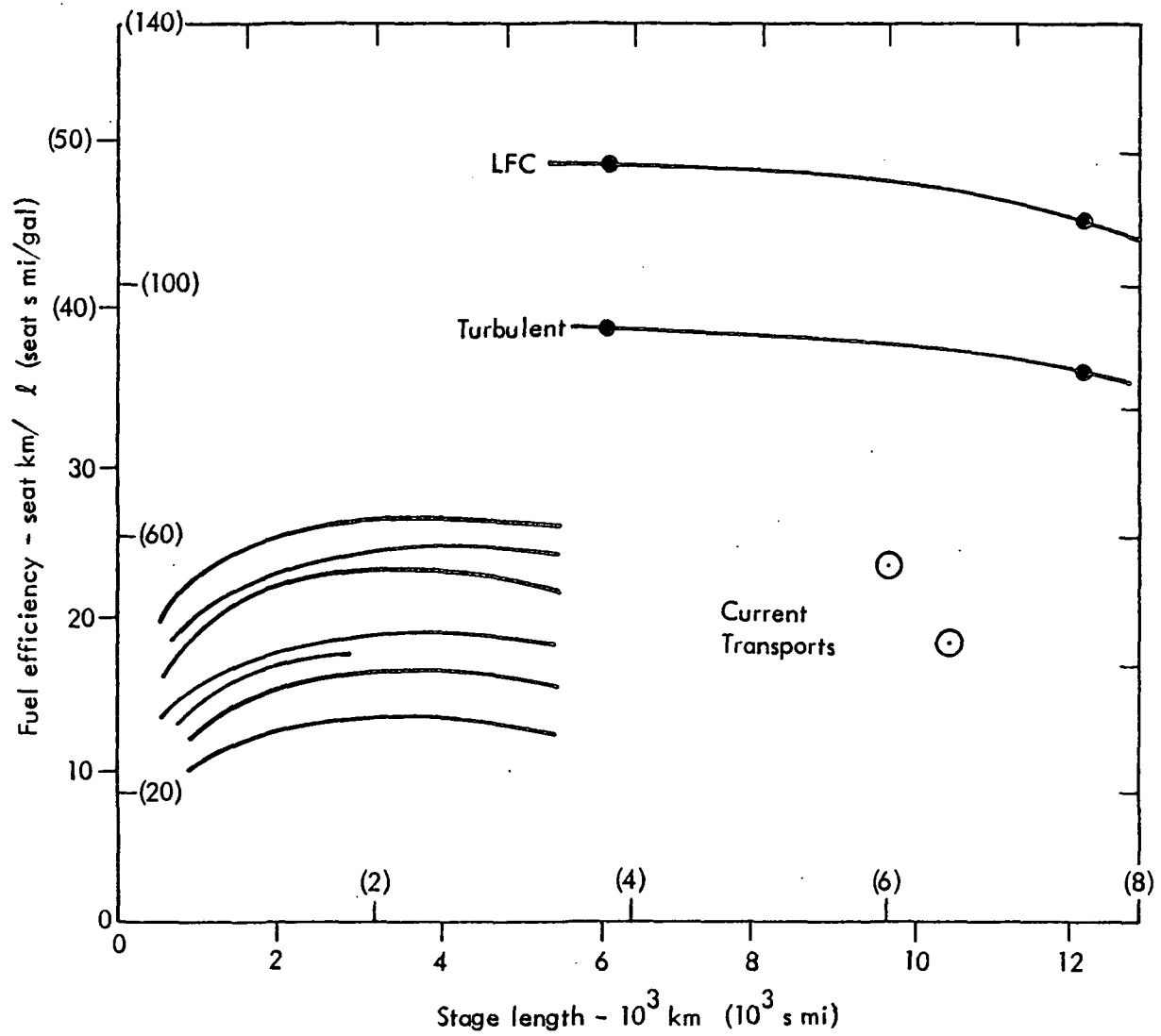


Figure 58. Fuel efficiency comparison

7.0 RECOMMENDED SUBSYSTEM DEVELOPMENT

Requirements for future development include the refinement of design criteria and methodology, the validation of current concepts, the continued development of manufacturing procedures, and the investigation of operational characteristics in flight. To a great extent, these requirements can be satisfied by the major programs currently included in the NASA LFC program plan. These programs are: (1) the NASA high-speed wind-tunnel program; (2) the JetStar leading-edge flight test program; (3) the LFC wing panel structural design and development program; and (4) the LFC validator flight test program.

