APPLICATION OF LAMINAR FLOW CONTROL TECHNOLOGY TO LONG-RANGE TRANSPORT DESIGN

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SUMMARY

Recent implementation of new initiatives to develop Laminar Flow Control (LFC) technology is due largely to the urgency of the energy problem and the realization that successful application to long-range transport aircraft can produce substantial improvements in fuel economy and airline economics. While the techniques of LFC are primarily aerodynamic, the impact on airplane structural concepts and systems is significant and requires a new approach to design integration of the airplane. Based on some 18 months of effort under the NASA LFC program and independent work by Boeing, some critical areas of LFC technology and the potential impact on airplane design are discussed and the corresponding benefits are shown in terms of performance and fuel economy.

Thus, recent advances in laminar boundary layer development and stability analysis techniques are shown to provide a more definitive basis for suction requirements and wing suction surface design. Equally important is the improved physical understanding of disturbance phenomena and the identification of means to cope with real disturbances such as surface imperfections, noise, erosion, ice crystals and other sources. Validation of theory and realistic simulation of disturbances and off-design conditions by wind tunnel testing under appropriate, controlled conditions at full-scale Reynolds numbers are also discussed. The favorable results of an initial series of tests on a partially laminarized wing are presented. Modern developments in the aerodynamic design of airfoils and wings are shown to be compatible with LFC requirements and indeed, to provide a more favorable combination with LFC than could be expected with older aerodynamic design concepts.

As expected, the necessity for slots or porous aerodynamic surfaces and the requirements for surface smoothness and structural integrity pose special and difficult problems for the designer. These imperatives force consideration of structural alternatives involving advanced alloys or composites in combinations now made possible by advanced materials processing and manufacturing techniques. Representative structural arrangements involving the use of advanced materials are presented and the results of their evaluation discussed. The incorporation of active controls concepts in the basic airplane design is shown to provide a means of offsetting weight penalties which would normally result from design requirements peculiar to long-range LFC airplanes.

An outstanding example of systems requirements imposed on the airplane because of LFC is the addition of suction compressor and drive units. The design implications of the choice of units and their location on the airplane

are discussed in relation to performance and reliability. Certain problems associated with operation of LFC airplanes require unusual technological innovation and imaginative design solutions to permit practical operation and economic airline use. The accumulation of insects at low altitudes and the need to cope with various environmental situations are but two areas of concern where possible solutions are presented.

Finally, the manner in which the various design choices are influenced by the state of LFC technology will be displayed. Alternatives for basic airplane arrangement will be shown to depend significantly on answers to crucial questions which are at present unresolved. It will be concluded that the potential for successful application of LFC technology to long-range transport aircraft is only beginning to be understood. Possible directions for and means of future implementation of research and hardware development are outlined.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

A_{π}	suction unit frontal area, m^2 (ft^2)
c	local wing chord, m (ft)
C_D	drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
C'_Q	slot suction coefficient
h	height of wave on structural surface mm (in.)
L/D	lift drag/ratio
$\dot{m}$	mass flow rate, kg/s (slug/sec)
M	Mach number
q	dynamic pressure, kPa (lb/ft^2)
R	Reynolds number
R/ft	Unit Reynolds number
$R_{\theta_{a.l.}}$	Reynolds number based on θ at the leading edge attachment line
s	distance along airfoil surface, m (ft)

Δs	distance between adjacent slots, m (ft)
S	wing area, m^2 (ft^2)
t	wing thickness, m (ft)
U	freestream velocity, m/s (ft/sec)
U_e	velocity at edge of boundary layer, m/s (ft/sec)
V_{app}	airplane approach speed, m/s (kt)
ΔV	root mean square disturbance velocity, m/s (ft/sec)
w_s	suction slot width, mm (in)
x	distance along chord, m (ft)
δ	boundary layer limit thickness, mm (in)
θ	boundary layer momentum thickness, mm (in)
η	spanwise position (fraction of semi-span)
λ	wave length of structural surface wave, cm (in)
ν	kinematic viscosity, m^2/s (ft^2/sec)
ψ	disturbance wave angle, degrees
ρ	mass density, kg/m^3 ($slug/ft^3$)

Subscripts:

c	chord
cr	critical
L	laminar
REF	reference value
s	slot
T	turbulent
TR	transition
∞	free stream

INTRODUCTION

A resurgence of interest in laminar flow control (LFC) technology is due largely to the urgency of the energy problem and the realization that successful application to long-range transport aircraft can produce substantial gains in fuel efficiency and airplane economics. Significantly, LFC has been identified as one of the few remaining possibilities for achieving the gains noted above and this has resulted in the implementation of a major research effort by the NASA. As part of the Aircraft Energy Efficiency program (ACEE) outlined in reference 1, it involves participation by both industry and the NASA with the ultimate objectives of creating a demonstrator LFC aircraft to establish the economic and operational feasibility of such aircraft in airline service.

The USAF/Northrop X-21 airplane program in the early 1960's (ref. 2) was a major effort to demonstrate the feasibility of LFC on large subsonic aircraft. While substantial success in maintaining laminar flow was achieved, significant design compromises and the lack of overall reliability in a variety of flight conditions left many technical questions unanswered and provided serious concern about the eventual adaptability of LFC to practical operation. From the current vantage point, the need for further research and development is obvious and validates the NASA approach in the ongoing LFC program.

While the techniques of LFC are primarily aerodynamic, the impact on airplane structural arrangements and systems is substantial and requires a new approach to design integration of the airplane. Based on some 18 months of effort under the NASA LFC program as well as independent work by Boeing, this paper will discuss progress in some of the critical areas of LFC technology and show the potential impact on airplane design and the corresponding benefits in terms of performance and fuel economy. Figure 1 illustrates an LFC transport configuration that has evolved from the effort referred to above (ref. 3). It represents a fairly conservative application of LFC technology to a long-range (10 180 km (5500 n. mi.))transport design sized for 201 passengers with cruise operation at Mach .8 and 12,800 m (42 000 ft) altitude. The layout is conventional for a trijet and was chosen to avoid adverse interaction with laminar flow on the wing due either to engine noise or aerodynamic interference between the nacelles and the wing. The wing is laminarized to 80% chord on the upper surface and 70% chord on the lower surface since high suction requirements in the trailing edge areas tend to make further laminarization of marginal benefit. This is compatible with area requirements for ailerons, spoilers and flaps which are less complex and occupy less space than is normal for turbulent airplanes. This characteristic and the elimination of leading edge devices is acceptable because of design requirements peculiar to long-range LFC airplanes. A more aggressive approach involving the use of LFC in appropriate areas of the empennage can be expected in future designs. In any case, the above airplane should be recognized as the basis for the development of the LFC technology applications which will be discussed in this paper.

WING DESIGN FOR LAMINAR FLOW

The central problem in the successful application of laminar flow control is the development of a wing design which permits the maintenance of laminar flow while making efficient accommodation for the structural arrangements and systems necessary to provide LFC. This must be accomplished for a range of flight and environmental conditions corresponding to practical operation in today's airline systems.

Since the fundamental aim is to provide laminar flow over as much of the wing surface as possible, aerodynamic considerations demand first priority. The maintenance of laminar flow at high Reynolds numbers has long been recognized as a laminar boundary layer stability problem requiring increasing amounts of suction on wing surfaces, as Reynolds number increases, to limit the growth of disturbances in the boundary layer. These disturbances can arise from a variety of sources and, if not avoided where possible, or sufficiently controlled, will cause transition to turbulent flow. Thus, it is important to develop a complete understanding of the dynamics of the laminar boundary layer and the methods for its analysis under a variety of conditions encompassing those to be expected in actual operation. This is also essential for the intelligent pursuit of practical design solutions. These solutions must include provisions for wing surface openings of appropriate size and distribution and the internal ducting needed to carry the suction airflow to the suction pump. The suction pump itself must have an efficient driver and the entire unit located to minimize aerodynamic interference and weight. Special considerations include use of a device (e.g., fence or notch) at the wing root to avoid contamination of the wing leading edge flow by the turbulent boundary layer from the fuselage.

Boundary layer analysis methods have undergone considerable development since the X-21 application and figure 2 is intended to show this progression. The classic methods (X-21 period) involved the approaches indicated for the problems of boundary layer development prediction, turbulent boundary layer contamination and laminar boundary layer stability.

Boundary layer development analysis was generally limited to the infinite yawed wing case with approximate means of accounting for compressibility. Even this approach was laborious since computerized methods were usually not available. Analysis of the leading edge area was handled as a special situation which was later recognized to require limiting the attachment line Reynolds number ($R_{\theta_{a.l.}}$) to values less than 100 to 200 for swept, tapered wings. The current approach to development analysis is based on the swept tapered-wing model with full accounting for compressibility and relies heavily on the use of modern computer techniques. The attachment line boundary layer can now be used as the starting point for the stability analysis although the $R_{\theta_{a.l.}}$ criteria may still be invoked under some circumstances; e.g., where turbulent boundary layer contamination from the fuselage is involved. Future developments are likely to involve only minor improvements (e.g., automation, special cases) since today's methods are essentially complete.

Contamination of the laminar boundary layer at the wing leading edge due to convection of turbulence from the fuselage is a practical problem which has been handled by ad hoc solutions and is not presently susceptible to analysis. The interplay between the various measures indicated in figure 2 is incompletely understood and requires experiment to establish the most favorable configuration for a given application. Also, the turbulent flow at the wing root intersection causes a significant area to be not laminarizeable with current techniques. Further innovation is required to evolve approaches to maintain laminar flow in intersections, particularly if LFC on the fuselage becomes an objective.

Classic methods to analyze laminar boundary layer stability involve the separate treatment of the crossflow and the tangential flow. For the crossflow the streamwise vortices ($\psi \doteq -90^\circ$) are considered the most unstable mode while the Tollmien-Schlichting mode ($\psi = 0^\circ$) is assumed to be critical for the tangential flow. Although this approach has appeared reasonably successful in estimating amplification levels to establish suction requirements, the tenuous connection between predicted amplification and boundary layer disturbance levels has been unsatisfactory and remains so today.

Recently developed methodology has a number of advantages over the classic approach including the implementation of computing techniques to greatly reduce the labor involved in analysis. Moreover, the unified treatment of the compressible three-dimensional boundary layer avoids the artificial separation into the crossflow and tangential flow modes by introducing the disturbance wave angle as a separate variable along with frequency. It also introduces the influence of compressibility on a systematic basis. The calculation of allowable disturbance amplitude ratio and the relationship to the ambient disturbance levels has progressed little beyond that of the classic analysis. The allowable amplification ratio is generally believed to be in the range e^9 to e^{12} although this implies several assumptions which cannot be verified. A major assumption seems to be that the "normal environment" for laminar flow involves a certain initial level of disturbance which, when amplified to some threshold value, will produce transition. Specification of the allowable amplification ratio implies that the ratio of initial disturbance level to the threshold level is known. This is a dubious proposition in view of the fact that different types of disturbances may exist in the environment or be produced in the course of flow over the surface, each having its own peculiar modal and energy transfer characteristics.

Thus, we are led to hope that the future will see the development of better methods of coping with disturbance growth analysis. New methods are needed to analyze the local effects of flow through slots or porous surfaces including disturbances generated in this process which may persist downstream. Ultimately, a complete three-dimensional analysis involving all possible modes including sound may be required to establish a valid theoretical basis for predicting suction requirements and defining system geometry.

From the previous discussion it will be apparent that the disturbance environment and the control of amplified disturbances in the boundary layer is a major hurdle in the successful design and operation of an LFC airplane. There are many external disturbance sources and the chart of figure 3 illustrates typical allowable levels for those sources of significance. The areas of major design impact are also shown. The allowable engine noise is based on a recent analysis and depends on the criteria assumed for transition and, to a lesser degree, on the portion of the wing surface involved. Surface imperfections can have various manifestations and the ranges shown generally apply for single elements, or elements widely separated on the wing surface. While the values given are representative, they will vary somewhat depending on the unit Reynolds number and the local state of the boundary layer. For closely spaced elements, the allowable levels are obviously much less but remain undefined. It should also be recognized that the values given above are subject to considerable revision depending on the precise configuration of roughness elements, and the presence of other disturbances of any type.

The presence of ice crystals is widespread throughout the upper atmosphere and can substantially influence the choice of cruise altitude even on a daily basis. This is illustrated by the data of figure 4, taken from reference 4, which show the effects of ice particles on LFC degradation at 12 100 m (40 000 ft) altitude and Mach .8. The threshold for significant loss of LFC depends on both particle diameter and concentration as shown and becomes higher as altitude increases. Based on data measured over Kwajalein Atoll throughout the late summer months (ref. 5), it is apparent that, near the equator, the ice particle distribution is such that some loss of LFC could be expected a substantial fraction of time. Fortunately, at higher latitudes, available evidence indicates that the critical particle distributions occur at lower altitudes and tend to diminish rapidly above the tropopause. Thus, an LFC airplane capable of cruise above 12 200 m (40 000 ft) could operate reliably over most of the major airline routes. However, long-range routes involving penetration of the lower latitudes would apparently need additional aids such as weather monitoring, particle sensors, etc., to permit economic operation. Additional data are needed to provide a clear understanding of the operational requirements associated with ice particles and the design requirements for cruise altitude capability.

The presence of atmospheric turbulence is known to have some effect on laminar flow but these effects are difficult to measure and are generally judged from the X-21 experience to be unimportant. This is because the normal atmospheric turbulence spectrum contains very low levels of turbulence in the frequency range critical to laminar boundary layers.

Returning now to the question of engine noise, its potential impact on airplane design can be illustrated by reference to a study (ref. 6) based on noise data taken in flight on a 747 airplane. For conditions appropriate to the LFC airplane of figure 1, the spectrum of the noise incident on the wing lower surface was analyzed to establish the contributions of its significant components, i.e., jet, turbomachinery, boundary layer, etc. Based on the appropriate incident noise levels, the disturbance levels in the boundary layer were estimated using calculated amplification factors for the critical frequency range. Transition was estimated to occur when the disturbance level exceeded a certain value in terms of $\Delta V/U$. This approach was validated using the results of wind tunnel tests with several types of noise spectra incident on laminar flow surfaces. Analyses were accomplished for several cases involving different engine and acoustic lining combinations. The results are given in figure 5 which shows the potential loss of laminar area on the wing lower surface for two values of transition criteria $(\Delta V/U)_{TR}$ to indicate the sensitivity of the results to the criteria. It is apparent that the 1985 engine having a high bypass ratio (BPR = 7.5) and with LFC lining to reduce internal noise in the critical frequency range will not cause significant loss of laminar area even on the basis of a conservative transition criteria. Moreover, the current engine with LFC lining would, on the basis of a more reasonable criteria, produce essentially no loss in laminar flow. The incident noise range given in figure 3 corresponds to the limits for the above cases. Based on the above results, wing-mounted engines for LFC airplanes could be considered feasible provided that aerodynamic interference between nacelle, strut and wing is not excessive. The inherent advantages of wing-mounted engines in terms of weight and balance provide incentive to further explore this design alternative.

The development of advanced high-speed airfoils for modern wing design has continued to receive attention in relation to their potential for increasing wing thickness, and thereby reducing wing weight, with no reduction in speed. For a number of reasons, the impact of advanced airfoils is even more favorable for LFC airplanes. The following are of principal importance:

1. The increased volume available with greater thickness provides critical accessibility and the space to accommodate internal ducting for suction airflow collection and removal.

2. With laminar flow surfaces, no significant drag penalty due to thickness occurs as in the turbulent wing case.

3. Tailoring the wing pressure distribution to achieve straight isobars with relatively flat chordwise distributions is more easily achieved. This is highly important for LFC wings since proper suction inflow distributions must be achieved with minimum flow losses.

Wing geometry and pressure distribution are shown in figure 6 for the reference airplane (fig. 1) for representative flight conditions. The airfoils at 28% semi-span ($\eta = .28$) and beyond are designed with the pressure recovery starting at about 70% chord providing a nearly constant pressure over the major portion of the wing. A slight recovery occurs just behind the leading edge peak to suppress the remaining boundary layer crossflow. The leading edge radius is sufficiently small to maintain $R_{\theta_{a.l.}}$ below 100 for the 25° swept wing. Inboard of $\eta = .28$, the airfoils deviate progressively from the basic section shape to that shown at the wing root ($\eta = .11$). This shape is fairly characteristic and provides an upper surface pressure distribution compatible with other areas on the wing. To provide flow conditions limiting $R_{\theta_{a.l.}}$ to 100 in this area, the leading edge radius is held within limits by somewhat flattening the leading edge contour on the lower surface to produce the pressure distribution shown. The wing can be expected to operate over a substantial range of lift coefficient with relatively minor adjustments in suction flow, particularly if slight adjustments in wing flap angle are made. The loss of laminar flow in unusual situations can be expected to produce no adverse flight or performance characteristics beyond those associated with the increased drag due to turbulent flow.

For a laminar flow wing design, a fundamental requirement is the determination of the suction distribution to maintain laminar flow under the appropriate range of operating conditions. This will include variations in chordwise and spanwise pressure distributions, Reynolds number, Mach number, disturbance environment, etc. Thus, as shown in figure 7, the characteristic slot orientation is generally spanwise and along isobars insofar as possible. The suction distribution on both upper and lower surfaces is shown on the right for three spanwise locations. This is given in terms of C_Q' which is based on the mass inflow and average spacing corresponding to each slot. Thus, on upper surface, the spacing is quite small in the leadingeedge area, reflecting the high suction requirement for the unstable boundary layer crossflow situation there. Slot endings at certain spanwise locations are selected to maintain a reasonable slot Reynolds number ($R_s = Uw_s/\nu$) distribution and adhere to proven slot width (w_s) criteria. Avoidance of significant disturbances from the slot ends is extremely important. Over the main portion of the wing box the slot spacing is characteristically wider, corresponding to lower suction requirements in the area where the Tollmien-Schlichting mode is critical. In the pressure recovery area, the combination of adverse pressure gradient and crossflow again raises the suction requirement necessitating smaller slot spacing back to the 80% chord position. Laminarization beyond this point was not used because of high local suction requirements which result in high equivalent suction drag and excessive suction unit size. Thus, the incremental performance gain is very small for laminarization beyond 80% chord. The extreme difficulty of providing suction in areas occupied by ailerons, spoilers and flaps is also a major inhibiting factor.

On the lower surface, the gain due to laminarization is relatively smaller so the suction is terminated at the rear spar position (70% chord). The suction distribution requirements are similar to those of the upper surface, but the quantity is somewhat higher. The slot spacing variation is also similar but the actual number of slots is larger. The above characteristics are due to the longer chordwise extent of both the leading edge crossflow and the trailing edge pressure recovery areas. It will be noted that the slots do not extend spanwise into areas where the turbulent contamination from the wing/body intersection and the wing tip are propagated.

LFC WIND TUNNEL TESTING

From the preceding discussion it should be apparent that wind tunnel tests will be vital to the successful development of LFC wings and the system elements which serve essentially aerodynamic functions. Furthermore, the need is urgent to conduct these tests under realistic conditions, specifically including both unit Reynolds numbers and chord Reynolds numbers, because of the overriding importance and sensitivity of these parameters in relation to boundary layer stability and the effects of disturbances. Because of the latter, the test environment should be one of low ambient disturbance levels--especially the stream turbulence and noise. The effects of Mach number, while significant, are generally not large and can readily be estimated for correlation between low-speed test results and expected flight performance. Some uncertainty currently exists as to the importance of local Mach number effects on slot inflow stability and possible induced downstream disturbances. Although the mechanism is poorly understood, it is not anticipated that the above effects will be of major importance. Several means of minimizing the impact have been considered in suction surface design such as using closely spaced slots or dual-slot arrangements. On the basis of the above considerations, the Boeing Company, in support of LFC design studies done under NASA contract, decided to develop an experimental facility (ref. 7) to permit investigation of the problems associated with laminar flow control by boundary layer suction on large subsonic transport aircraft. The low-speed Boeing Research Wind Tunnel (BRWT) was chosen as the basic facility for the LFC wing model testing since measurements have indicated the turbulence and noise levels were within acceptable limits; i.e., $(\Delta V/U) \doteq .0015$. The 1.53m (5 ft) by 2.44m (8 ft) test section will accommodate a large model permitting near full-scale test Reynolds number (up to $R_c = 25 \times 10^6$). The 2.44m (8 ft) span, 6.1m (20 ft) chord model dimensions were chosen to represent a typical section of a 30° swept wing. The LFC wing test arrangement is shown in figure 8 as installed in the BRWT between floor and ceiling. The airfoil section was designed to provide, in the presence of the tunnel walls, an upper surface pressure distribution typical of the mid-span portion of an LFC transport wing at cruise conditions ($M = .80$, $C_L = .5$). The leading edge was shaped to provide a value of $R_{\theta_{a.l.}}$ approaching 100 at the above condition. Although the general pressure level on the model lower surface corresponded to that of the airplane, the independent selection of leading edge radius (shape) produced nonrepresentative pressure variations near the leading edge. These can, however, be appropriately controlled by selecting a different incidence angle when the lower surface flow is of primary interest. The installation also included fairings on the tunnel floor and ceiling to prevent significant spanwise pressure gradients on the model. A three-segment trailing edge flap was also used to provide flexibility in pressure distribution adjustments.

For the initial phase of the test program, only the first 30% of the upper surface and the first 15% of the lower surface had provisions for LFC. Although these areas are the most critical, the suction area will ultimately be extended to the flap hinge line (80% chord). The suction surface is divided into four sectors each served by a separate plenum chamber. Each plenum has a separate metering and measuring apparatus and the distribution of the suction flow between individual slots is controlled by slide-valves running the length of each slot. Pumping power is provided by an ejector driven by high pressure air. Two views of the physical installation are provided by the photographs of figure 9. The characteristics of the model described above are evident including the suction slots near the wing leading edge (downstream view).

Validation of the test apparatus has been accomplished in two steps. First, the model was tested with an alternate forward section which had no suction slots but incorporated an ample number of surface static pressure taps. The main objectives were to verify that the desired pressure distributions could be achieved by appropriate settings of the model incidence and flap deflection, and to determine the extent of natural laminar flow and general boundary layer development on the test surfaces. A detailed investigation of the leading edge flow pattern by means of several flow visualization techniques clearly indicated the nature of the transition phenomena on the leading edge. Figure 10 is a photograph of the wing leading edge on which the flow pattern is made visible by painting the surface with a lampblack and kerosene mixture. After long exposure to the flow, the coating is thinly distributed downstream revealing the random wedge distribution pattern which tends to remain stable with time. Although it is apparent that disturbances originate at the apex of each wedge, later inspection generally showed no discernible surface imperfections or accumulation of particles at these locations. The progressive appearance of wedges as the flow velocity is increased indicates the sensitivity to unit Reynolds number and the onset of unstable boundary layer flow conditions in the region of intense crossflow. Boundary layer measurements in the areas of wedge accumulations indicated early transition to turbulent flow, whereas in wedge-free areas the flow remained laminar. Based upon the infrequent appearance of disturbances forward of $s/c = .01$, the first suction slots were provided near this location ($s/c = .013$) on both upper and lower surfaces, thus avoiding the complex vertical slots originally contemplated for the attachment line area.