As a part of the task devoted to the identification of future development requirements, studies were conducted which demonstrated the feasibility of using the NASA JetStar aircraft as a test bed for the evaluation of leading-edge cleaning concepts and established the feasibility of integrating the Lockheed LFC wing design into a DC-9-10 aircraft to form a LFC validator configuration. This section summarizes the results of those studies and outlines additional LFC technology development requirements.

7.1 LFC TEST BED DEVELOPMENT

The current NASA LFC Program Plan includes the flight validation of the LFC leading-edge concept described in Section 5.2.3, using an aircraft in the JetStar/DC-9-10 class as a test bed. This section summarizes the results of a study conducted to assess the feasibility of using the NASA Dryden JetStar aircraft as a test bed for the proposed flight validation.

7.1.1 Objectives

The overall objective of the Leading Edge Glove Flight Program is to demonstrate the effectiveness of LFC leading-edge system under representative flight conditions. Specific objectives of the program are:

- (1) Install an operable LFC system in a segment of the leading edge of an aircraft.
- (2) Demonstrate the effectiveness of leading-edge cleaning/de-icing systems.
- (3) Achieve LFC in flight at conditions representative of commercial transport operations.
- (4) Examine systems performance from an operations and maintenance standpoint.

The objective of the study summarized in this section was to evaluate the feasibility of using the JetStar aircraft as a test bed for the Leading Edge Glove Flight Program.

7.1.2 Configuration Description

A plan view of the JetStar aircraft modified to achieve study objectives is shown in Figure 59. The leading-edge test article is located in the area currently occupied by the external fuel tanks. This region was selected to achieve a chord length representative of a chord length existing on the Lockheed 1990 LFC transport and to minimize modifications to the aircraft and effects on aircraft performance. The test section has a leading-edge sweep of 0.524 rad (30.01 deg) and a swept length of 2.44 m (96.09 in).

The test section is isolated from the basic wing and blended into the existing wing contour through the use of appropriate fairings. Fairings are required in the areas between the test section and existing leading-edge structure. These panels are of built-up aluminum construction and mechanically attached to the wing.

The fairing panels required on the upper and lower surfaces to provide a smooth transition from the test section, and the entire fairing structure on the right hand wing are fabricated of fiberglass and bonded to the wing box to prevent fastener penetration of the fuel tanks.

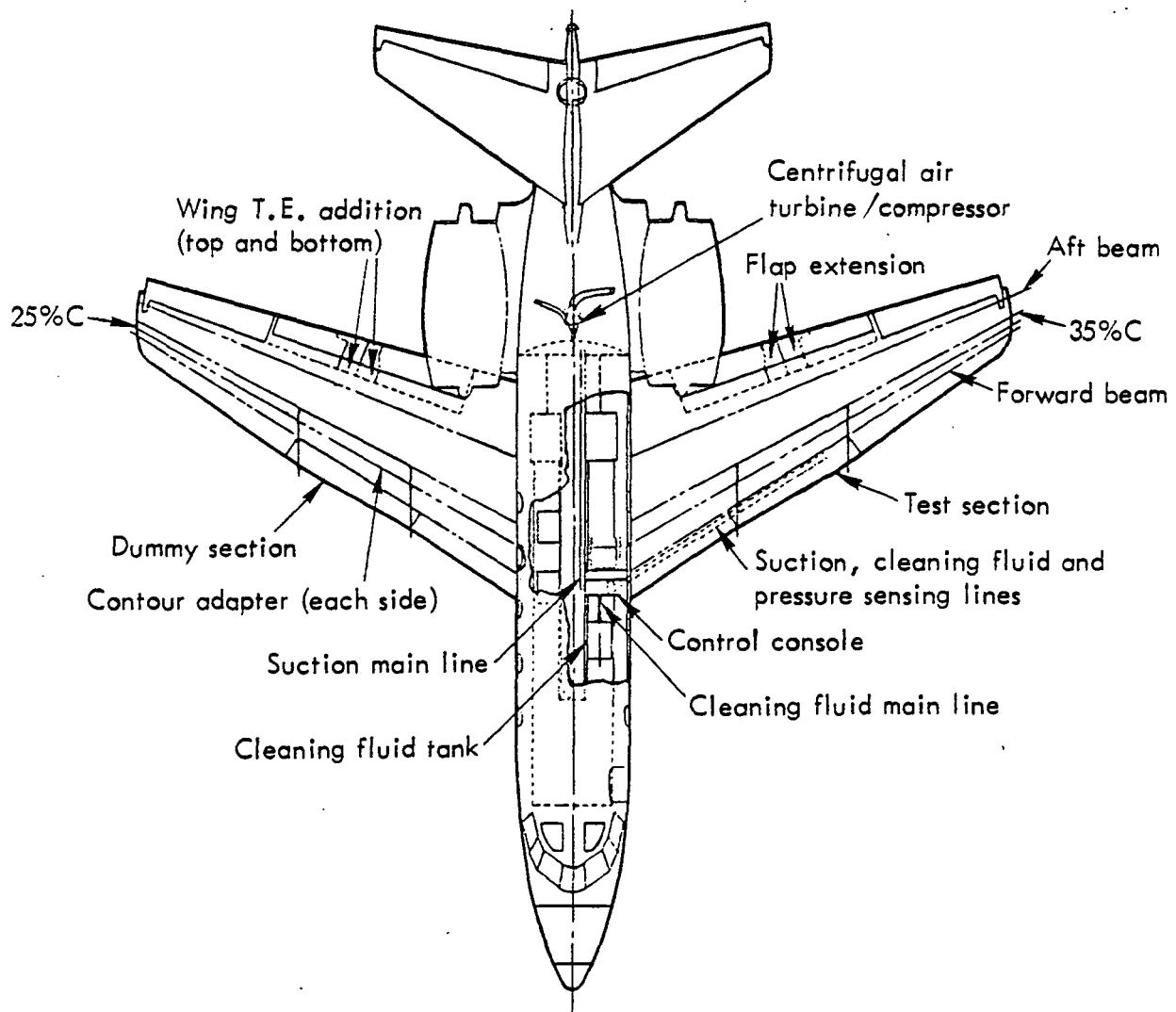


Figure 59. Plan view of modified JetStar

7.1.2 Conclusions

The analyses conducted in the development of the test configuration indicate that it is feasible to use the NASA JetStar as a test bed for flight validation of the Lockheed LFC leading-edge concept. Following are conclusions pertinent to specific elements of the feasibility assessment:

- (1) It is possible to integrate the leading-edge test section into the JetStar wing in a configuration which satisfies aerodynamic requirements for validation of the leading-edge systems.
- (2) The JetStar aircraft can be modified for installation of the leading-edge test section and required suction, cleaning, and instrumentation systems in a manner which permits restoration of the aircraft to original condition.
- (3) There are no structural problems attending the proposed modification. It is recommended that a reduction of flight speeds and load factors be observed for the modified aircraft.
- (4) Performance of the modified JetStar exceeds the specified nominal test conditions of $M = 0.80$ at 12 192 m (40 000 ft).
- (5) There are no stability and control problems as a result of the proposed modification.
- (6) There are no safety-of-flight problems as a result of the proposed modification.

While development programs are required for both the leading-edge test section and the modified aircraft, the NASA JetStar is compatible with the requirements of the Leading-Edge Glove Flight Program.

7.2 VALIDATOR AIRCRAFT DEVELOPMENT

In order to fully establish the feasibility of LFC in a high utilization environment, a flight validation program closely approximating airline operations is required. A study was conducted to define and evaluate a representative LFC Validator Aircraft based on the integration of the Lockheed LFC wing concept described in Section 5.2 into a DC-9-10 aircraft.

7.2.1 Objectives

This study has two major objectives:

- (1) To develop and evaluate an LFC validator aircraft configuration based on integrating an LFC wing concept of Lockheed design into a DC-9-10 aircraft.
- (2) To develop program schedule and cost estimates for the validator aircraft program.