Having accomplished the first objectives, testing of the suction model followed. The initial aim was to demonstrate that the suction system would function properly and was capable of maintaining laminar flow reliably over the areas where suction was applied. Additional objectives were to establish the suction distribution for maximum efficiency, explore the sensitivity to oversuction and the effects of shutting off certain slots. A further goal was to evaluate several experimental techniques for detecting transition and monitoring LFC system effectiveness. Typical test conditions are given in figure 11 which shows the airfoil pressure distribution and suction flow in individual slots corresponding to an efficient suction level and distribution required to maintain laminar flow to 30% chord. The corresponding slot Reynolds numbers, R_s, are shown on the right-hand scale of the lower plot indicating general adherence to the criteria $R_s \leq 100$. No difficulty was experienced with operation of the first slot beyond $R_s = 150$ and, indeed, operation at suction levels 50% higher than normal exhibited no critical characteristics.

Typical results of boundary layer surveys are presented in figure 12 which shows profiles at the same location just downstream of the last suction slot. Without suction the characteristic turbulent boundary layer profile appears, as would be expected, and the thickness, δ_T agrees well with predicted growth. With suction applied, the flow remains laminar although the profile shape is fuller than the characteristic Blasius shape as would be expected just downstream of a suction slot. The profile in this case is only about 80% as thick as could be expected from normal laminar boundary layer growth, reflecting the application of suction ahead of the measuring point. Although an ultimate objective is to compare the suction requirements with theory, considerable analytical development along the lines suggested in figure 2 will be required before valid comparisons can be made. This is because the presence of noise and turbulence in the wind tunnel, for example, introduces disturbances in the laminar boundary layer which can only be roughly accounted for. The best to be expected for the immediate future is to compare calculated disturbance amplification ratios corresponding to observed positions of transition in these wind tunnel tests for a variety of test conditions. These comparisons can also be assessed in relation to data from other sources. If a history of correspondence in amplification ratio can be shown to exist, a certain confidence in the validity of this criteria may be established for known types and levels of the disturbance environment. Regardless, an assessment of the test results and the general experience to date leads to the conclusion that the objectives outlined above have been achieved. Although much experience and considerable data has been accumulated in connection with the X-21 program and related activities, much remains to be accomplished; particularly the investigation of the myriad questions associated with design choices which must be made in the development of efficient and practical LFC systems. The Boeing facility will be useful for such work and will, hopefully, contribute substantially to the advancement of LFC technology.

STRUCTURAL CONCEPTS FOR LFC

The previous discussion has emphasized the characteristics of LFC wings which are unusual and stem primarily from the fundamental requirement to establish and maintain laminar flow throughout a reasonable flight envelope. As expected, the necessity for maintaining suction through slots or porous aerodynamic surfaces and the requirements for surface smoothness while maintaining structural integrity pose special and difficult problems for the designer. These imperatives force consideration of structural arrangements involving advanced alloys or composites in combinations now made possible by the use of advanced materials processing and manufacturing techniques. The familiar requirements for achieving acceptable reliability, repairability and maintainability characteristics remain as demanding as in today's structures, while more elusive in the design process due to the added complexity of structures and systems. The search for satisfactory solutions involves the consideration of a large number of alternative concepts and arrangements which must be carefully evaluated in relation to the design requirements and objectives. Of fundamental and, in some cases, overriding importance is the weight impact of the various candidate designs under consideration. No design can be expected to be ultimately successful which does not closely approach the unit weight level of the best of today's wing structures. Thus, attention to selecting concepts which minimize parasitic weight features must be emphasized at the outset. During the extensive design activity phase of the current contract, many alternatives have been considered and subjected to critical review based on the criteria discussed above. Promising candidates continue to be evaluated and quantitatively compared to a contemporary baseline structure of aluminum skin-stringer design.

One of the more promising concepts is illustrated in figure 13 which shows a typical wing cross section and details of the wing box structure. The laminated aluminum honeycomb design is a sandwich arrangement which features laminated inner and outer skins built up of aluminum sheet sections. These overlap sufficiently to provide required fail-safe characteristics. The skin bonding operations are done in a bonding assembly jig contoured to required surface tolerances. During the bonding cycle, pressure is maintained sufficient to insure proper wing shape and smoothness. The intermittent honeycomb core is placed with appropriate gaps to form the spanwise duct edges so that, with the assembly and bonding of the inner and outer skins and the core, a complete sandwich is formed incorporating spanwise ducts of the required cross-sectional areas. This second stage operation, which includes bonding of the rib chords and spar chords to the inner skin, is carried out in the same bonding assembly jig used in the skin manufacture. Assembly of the upper and lower sandwich panels to form the complete wing box is done by attaching the rib and spar webs to their respective chords with mechanical fasteners.

The suction air is removed through continuous spanwise slots. In this case, the slot is formed by bonding two strips into a machined recess in the outer skin. The stepped recess also provides a plenum area below the slot to diffuse the flow before it passes through appropriately spaced bleed holes into the tributary ducts. The bleed holes are drilled and cold-worked to avoid fatigue penalties which can be significant, particularly for the wing lower surface. Section A-A shows a better view of these ducts which serve to meter the flow through the nozzles into the main spanwise duct which carries the flow to the suction unit. An evaluation of the wing weight potential of this LFC concept shows it to be only about 6% heavier than the conventional riveted skin-stringer aluminum wing of a turbulent airplane.

The suction slot arrangement is shown in figure 14 for both the upper and lower wing surfaces. The slots have the same orientation as the spanwise ducts located directly below them and each slot is served by a single spanwise duct. For slots ending at various spanwise positions, the ducts will also end at corresponding locations. It will be apparent that with this particular concept, the structural arrangement is closely tied to the slot arrangement. Since this poses some difficulties, other concepts are being explored to provide some independence between structural elements, slots and associated ducting.

A variation of the arrangement shown is one involving the use of essentially constant slot spacing at least over major portions of the wing box. If the front spar is used as the base position, this allows considerable reduction in total slot length and avoids the spanwise termination of slots in the laminar areas. In the pressure recovery areas, spanwise tapering of the slot spacing can again be used to accommodate suction requirements as a function of spanwise position. The use of suction opening designs which avoid rigid adherence to current slot Reynolds number criteria can also be used to permit a slot configuration which is more adaptable to the efficient arrangement of structural elements.

For each suction position, the geometry of the flow passages should ideally match the local inflow requirement. However, it is generally possible to select a suction surface configuration such that a small number of standard slot widths can be used to accommodate the various local needs. Also, a large number of possibilities exist for the design of the opening itself. Figures 15(a) and 15(b) present a number of candidates each having its own set of advantages. The first option (integral slot) is basic and has been used on the X-21 airplane, other flight hardware and wind tunnel models. In the laminated structural design of figure 13, the cavity would be machined and the bleed holes drilled and cold-worked before bonding of the outer ply. The slot sawing is the final operation and may represent the most critical part of the process. Because of the inherent disadvantages (i.e., manufacturing, maintenance, etc.) of the integral slot, various types of inserts have been devised to facilitate the manufacture, installation, maintenance, repair and replacement of suction surface openings. Concepts 2 and 3 are simple slotted inserts which function in the same way as Concept 1. Concept 4 consists of an insert assembly which contains not only the slot but the plenum cavity. This avoids some of the difficulties of manufacture and tolerance control of Concepts 2 and 3 but will tend to produce higher flow losses. However, it has the further advantage that the suction flow can be metered as a function of position on the wing, thus avoiding the use of tributary ducts and allowing more flexibility in the geometry of the main bleed holes. Concept 5 is another attempt at simplifying manufacture and installation through the use of an aluminum foam base which can be depressed on installation to minimize joint discontinuities. Concept 6 is a simple strip containing an appropriate perforation pattern which can be readily manufactured using the Steigerwald electron-beam drilling process. Fatigue sensitivity is a disadvantage unless an appropriate material can be found. These and other variations are all adaptable to the basic structural arrangement shown in figure 13. A final choice will depend on many factors which can be appropriately balanced only after complete evaluation and testing to determine structural and functional suitability in the realistic operating environment.

Reference has previously been made to studies of a number of structural alternatives based on promising combinations of innovative arrangements and advanced materials made possible by new processes or manufacturing techniques. The arrangement shown in figure 13 is one such based on the extensive use of bonding and improved aluminum alloys to reduce weight and meet the smoothness requirements for laminar flow surfaces. This concept has been chosen (ref. 8) as the most likely candidate for application in the relatively near term since it involves the use of familiar materials and processes and would probably not involve long-term, extensive development programs. Other promising concepts which have undergone considerable design development and evaluation are shown in figure 16. The first concept, using graphite fibers with an epoxy matrix, is characteristic of several evolving from the work being carried on today under the NASA-sponsored composites activity in the ACEE program. This particular arrangement incorporates a thin titanium outer skin to provide a smooth, durable surface and protection against lightning strike. Evaluation of this concept has shown it to be generally compatible with LFC requirements and to have outstanding weight reduction potential; i.e., about 14% lighter than conventional structure. However, on the basis of current and foreseeable development activity, it is considered to be applicable only in the longer term

The bonded aluminum skin-stringer arrangement shown next permits efficient distribution of material throughout most of the wing and avoids the use of elements tending to be parasitic (e.g., honeycomb). It has the added advantage that bonding provides better fatigue resistance in comparison to conventional riveted skin-stringer arrangements, but the question of shear-tie effectiveness remains a cause for concern and further study. It is potentially competitive from a weight standpoint with conventional structure and thus continues to be an attractive structural alternative.

The third concept (fig. 16(b)) contemplates the use of titanium throughout and fabrication by means of the simultaneous superplastic forming and diffusion bonding process (SPF/DB) which is currently undergoing development for higher temperature applications. This was considered to be a candidate for LFC structures because of its apparent adaptability to forming of intricate assemblies involving many parts where significant production economies might be realized. However, an evaluation of variations on this approach have not been competitive from a weight standpoint. The recognized long-term nature of the development cycle and the facility expense involved for production have served to discourage further effort in this direction.

The fourth concept is very similar in arrangement to the laminated aluminum honeycomb design and contemplates using a suitable chemical bonding process for assembly which would require development for production application. This approach has not proven competitive with the aluminum concept primarily because the structural elements tend to be somewhat less stable and, therefore, heavier.

The last two concepts (fig. 16(c)) are characterized as riveted skin-stringer types because the basic underlying structure uses aluminum with conventional structural shapes and assembly processes. For the fifth concept, the fiberglass outer skin panel(s) can be configured more or less independently of the main structure and are applied after the latter is built. This final phase is accomplished by bonding spacer strips to the stiffener flanges and machining to contour. Bonding of the outer fiberglass skin containing slots (or suitable inserts) is done last. Although this approach involves parasitic elements and less efficient use of structural material, the manufacturing advantages appear significant and further design development may lower the overall weight into the range of interest. This possibility will become more attractive if the costs of other, more exotic approaches prove to be unacceptable.

The sixth concept shown contemplates the use of so-called "snap-in" strips to close out the space between structural elements and provide a continuous outer surface. The use of a resilient material for the strip or a slightly deformable insert design of standard sectional shape is essential for this concept. The strip also incorporates the suction opening, the sub-surface plenum and bleed hole pattern which carries the suction airflow into the inter-stiffener spaces which form the spanwise ducts. Of the various concepts discussed above, the first four have been evaluated and their relative potential for application has been discussed above. The last two concepts and options derived from them are still in various stages of development and evaluation.

ADVANCED TECHNOLOGY IMPACT

The above discussion highlights structural concept development in which favorable combinations involving different materials and types of construction have been sought. The application has been to the wing structure where it is difficult to assess the separate impact of each new technology element. While it is recognized that these developments can benefit the turbulent airplane as well as the laminar airplane, the overall effect is significantly greater for the latter since design studies continue to point toward higher wing area and span for LFC airplanes. The use of advanced materials and construction techniques is thus more important to reduce wing weight in this case. The chart of figure 17, however, avoids the above type of comparison and instead provides a simple statement of impact on the weights of major LFC airplane components. A definitive comparison of the relative impact for laminar versus turbulent airplanes is left for the time when final designs of each aircraft, both performing the same mission, are available. It is apparent from figure 17 that extensive application of graphite/epoxy composites to the airplane exhibits the greatest potential for weight saving. However, it must be recognized that these gains are applicable in the longer term than are those for improved alloys and bonded construction. However, application of composites to trailing surfaces is considered appropriate in the near term.