7.2.2 Configuration Description

The validator aircraft configuration developed in the study, shown in Figure 60, is a DC-9-10 airplane modified to accept a new wing incorporating laminar flow control. The new wing duplicates in planform geometry the Lockheed LFC concept selected for the 1993 commercial transport and described in Section 5.2.

In general arrangement, the validator is a low-wing, T-tail, aft-fuselage-mounted two-engine transport with tricycle landing gear. In appearance it is not unlike the basic DC-9-10 from which it is developed. Readily noticeable differences are the increased wing span due to the

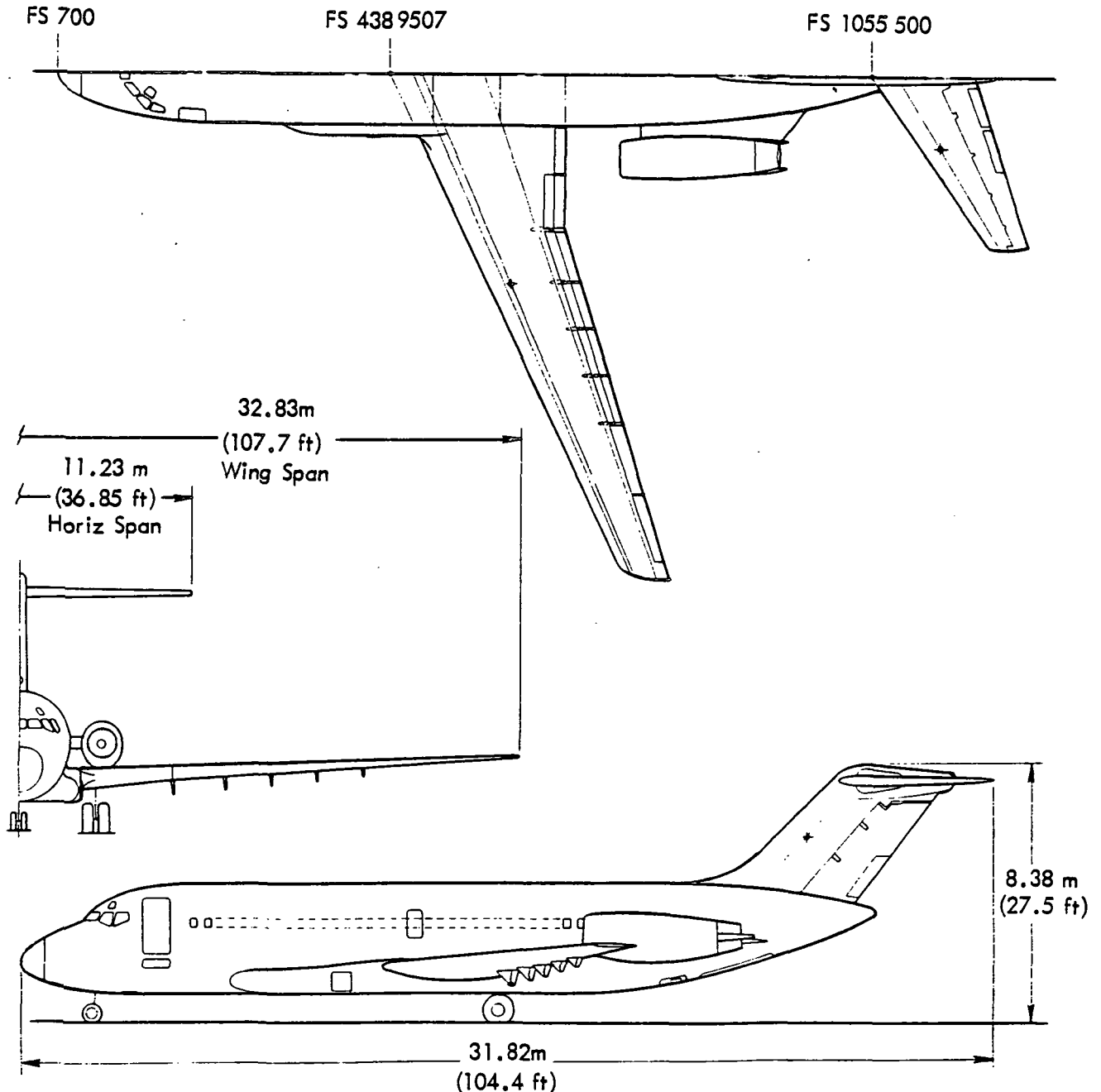


Figure 60. General arrangement - LFC validator/DC-9

higher aspect ratio and the fuselage/wing intersection pods housing LFC pumps. These pods are located beneath and extend well forward of the wing/fuselage fairing. LFC capability is provided on both upper and lower wing surfaces to approximately 75% chord. The leading-edge cleaning/de-icing system duplicates the one selected by Lockheed for its 1993 LFC transport.