To complete the assessment of various elements of advanced technology that could be applicable to an LFC transport airplane in the 1990 time period, figure 18 summarizes the gains appropriate to each element. Of major significance, of course, is laminar flow control itself which provides a 26% gain in lift to drag ratio with wing LFC only. The weight impact, which applies mainly to wing and systems, continues to be assessed and remains to be determined (TBD). As previously pointed out, advances in airfoil design are of somewhat greater significance for an LFC airplane and result in substantial weight improvements without the corresponding drag penalties associated with increased thickness for the turbulent airplane. Reduced roughness provides a significant L/D gain which arises because of the inherent smoothness of the LFC wing and also the smoothness associated with bonded construction on the fuselage and empennage.

The projected incorporation of active controls provides significant improvements in both weight and drag, primarily through reduction in horizontal tail size and trim drag. Load alleviation impact will tend to vary with airplane configuration but recent analyses support a conservative 8% reduction in weight of the wing box. This again tends to be higher for the LFC airplane because of the basic tendency toward higher aspect ratio and lower wing loading than for the turbulent airplane. The use of a flutter suppression system (FSS) may be appropriate depending on the airplane configuration and the wing weight penalty associated with providing normal flutter margins. A small penalty is preferable to the added complexity of a FSS. However, if the performance benefits of high wing aspect ratio become sufficiently important, the use of a FSS should be considered.

An advanced turbofan may be a reasonable possibility in the 1990 time period provided that continuing studies (e.g., the EEE program) continue to support substantial performance and weight gains such as those shown. Such gains would have to be achieved with high confidence that unfavorable maintenance trends with current high bypass ratio engines could be avoided. Results of current LFC airplane studies tend to show significant fuel savings for bypass ratios up to 7.5 with small effects on direct operating costs (DOC).

LFC SYSTEMS

The suction system is a prominent example of systems requirements imposed on the airplane because of LFC which impacts many areas of the airplane design as well as its performance and reliability. Studies directed toward the evaluation of various alternatives for suction system elements and compressor/drive components have been completed and a system selection made for the baseline airplane as reported in reference 9. The chart of figure 19 displays the important options for both the suction compressor and the power source together with the related choice of unit location on the airplane. The two-pressure level compressor arrangement appears to provide the best compromise between the need for high system efficiency and the desire to avoid undue complexity. The two levels generally correspond to those for the upper and lower wing surfaces with appropriate allowance for inflow and duct losses which are characteristically about $.05q_\infty$ and $.15q_\infty$, respectively. Trade studies to determine the appropriate exhaust velocity levels for both the suction compressor and the drive unit are the subject of current study.

The drive type selection involves a number of possibilities which have to be evaluated on a consistent basis. This has been done for all the options shown in the first category under "drive-type" (except electrical and hydraulic) for systems located in the aft-body area close to the main engines and below floor level. Suction air in this case was ducted from the wing root through an unpressurized area below floor level back to the suction units as described in reference 3. In this location the turboshaft engine drive rated consistently high in all areas including performance, except in comparison with the direct mechanical coupling where its fuel consumption was only about .5% higher. The turboshaft engine was also the logical choice for the wing-mounted location because of distance from the main engines. In a case where the empennage is also laminarized, the use of an APU which would normally be provided for the airplane, is considered to be appropriately sized and would be located in the aft-body area.

Based on studies carried out to assess the relative advantages of the various options above, the suction unit installation on the wing appears most desirable and the location at the root was selected on the basis of arrangement convenience and least interference with laminar flow areas. The main features of this installation are shown in figure 20. Although this location appears attractive, the configuration details are important to the overall performance. Of major significance is the effect of the suction unit on drag. The wind tunnel data of figure 21 show this impact for a representative simulation of the suction unit fairing. It is apparent that a significant increase in drag and reduction in critical Mach number occurs in the cruise C_L range. The oil flow picture shows the disturbed area which tends to go beyond the normal turbulent wedge from the wing/body intersection. Such effects are unacceptable and highlight the need for further tailoring of the installation or perhaps reconsideration of the initial choice of location.

As shown previously, one of the major factors affecting the maintenance of laminar flow is the disturbance environment in which the airplane must operate. The leading edge roughness associated with the residues of insects encountered at low altitudes is recognized as a major operational problem. Thus substantial effort has been devoted to developing solutions which are reliable and do not adversely affect other operational characteristics or the economics of the airplane. Many solutions have been proposed which, for one reason or another, are impractical or difficult to implement. Past approaches include:

- "Superslick" films
- Hydrophobic sprays
- Sublimation coatings
- Mechanical scrapers
- Deflectors
- Fly-away covers
- Washing systems
- Liquid films

Of these, the last technique appears to have some promise based on recent NASA tests on a Jetstar aircraft at Dryden FRC. Figure 22 illustrates a variation of this concept in which the liquid (H_2O + anti-freeze) is continuously ejected during takeoff or landing to prevent adherence of impinging insects to the surfaces. An obvious disadvantage is the requirement for system maintenance and continuous liquid supply.

Two other candidates are also shown which appear to have potential. The cryogenic frost system operates on the principle of expanding a cryogen (LN_2) into a mixing chamber to provide cold air (about -15°C) for distribution along the leading edge. The cold metal would, except in a dry atmosphere, cause the formation of frost in a relatively short time prior to takeoff. During the takeoff and climb, adherence of impinging insects would be inhibited by the frost. With shutdown of the system, the airstream would quickly melt the frost leaving a clean surface for laminar flow. However, this type of system would not be effective during landing approach so that ground preparation for following flights would frequently involve manual cleaning of the leading edges.

The third concept uses high pressure bleed air to provide two-dimensional jets directed forward into the airstream. At flight speeds, the jets are turned back onto the leading edge to avoid significant adverse aerodynamic effects while acting as a shield to prevent the impingement of insects on the leading edge. Although the principles involved in the approaches shown are obvious, considerable development and testing under simulated operating conditions is required to establish feasibility and determine the appropriate system parameters and characteristics.

Additional features of the cryogenic frost system are shown in figure 23, which illustrates the combination of the frost system and the anti-icing system which share a common distribution duct having a spanwise series of holes to direct the flow toward the wing leading edge. In the frosting mode of operation, the return flow through the auxiliary spar mixes with the primary flow of N_2 in proportions controlled by the characteristics of the ejector nozzle to yield the proper leading edge temperature. The pressure bleed valve is used to maintain the appropriate pressure in the wing cavity. For the anti-icing mode, engine bleed air is mixed with the return flow in a similar manner to provide a controlled temperature as required.

In addition to the leading edge insect protection and anti-icing systems described above, the LFC suction air must be conveniently routed to the suction unit. Since the suction rates in the leading edge area tend to be high, with correspondingly smaller slot spacing, it has been found desirable to provide plenum type ducts for both upper and lower surfaces in this area, since individual ducts serving each slot would tend to physically interfere. Figure 24 shows a workable arrangement for the portion ahead of the front spar which can be used with many of the structural concepts previously discussed. Honeycomb sandwich panels are used for both upper and lower surfaces and the divider separating the plenum ducts. The nose portion ahead of the auxiliary spar contains no slots and is made of titanium to minimize erosion problems and susceptibility to other damage. The distribution duct in this area serves the function described above for the frost/anti-icing system with the nose cavity providing the return path. No return flow crosses the auxiliary spar in this case.

AIRPLANE DESIGN REQUIREMENTS AND ALTERNATIVES

Airplane design requirements appropriate to long-range LFC transports were discussed briefly in connection with the presentation of the configuration shown in figure 1. Based on operational requirements studies to date, cruise altitude and climb capability under turbulent flow conditions emerge as controlling factors in the design which largely determine wing loading and thrust loading. Because of this, the takeoff distance and approach speed requirements no longer tend to dominate as in the case of the turbulent airplane. The way in which these factors interact will be illustrated in relation to the important configuration parameters such as wing loading, aspect ratio, sweep, etc., in the following discussion. Before doing this, however, it should be pointed out that the baseline airplane is the product of a design cycle involving a number of preliminary trade studies such as required to determine extent of laminarization, high lift system configuration, engine location, empennage configuration and other features. Thus, for example, laminar area on the wing has been defined to extend to 80% chord on the upper surface and 70% chord on the lower surface. This relationship works out to be appropriate because high suction requirements in the trailing edge area lead to only marginal net benefits for laminarization beyond the points chosen. This turns out to be compatible with smaller chord flaps and spoilers than normally found useful, because low speed requirements are no longer critical.

For a laminar airplane, the choice of wing sweep turns out to be strongly influenced by considerations which relate directly to the maintenance of laminar flow in the critical leading edge area. Reducing sweep is beneficial from this standpoint since it reduces the requirement for suction quantity and allows the placement of the first slot further downstream where there is less susceptibility to erosion and other incidental damage. On the other hand, increasing sweep allows greater wing thickness, reduced weight and better accessibility. A final selection of wing sweep will have to be based on a balanced compromise and supported by extensive analyses and wind tunnel tests still to be accomplished.

Returning to a consideration of the primary factors governing airplane configuration, it is appropriate to choose an example illustrating some fundamental relationships when wing sweep and aspect ratio are fixed. Although the 15° swept wing configuration was selected for illustration, trade studies show that very similar trends exist for the 25° swept wing (baseline) which has somewhat better levels of performance and DOC. Thus, the principal effects of cruise altitude on performance and direct operating costs (DOC) are shown in figure 25. Here it is apparent that increasing altitude substantially increases gross weight because engine size and wing area must increase to permit flight at higher altitudes. At some value of wing loading, there is a minimum gross weight for each altitude which occurs at progressively lower wing loadings as altitude increases. Corresponding relationships are evident for block fuel as a function of altitude. When the effects on DOC are examined, it is apparent that DOC variations more closely parallel those for gross weight as is usually the case when payload is held constant. Since the effects of altitude on DOC are significant, it is important to consider carefully the factors which tend to dictate high cruise altitude. Since the prevalence of ice crystals is of major concern, there currently appears to be no reasonable basis to relax the requirement for cruise above 12 200 m (40 000 ft). Nevertheless, it is necessary to continually seek ways of alleviating this requirement. The acquisition of further data in global areas of the major airline routes may provide better guidance toward the final resolution of this question.

With a provisional selection of wing sweep, a choice of wing aspect ratio in combination with wing loading must be made and expansion of studies like that discussed above to include other aspect ratios is required. Recently completed analyses show the significant relationships when plotted in the form given in figure 26. This is constructed by selecting points from the relative DOC curves for each altitude to correspond to a .5% increase in DOC from the minimum value. Since there are two such points for each curve, the one with the lowest value of wing loading is selected. This results in less block fuel in all cases providing a hedge against possible rises in relative fuel costs. The upper plot shows that the DOC is nearly independent of aspect ratio but sensitive to increasing altitude as seen previously. Also, higher altitudes correspond to lower wing loadings as do lower aspect ratios.

On the other hand, as shown in the lower half of figure 26, block fuel levels are generally sensitive to aspect ratio changes, decreasing significantly with increase in aspect ratio. Thus, with a given requirement for cruise altitude (e.g., 12 800 m (42 000 ft)) the choice would tend to hinge on the potential for fuel saving which favors higher aspect ratio. Studies of this type are usually based on strength-designed wings and considerations such as flutter penalties are initially set aside, unless the selection tends to move in directions where such factors would significantly modify the conclusions. More complete analysis usually tends to show that higher aspect ratio wings (i.e., beyond 10) particularly without wing-mounted engines, are increasingly sensitive to flutter. While the acceptance of small flutter weight penalties may permit a somewhat higher aspect ratio (and performance gains), the need for a flutter suppression system as much higher aspect ratios are approached is increasingly likely. Thus, a conservative choice would be aspect ratio 10 corresponding to a wing loading of about 4.3 kPa (95 psf) for a cruise altitude of 12 800 m (42 200 ft). This selection would have the added advantage that smaller chord and simpler flaps could be used and thus reduce weight, cost, and complexity. This is possible because the approach speed requirement is not critical in the range of interest and permits the use of less effective but simpler high-lift systems. While the above conclusions tend to appear definitive, it should be recognized that results are sensitive to requirements and the state of LFC technology development at any given time. Consequently, conclusions may change somewhat, hopefully in the direction of improving DOC and fuel usage.

CONCLUDING REMARKS

Significant results of the NASA-sponsored LFC technology development effort continue to show progress and to indicate the potential for airplane operating cost reductions and substantial fuel savings. Airplane design work actively supports this development by following closely or anticipating technology advances and solutions to critical problems.

Recent advances in laminar boundary layer development and stability theory provide important new aids for the aerodynamic design of LFC wings. There is, however, a need for further validation and automation of methods to facilitate design decisions. New methods are needed to analyze the local effects of flow through suction surfaces including disturbances generated in this process. Ultimately, a complete three-dimensional analysis involving all possible modes including sound, may be necessary to provide a valid theoretical basis for predicting suction requirements in the presence of disturbances present in the flight environment.

The continuing development of advanced high-speed airfoils for modern wing design is important to provide increasing wing thickness and reduced weight with no reduction in speed. The impact of such development is even more favorable for LFC airplanes since their requirements for wing volume and controlled pressure distributions are more demanding than for turbulent airplanes.

Wind tunnel testing is an essential supporting activity which is needed to provide basic data leading to design decisions which result in airplane performance improvements. The implementation of a wind tunnel test program by Boeing and the achievement of initial test objectives represents a first step toward filling these needs and will hopefully contribute to the advancement of LFC technology.

The search for satisfactory solutions to the structural and systems problems imposed by the requirements for maintaining laminar flow has involved the consideration of a large number of alternate concepts and arrangements. This has resulted in the development of at least six major structural approaches involving the use of advanced structural arrangements and materials. These have been subjected to critical evaluation and review resulting in the preliminary selection of the laminated aluminum honeycomb concept for application in the near-term. The use of graphite/epoxy composites in wing structure has been shown to be compatible with LFC requirements and to provide outstanding weight reduction potential. However, on the basis of current and foreseeable development activity, it is considered to be applicable only in the longer term.

The major additional systems requirements due to LFC are associated with the wing suction distribution and ducting systems and the suction compressor and drive. The important options for the various elements of these systems including their location on the airplane have been evaluated and the overall arrangement selected. The suction units, each consisting of a 2-pressure level compressor with turboshaft engine drive, are located at the trailing end of each wing/body intersection.

In the category of special systems, that required to provide protection against the accumulation of insects at the wing leading edge is of critical importance. Several promising candidates for such a system have been identified and assessed for technical feasibility. These involve the use of 1) a liquid film (H_2O + anti-freeze), 2) a cryogen (LN_2) expanded into the leading edge cavity to produce frost on the leading edge, and 3) an air shield using high velocity jets. These must be subjected to further analysis and testing under simulated operational conditions.

Airplane design requirements, notably cruise altitude and turbulent climb capability, have been shown to have a major influence on the geometric definition of the long-range LFC transport to provide near-optimum performance and economics. In particular, configurations tend toward lower wing loadings and thrust loadings and somewhat higher aspect ratios than for turbulent aircraft. The wing sweep will tend toward a value which is close to optimum (25° sweep at Mach .8) without compromising reliability in the airline operational environment.

It is recognized that the work under existing Phase I contracts represents only a start toward full-scale system design and that further work is required in technology development and testing of advanced structural and systems concepts. The LFC program should continue to focus on hardware design and development leading to construction of a validator airplane. This is essential to provide the practical experience needed to determine the operational and economic feasibility of introducing LFC transport aircraft onto commercial airline routes in the foreseeable future.

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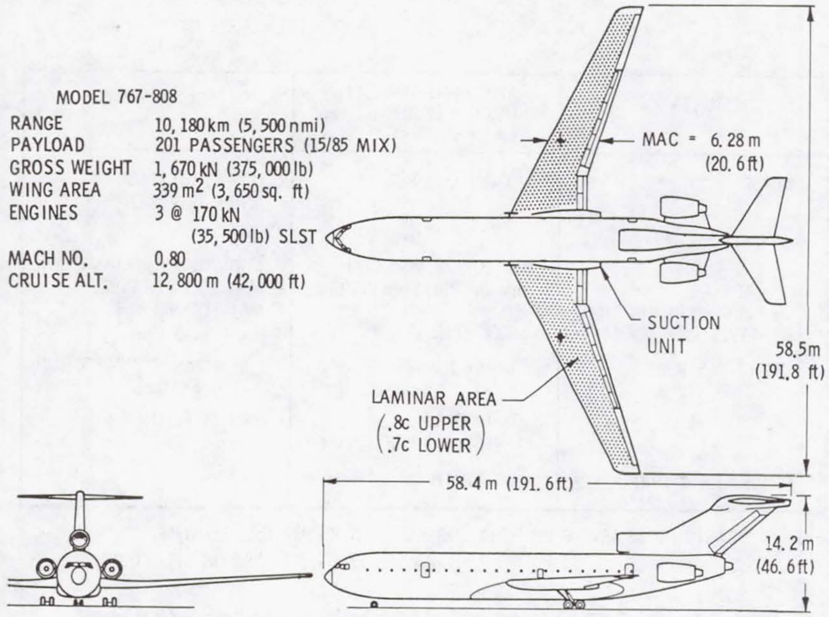


Figure 1.- LFC transport configuration.

	CLASSIC METHODS	CURRENT APPROACH	FUTURE
BOUNDARY LAYER DEVELOPMENT	INFINITE YAWED WING ($R_{\theta_{a.l.}}$ < 100 TO 200)	• TAPERED WING/COMPR. FLOW (COMPUTERIZED METHODS) • ATTACHMENT LINE BOUNDARY LAYER STARTING POINT FOR STABILITY ANALYSIS	POSSIBLE MINOR IMPROVEMENTS
TURBULENT BOUNDARY LAYER CONTAMINATION	• REDUCE SWEEP OR L.E. RADIUS • USE FENCE, BUMP OR NOTCH	SAME	?
BOUNDARY LAYER STABILITY	• CROSS FLOW AMPLIFICATION ($\psi \doteq -90^0$) • TANGENTIAL FLOW AMPLIFICATION (TOLLMIEN - SCHLICHTING, $\psi = 0^0$) • ESTABLISH SUCTION DISTRIBUTION (AREA SUCTION MODEL)	• BOUNDARY LAYER AMPLIFICATION (WAVE ANGLE ψ, FREQUENCY) • ALLOWABLE AMPLITUDE RATIO BASED ON ESTIMATED INITIAL DISTURBANCE LEVELS (NORMAL RANGE: e^9 TO e^{12}) • DEFINE SUCTION DISTRIBUTION (AREA SUCTION MODEL)	INCLUDE: - EFFECTS OF DISCRETE SLOTS, PERF. STRIPS, ETC. - DISTURBANCE GROWTH ANALYSIS - COMPLETE MODAL ANALYSIS INCLUDING NON-LINEAR EFFECTS

Figure 2.- Progress in boundary layer methodology.

DISTURBANCE	ALLOWABLE LEVEL AT 12,200 m (40,000 ft), MACH NO. 0.80	DESIGN IMPACT
NOISE	100 dB TO 110 dB	• ENGINE LOCATION* • NOISE TREATMENT
SURFACE IMPERFECTIONS:		
- STEPS	.2mm (DOWN)/.4mm (UP)	• STRUCTURAL DESIGN
- GAPS	2.5mm (ALONG)/5mm (ACROSS)	• MANUF. TOLERANCES
- ROUGHNESS (EROSION)	1.5mm	• MAINTENANCE
- WAVES (h/λ)	.0008 TO .0010	
INSECT RESIDUES	1.5mm TO 3mm	• L.E. CLEANING/PROTECTION SYSTEM
ICE CRYSTALS	30 μm DIA. 10^5/SEC m^2 PART. FLUX	• CRUISE ALTITUDE
ATMOSPHERIC TURBULENCE	NOT CRITICAL	

* BASIC NOISE LEVELS ON WING SURFACE: 120 dB (ENGINES ON WING)
100 dB (ENGINES ON AFT-BODY)

Figure 3.- Impact of disturbances on design.

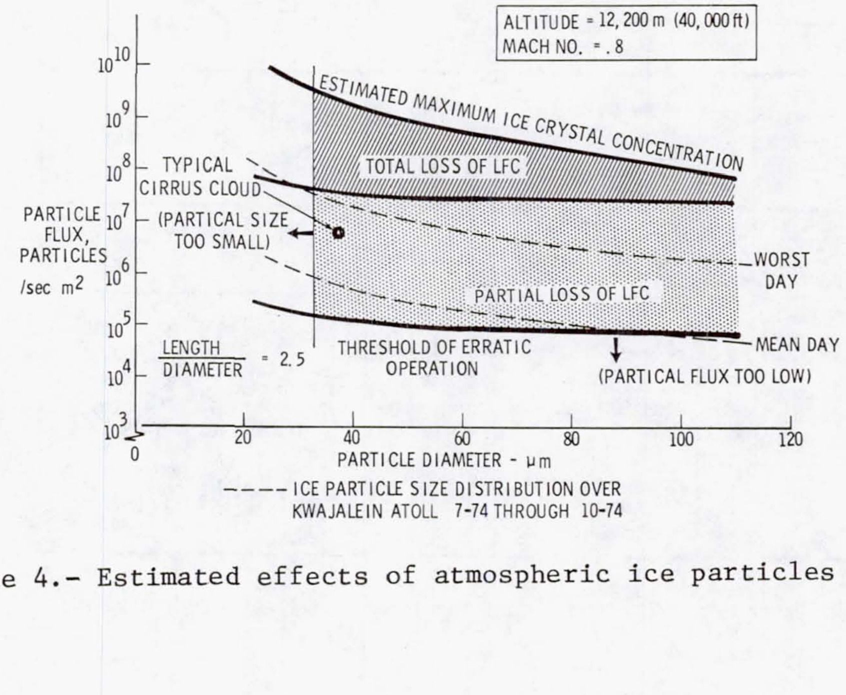
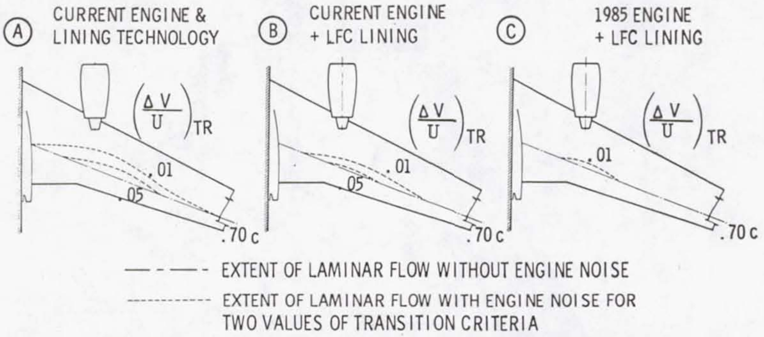


Figure 4.- Estimated effects of atmospheric ice particles on LFC.



$\left(\frac{\Delta V}{U}\right)_{TR}$	POTENTIAL LOSS OF LAMINAR AREA (LOWER SURFACE)*		
	Ⓐ	Ⓑ	Ⓒ
.01	20%	8%	2.5%
.05	7%	1.5%	0

* NORMAL SUCTION LEVELS

Figure 5.- Engine noise effects on laminarization.