Propulsion engine/nacelle packages are those furnished with the basic DC-9-10. No change in basic propulsion equipment is contemplated for the validator aircraft. Flaps, ailerons, and spoilers are new, but are configured to provide flying qualities similar to those of the DC-9-10.

The validator cabin is stripped of passenger amenities, such as seats and the galley, to provide space for test equipment and ballast tanks. An LFC instrumentation console and on-board data recording equipment are located in the cabin. Test engineer and observer seats are installed in existing seat tracks to provide accommodation for personnel to monitor LFC system performance during the early phases of the LFC flight test program.

Aircraft systems and sub-systems generally duplicate those of the DC-9-10 aircraft.

7.2.3 Conclusions

The analyses conducted in developing the LFC validator aircraft provide a basis for the following conclusions:

- (1) It is possible to integrate the Lockheed LFC wing concept into the DC-9-10 aircraft to form a feasible validator aircraft configuration.
- (2) The performance of the resultant validator aircraft is in excess of that required to satisfy the objectives of the validator flight demonstration program.
- (3) Including design, development, fabrication, aircraft modification, and a representative flight demonstration program, the estimated cost of the LFC validator program is 190.6 million 1980 dollars.
- (4) Assuming that the accumulation of 4500 flight hours of simulated airline service over a period of 27 months is adequate to establish the operational feasibility of the validator, the estimated duration of the validator program is 63 months.

7.3 ADVANCED DEVELOPMENT REQUIREMENTS

7.3.1 Aerodynamics

The present 2-D pressure distribution code, the recently developed FLO 22 and FLO 27 codes, the tapered semi-infinite swept-wing boundary layer code, and the 3-D stability code are useful and necessary computational tools in deriving a LFC 3-D swept-wing configuration. The basic design and analysis sequences originally conceived for external aerodynamics work are satisfactory. However, development of additional design and analysis tools

is needed particularly in the analysis of flow in the wing-root juncture, the tailoring of isobars, and the interfacing of individual computer codes into an integrated design and analysis fraamework.

As an example, the current Cebeci boundary layer code should be revised to a discrete-suction code to permit approximate solutions for configurations with slots or bands of porosity. In addition, codes should be added as subroutines so that slots conforming to various criteria can be automatically located on option.

The overall wing design and analysis methodology should be regularly updated to reflect the latest in computational codes for external flow, slot flow, stability/transition estimation, and other pertinent improvements. Particular attention should be directed towards establishing computer code interfaces and reducing design cost by developing improvements in computing efficiency for individual codes and reducing the number of design and analysis cycles necessary to achieve a satisfactory LFC wing configuration.

7.3.2 Structures and Materials

Major requirements for the development of LFC structure center around the use of advanced composite materials and characteristics peculiar to the fabrication of LFC surfaces. Additional effort is required in investigating the main landing gear support area, chordwise joints, access panels, and wing/fuselage joints.

Continued development of surface slotting procedures is required. Advances in laser and waterjet techniques should be monitored to evaluate potential improvements leading to reduced slot widths and faster cutting rates.

In advanced materials development, powdered aluminum sheet materials should be considered as a candidate for the slotted outer surface. Powdered aluminum is corrosion resistant and no anodizing or corrosion protection would be required. Powdered titanium sheet material should be evaluated as a candidate for a porous outer skin.

7.3.3 LFC Systems

An area of significant risk in the design of an operational LFC aircraft is the tolerance of the boundary layer to variations in LFC system performance. Previous efforts in the area of achieving and demonstrating the performance advantage of LFC, culminating in the X-21 flight test program, were largely oriented to construction and testing in a research atmosphere with careful hand-tuning to achieve the desired level and distribution of suction in order to optimize LFC performance.