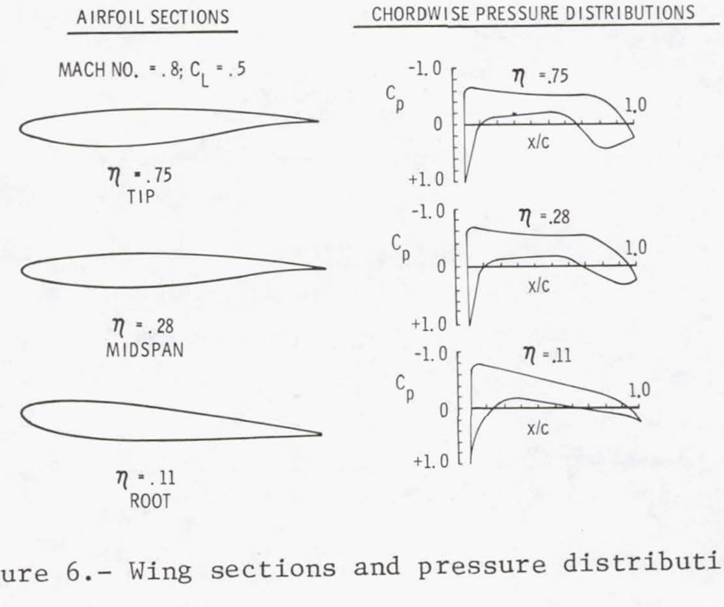


Figure 6.- Wing sections and pressure distributions.

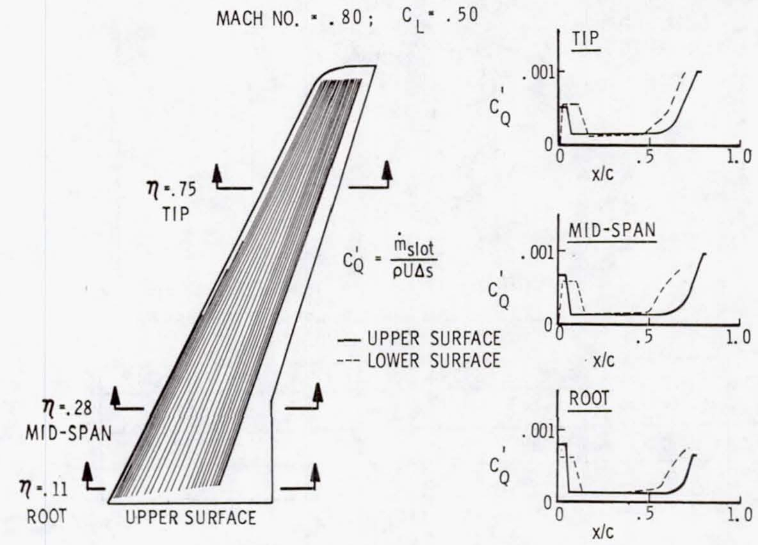


Figure 7.- Wing suction distribution.

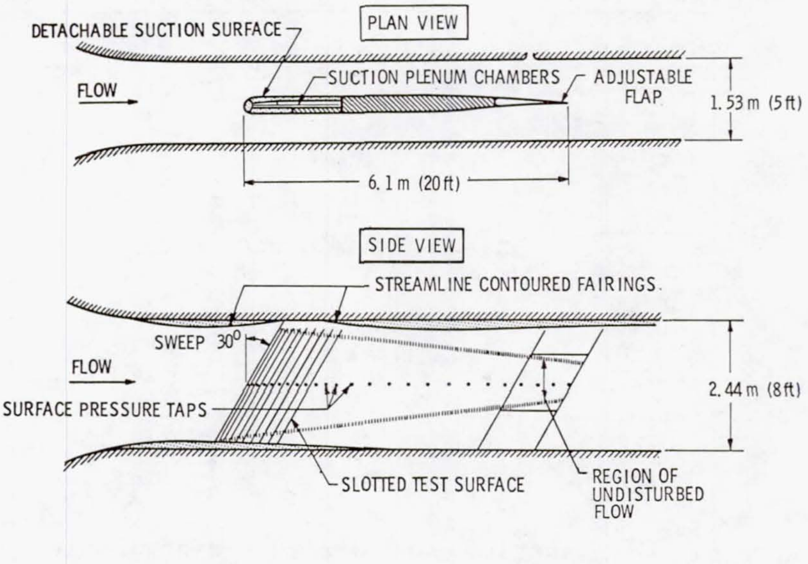


Figure 8.- LFC wing test arrangement.

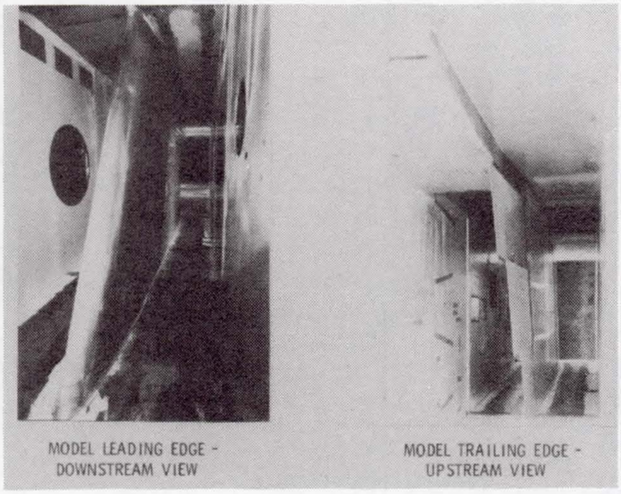


Figure 9.- LFC wing section installation Boeing research wind tunnel.

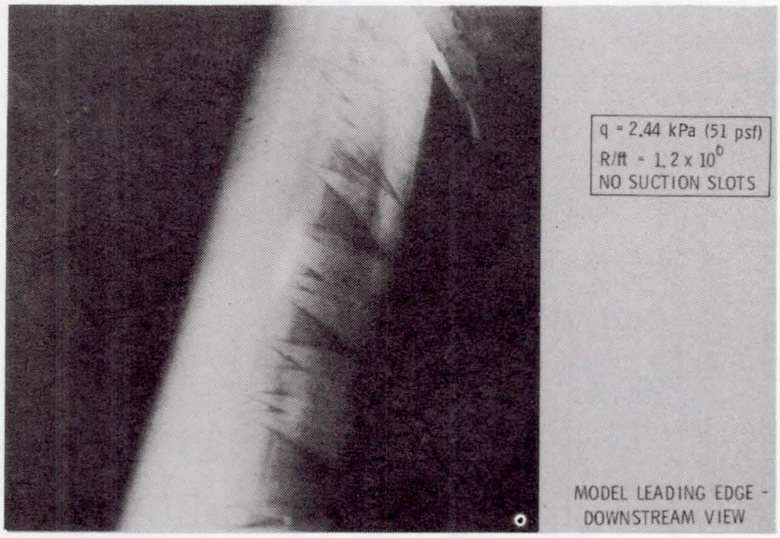


Figure 10.- Leading edge transition pattern.

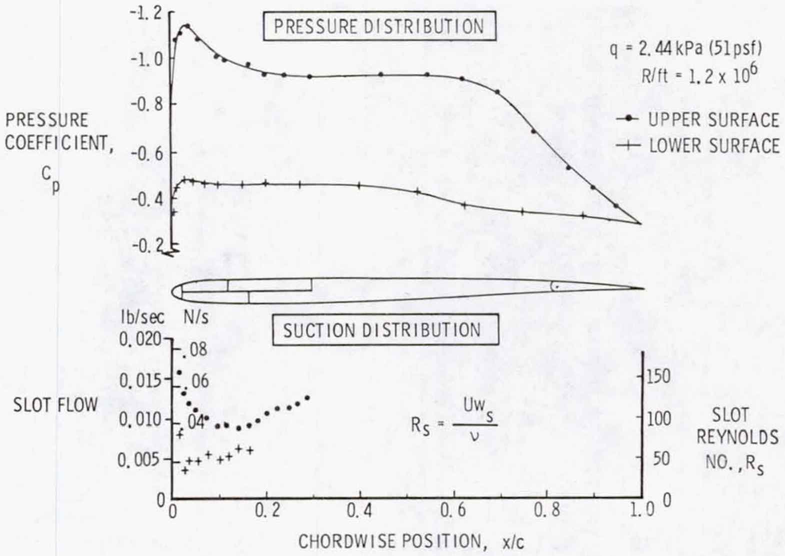


Figure 11.- LFC model test conditions.

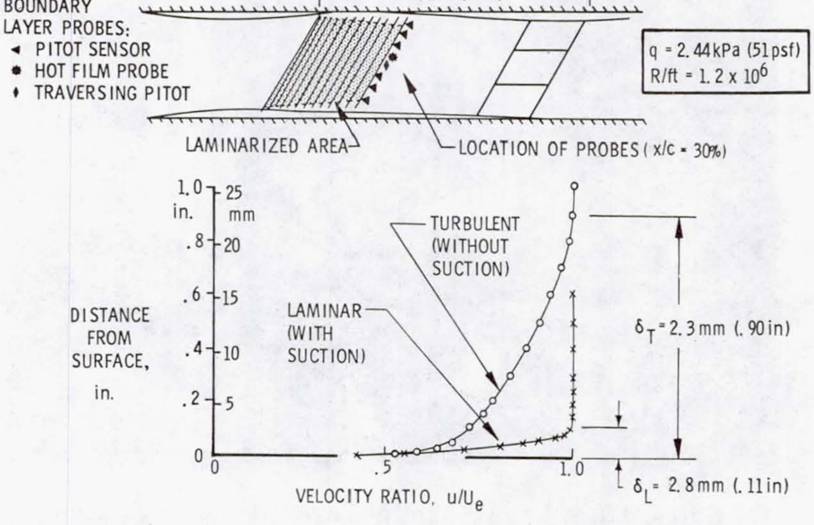


Figure 12.- Boundary layer survey results.

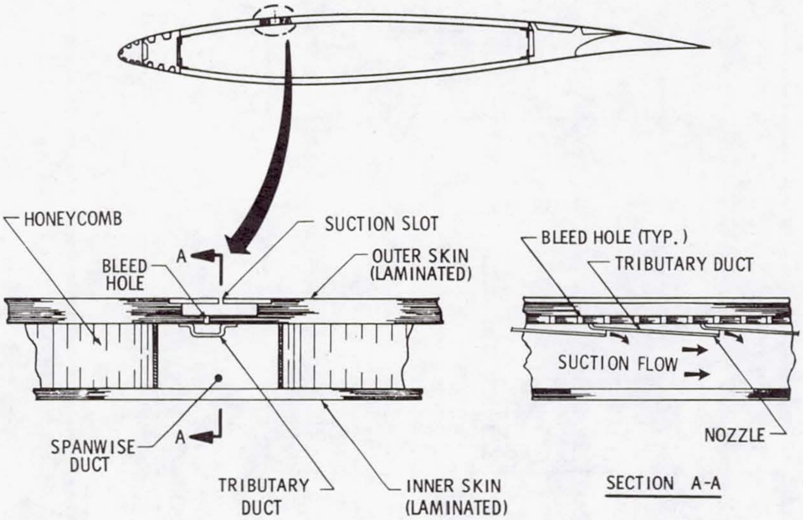


Figure 13.- Typical LFC wing section laminated aluminum honeycomb design.

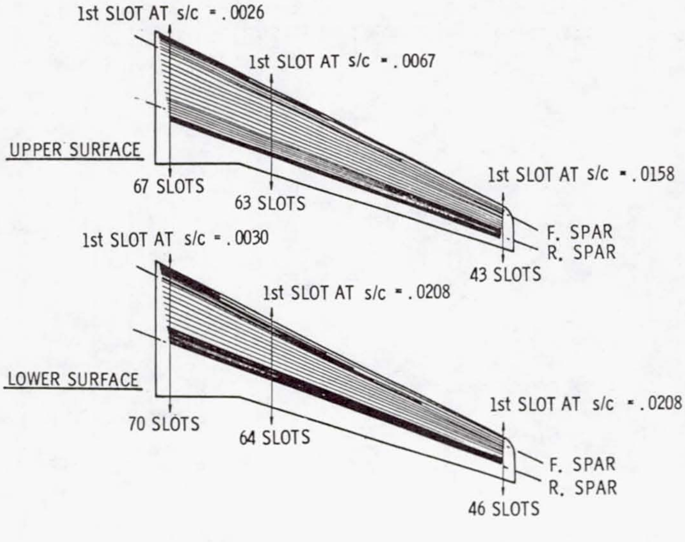


Figure 14.- Suction slot arrangement.

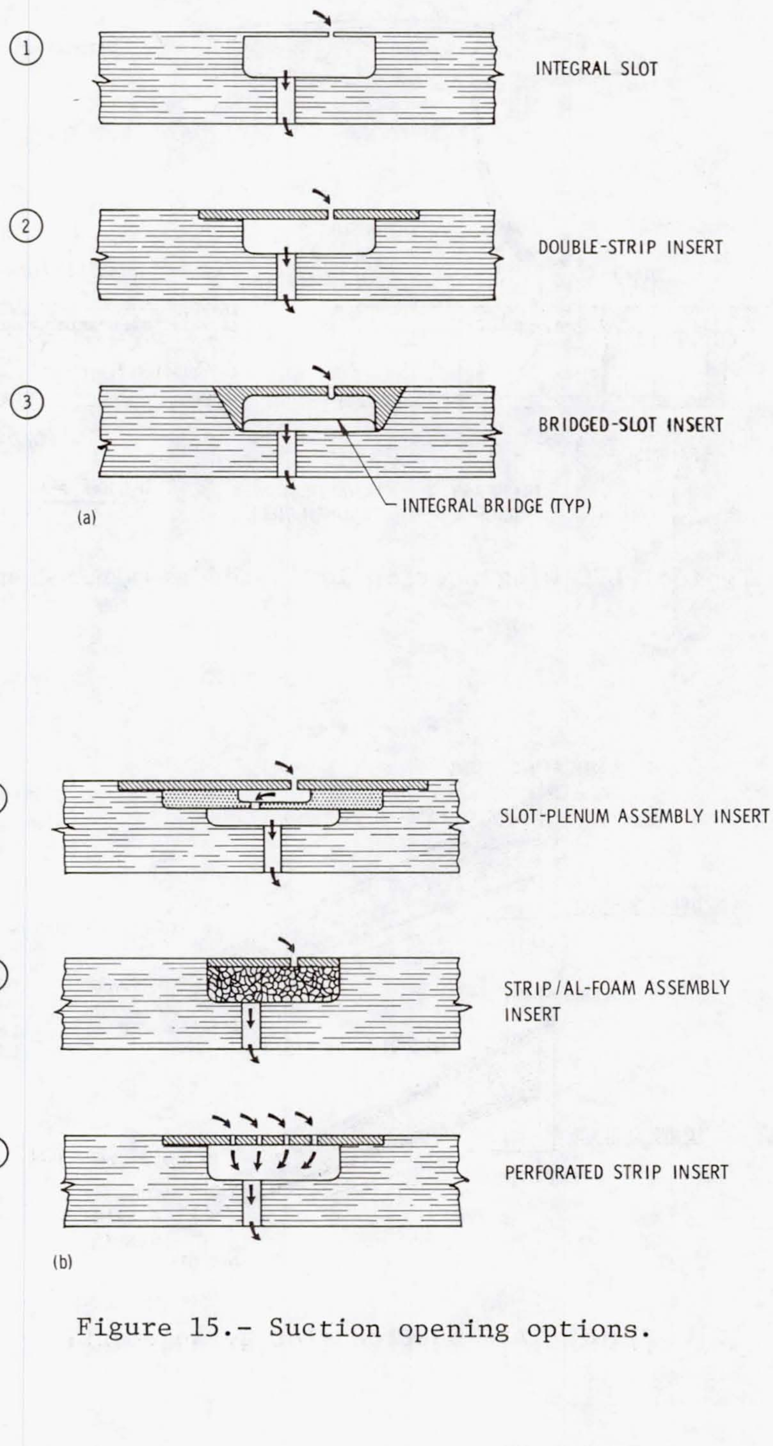


Figure 15.- Suction opening options.

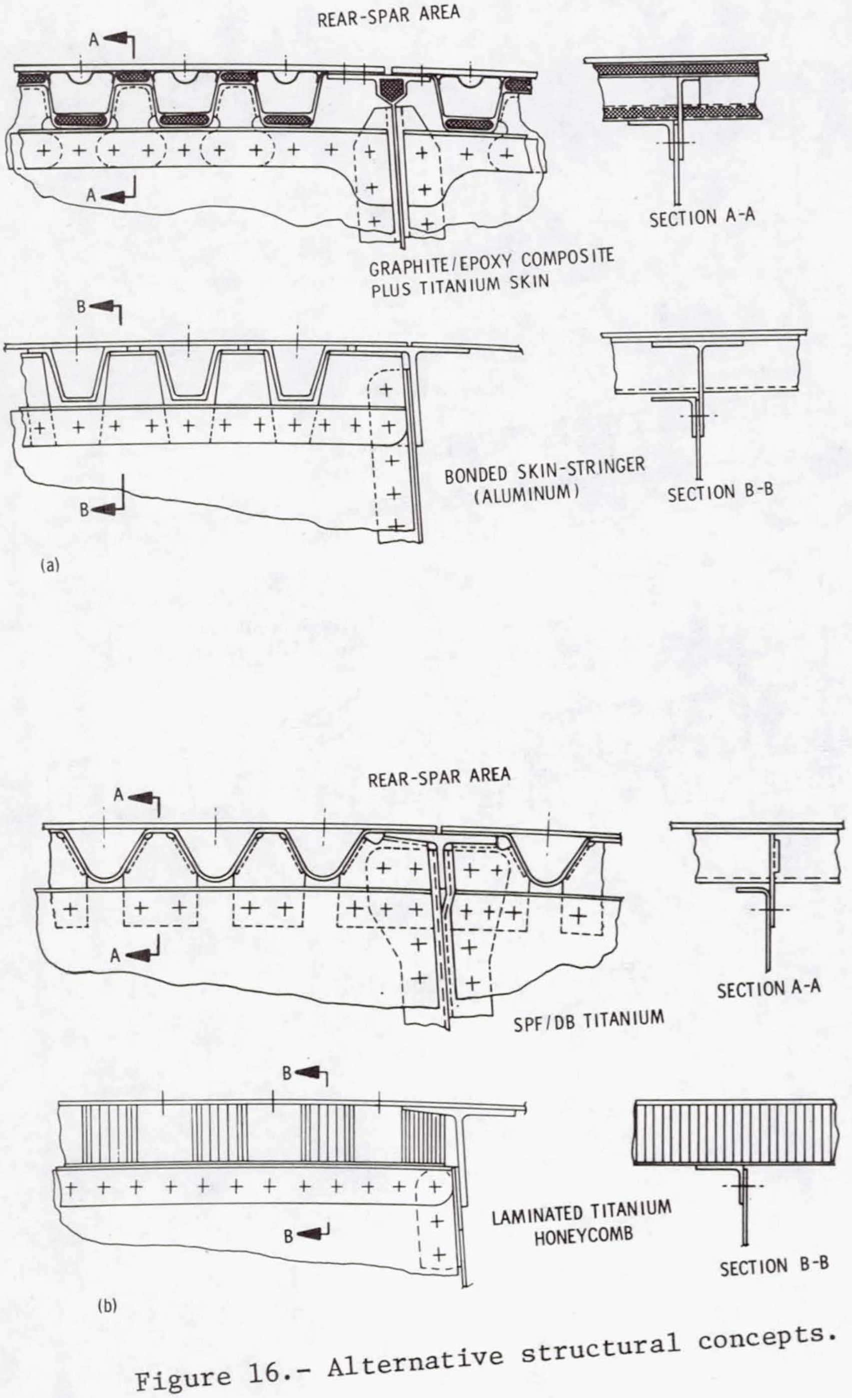


Figure 16.- Alternative structural concepts.

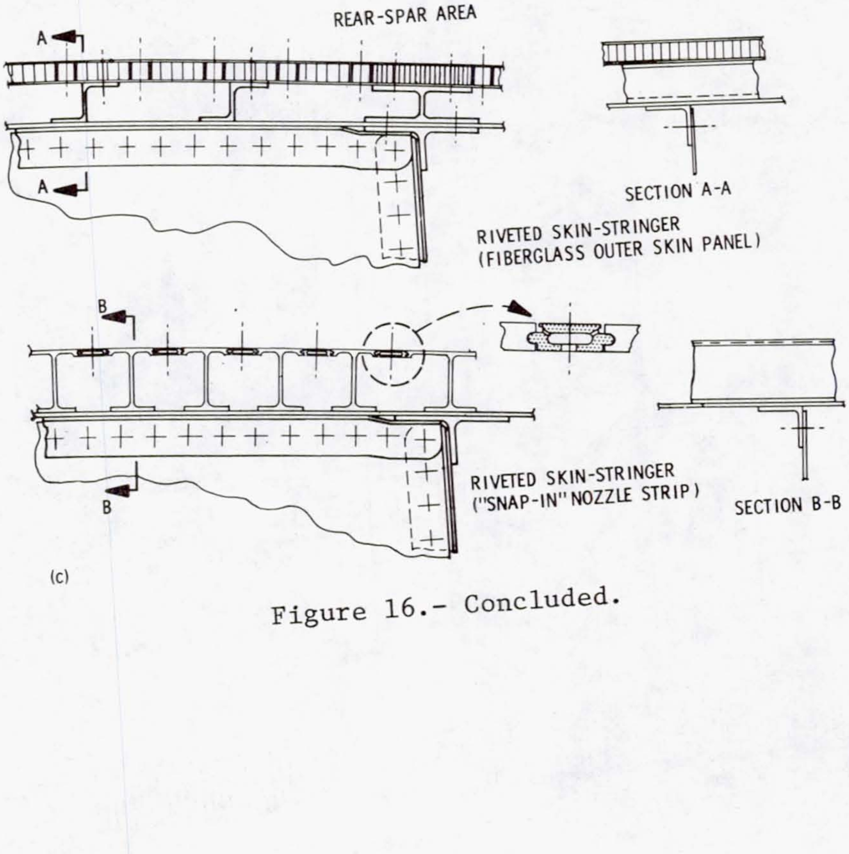


Figure 16.- Concluded.

REFERENCE: EXISTING LEVELS

	△ COMPONENT WEIGHT
ADVANCED STRUCTURES/MATERIALS	
- IMPROVED ALUMINUM ALLOYS	-7% WING BOX -4% FUSELAGE -4% EMPENNAGE
- BONDED CONSTRUCTION	-6% WING BOX -5% FUSELAGE -5% EMPENNAGE
- GRAPHITE/EPOXY COMPOSITES	-25% TRAILING EDGE SURFACES -27% WING BOX* -15% FUSELAGE* -15% EMPENNAGE*
- CARBON BRAKES	-10% LANDING GEAR

*APPLICABLE IF COMPOSITES USED IN PLACE OF IMPROVED ALLOYS AND BONDED CONSTRUCTION

Figure 17.- Advanced technology impact.

REFERENCE: EXISTING LEVELS

	△ COMP. WEIGHT	△(L/D)	△SFC
AERODYNAMICS			
- LAMINAR FLOW CONTROL	TBD	26% (41%)*	2.3% (3%)*
- ADVANCED AIRFOIL SECTION	- 14% WING BOX - 8% EMPENNAGE		
- REDUCED ROUGHNESS		2% (5%)*	
ACTIVE CONTROLS			
- REDUCED LONGITUDINAL STABILITY	- 20% HORIZ. TAIL	3%	
- LOAD ALLEVIATION	- 8% WING BOX		
PROPULSION			
- ADVANCED TURBOFAN (BPR = 7.5)	- 13% ENGINE		-14%

* APPLICABLE FOR LAMINARIZED WING AND EMPENNAGE

Figure 18.- Advanced technology impact.