For an operational commercial airplane, economical production must be achieved through the adoption of a simplified system, compatible with large-scale production techniques and tolerances. Little or no adjustment of the suction system will be acceptable on individual airplanes. As a consequence of these restrictions, suction flow profiles on new operational aircraft will reflect local chordwise and spanwise variations from the

optimum suction flows. These flow variations will influence the actual level of performance improvement available from LFC. It is therefore necessary to recognize the influence of these tolerances on LFC in the initial airplane suction system design.

Present manufacturing constraints, notably slot width and spacing, are such that the criteria limits set forth in the literature of the X-21 program cannot be met in the leading-edge region for a nominal configuration. Further, in some cases it is impossible to simultaneously meet all of these criteria limits and those from other sources, even without any production constraints, because the criteria limits are mutually exclusive. Thus, any system design must violate some of the existing criteria limits with selections based on the judgment of the designer. When realistic production tolerances are additionally superimposed on such a design, the effects on laminarization are totally unknown.

These considerations serve to illustrate the dilemma and risk faced in the suction system design. A comprehensive parametric test is needed to explore the applicable criteria and their upper and lower limits as they affect laminarization. This testing should range from an exploration of the upper and lower limits of suction allowable to achieve laminarized flow to an evaluation of the stability characteristics of various slot metering systems. The test should be oriented toward configurations that are more easily manufactured with low sensitivity to tolerances.

7.3.4 Leading-Edge Region Cleaning

The leading-edge cleaning system testing discussed in Section 5.4.4 provided substantial verification of the system. Residual cleaning liquid in the suction slots presented a potential problem that must be evaluated further. Initially, cleaning liquid composition investigations are required. If the system will not clear itself of improved fluids, a purge system may be required and should be included in any future test configurations.

The required cleaning liquid flow levels and distribution for both the prevention of insect accretion and for anti-icing requires further evaluation and development. These evaluations may best be carried out in the operational atmosphere of the flight test program.

7.3.5 Aircraft Design

Previous design efforts have been directed toward providing LFC capability on wing surfaces, and have produced several viable concepts for providing efficient suction flow paths from the surface to the suction pump. These conceptual design studies considered maintainability and reliability in a broad sense, but the limited scope and budget available precluded the detailed study and design required to evaluate the operational aspects of maintaining a fleet of LFC transports in a high-utilization environment. In general, direct maintenance costs and fuel costs represent comparable percentages of total direct costs. Thus, in order to maximize the benefits of LFC, maintenance costs attributable to LFC must be minimized.

To achieve this goal, in-depth study and demonstration of reliability/maintainability is required. This can be accomplished in the flight test and flight validation programs planned by the NASA. The leading-edge flight test program will provide experience in maintaining smooth slotted surfaces and some insight into potential operational problems. The wing surface panel program will permit design effort in the detail design of access openings for inspections and maintenance, the development and verification of techniques for inspection of layered composite/titanium structure, and the development and validation of repair procedures for the same surfaces. The validator aircraft program will impose the requirement for implementation of the "design for maintainability" concept. The validator program, with its design, manufacture, test, and demonstration phases, will provide the ultimate proof of LFC as a viable technology for future transports. That program will demonstrate the compatibility of LFC with the real world of airline operations in which maintainability/reliability share equal importance with system performance if fuel or cost savings are to be realized in fleet usage.

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16. Abstract A study was conducted to evaluate alternatives in the design of laminar flow control (LFC) subsonic commercial transport aircraft for operation in the 1990's period. Analyses were conducted to select mission parameters and define optimum aircraft configurational parameters for the selected mission, defined by a passenger payload of 400 and a design range of 12 038 km (6500 n mi). The baseline aircraft developed for this mission was used as a vehicle for the evaluation and development of alternative LFC system concepts. Alternatives were evaluated in the areas of aerodynamics, structures and materials, LFC systems, leading-edge region cleaning, and integration of auxiliary systems. Based on these evaluations, concepts in each area were selected for further development and testing and ultimate incorporation in the final study aircraft. Relative to a similarly-optimized advanced technology turbulent transport, the final LFC configuration is approximately equal in DOC but provides decreases of 8.2% in gross weight and 21.7% in fuel consumption.					
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