SUCTION COMPRESSOR	DRIVE TYPE	UNIT LOCATION
• SINGLE PRESSURE LEVEL • MULTI-PRESSURE LEVEL • EXHAUST VELOCITY LEVEL	• MAIN ENGINE: - BLEED AIR/TURBINE - MECHANICAL COUPLING - ELECTRICAL - HYDRAULIC • BLEED/BURN/TURBINE • TURBOSHAFT ENGINE	• AFT-BODY - SINGLE UNIT - MULTI-UNIT
	TURBOSHAFT ENGINE	• WING - MULTI-UNIT
APU	APU	AFT-BODY * (EMPENNAGE LFC)

* ASSUMES WING-MOUNTED UNITS FOR WING SUCTION

Figure 19.- Suction unit arrangement options.

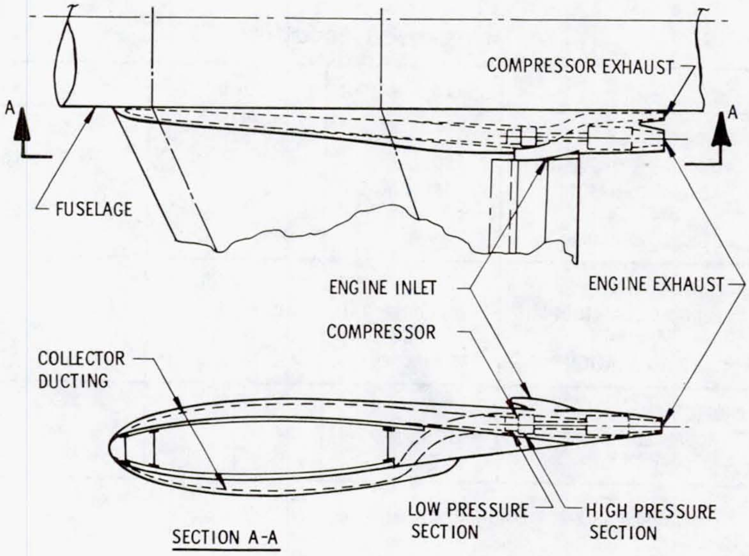
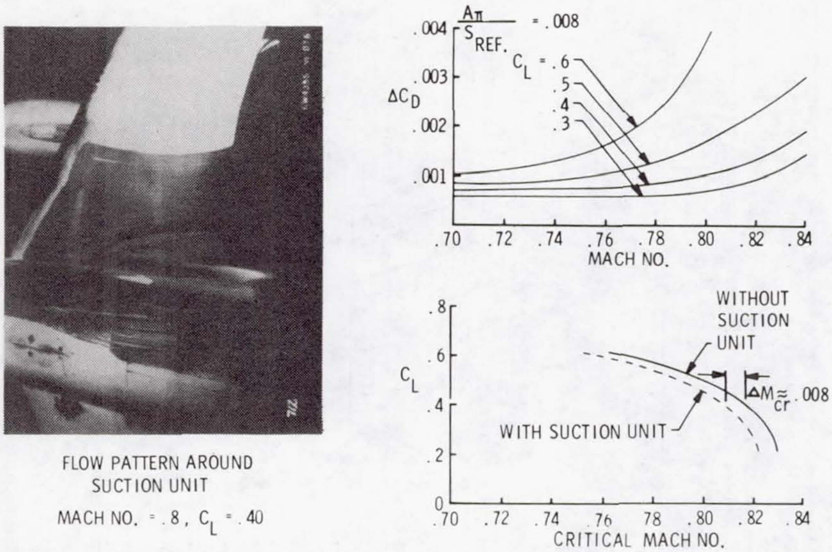


Figure 20.- Suction unit installation at wing root.



FLOW PATTERN AROUND SUCTION UNIT

MACH NO. = .8, C_L = .40

Figure 21.- Suction unit effect on drag.

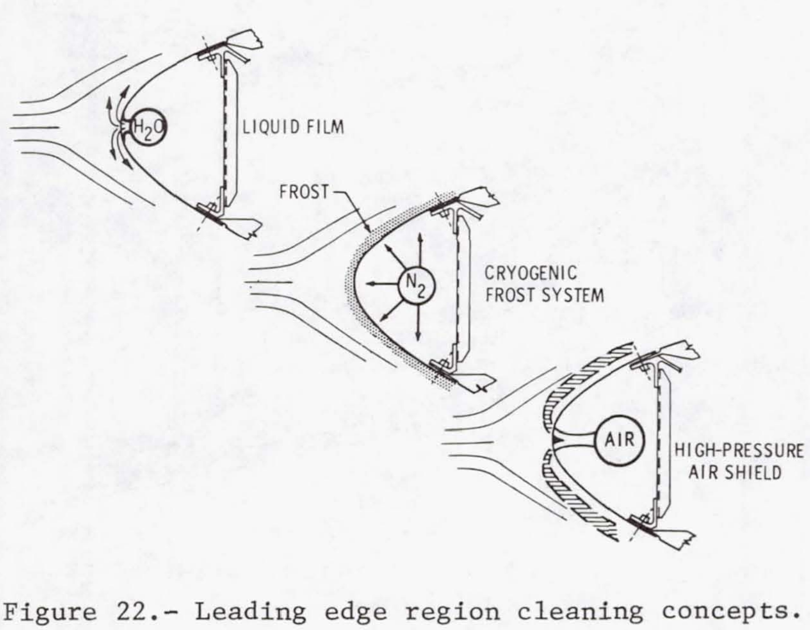


Figure 22.- Leading edge region cleaning concepts.

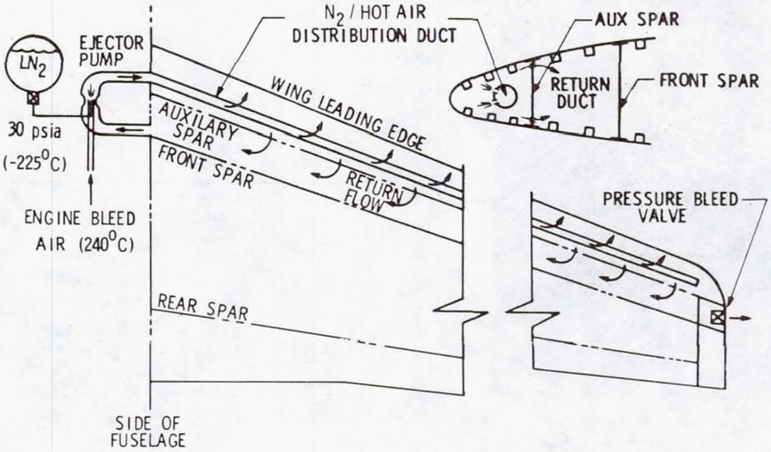


Figure 23.- Leading edge frost/anti-icing system.

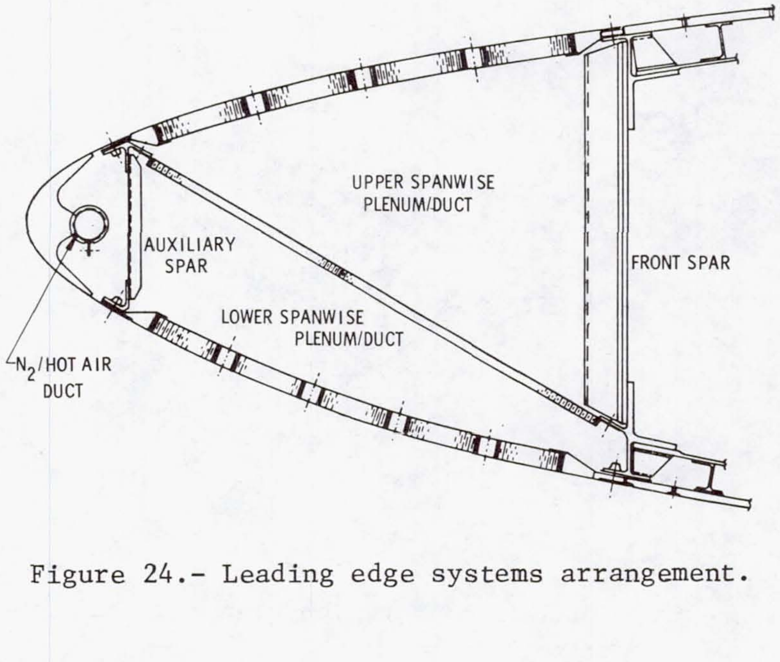


Figure 24.- Leading edge systems arrangement.

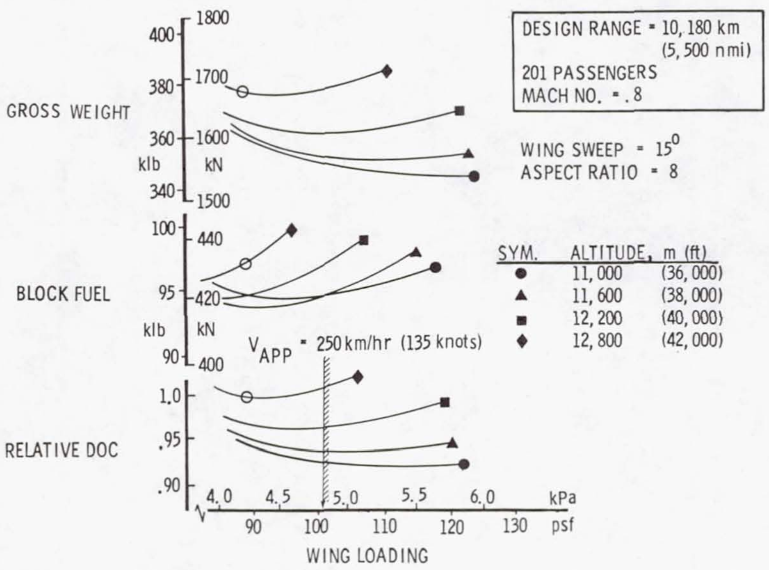


Figure 25.- Cruise altitude effects on performance and economics.

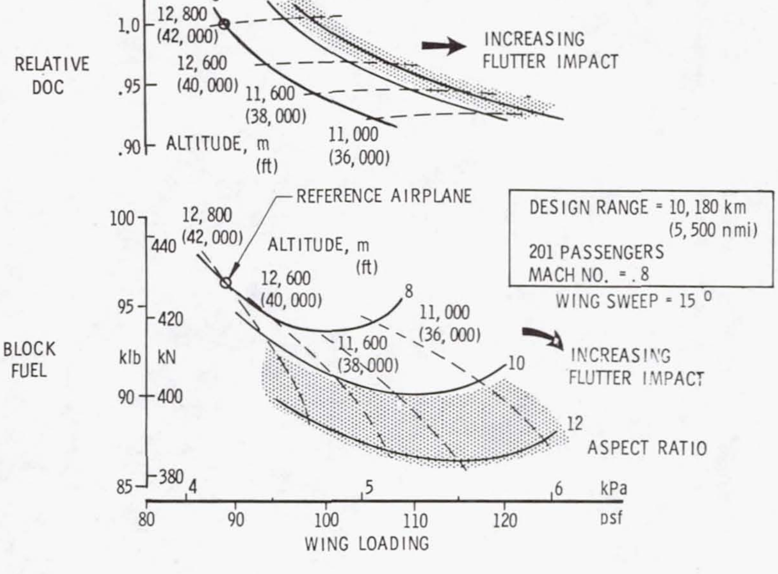


Figure 26.- Wing aspect ratio effects on doc and block fuel.