OPERATIONAL CONSIDERATIONS FOR LAMINAR FLOW AIRCRAFT

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SUMMARY

Considerable progress has been made in the development of laminar flow technology for commercial transports during the NASA Aircraft Energy Efficiency (ACEE) laminar flow program. Practical, operational laminar flow control (LFC) systems have been designed, fabricated, and are undergoing flight testing. New materials, fabrication methods, analysis techniques, and design concepts were developed and show much promise. The laminar flow control systems now being flight tested on the NASA Jetstar aircraft are complemented by natural laminar flow flight tests to be accomplished with the F-14 variable-sweep transition flight experiment. This paper presents an overview of some operational aspects of this exciting program.

SYMBOLS

ACEE	Aircraft Energy Efficiency
D	drag
EBP	electron beam perforated
GASP	Global Atmospheric Sampling Program
G/E	graphite-epoxy
L	lift
LEFT	leading-edge flight test
LFC	laminar flow control
M	free-stream Mach number
$M(L/D)_{MAX}$	aerodynamic efficiency
NLF	natural laminar flow
PGME	propylene glycol methyl ether

INTRODUCTION

Attainment of laminar boundary layer flow over transport aircraft has significant potential for drag reduction and fuel savings. The concept originated in the 1930's when boundary layer stability analyses showed that laminar flow could be stabilized by either a favorable pressure gradient or by a small amount of wall suction. Many efforts have been undertaken to achieve laminar flow using these two methods. Pressure gradient stabilization became known as natural laminar flow (NLF) and led to the development of the 6-series NACA natural laminar flow airfoils. Suction stabilization, referred to as laminar flow control (LFC), was intensively researched during the 1960's with flight tests of an unswept suction glove on an F-94 aircraft (ref. 1) and the swept wing X-21 tests (refs. 2-5) on a reconfigured WB-66.

Although these flight tests showed that laminar flow could be repeatedly achieved to chord Reynolds numbers as high as 47 million, LFC system maintenance and reliability concerns prevented serious consideration of LFC as a design option for aircraft at that time. In 1976, NASA initiated the Aircraft Energy Efficiency (ACEE) program to develop fuel-conserving technology for commercial transports. One program objective was to expand viscous drag reduction technology through laminar flow control applications. Although including LFC as part of the ACEE effort was based on previous flight success, other prime considerations were the large potential LFC fuel saving coupled with the impact of increasing fuel price on airline economics. New materials, fabrication techniques, and airfoil technology developed since the X-21 program offered hope of resolving practical concerns such as the need to produce and maintain smooth wing surfaces during typical airline flight operations. Throughout the ACEE program, NASA worked closely with industry. Impressive progress was made, particularly in the areas of practical LFC leading-edge systems and wing construction. These developments could lead to near-term application of laminar flow technology.

OPERATIONAL CONSIDERATIONS

Important factors that can affect the transition of a boundary layer from laminar to turbulent flow are given in figure 1. Most fundamental are the Reynolds number at which laminar flow becomes turbulent, the degree of wing sweep used, and the airfoil geometry. If velocity and altitude are constant, the larger the airplane, the higher the Reynolds number, and the more difficult it is to keep flow laminar over significant lengths of wing chord. If the airplane is also designed for high speed, weight considerations dictate that the wing have a significant degree of sweep. Sweep introduces three dimensional cross-flow boundary layer disturbances that may amplify, interact with two dimensional Tollmien-Schlichting waves, and cause transition. Airfoil geometry determines both favorable pressure gradient extent and suction requirements needed for boundary layer stabilization. Ideally, a laminar flow wing should achieve the drag divergence Mach number, thickness ratio, and lift capability attainable with turbulent supercritical wing technology. (Some compromises may be necessary to achieve extensive lengths of favorable pressure gradient.) New aircraft materials such as graphite-epoxy composites offer the promise of wing sections of nearly perfect shape, tolerance, and smoothness at reasonable cost -- provided fabrication methods and deformation under load result in surface deviations small enough to prevent occurrence of local pressure waves which can cause transition (ref. 6). Propulsion system noise is another disturbance source which can be amplified by the boundary layer and lead to transition. Other operational concerns include the surface suction system (used to stabilize the wing boundary layer) which typically has very fine surface openings that must be easy to clean and repair while resistant to clogging and corrosion. Atmospheric conditions such as ice crystals and rain are known to influence boundary layer stability and must be thoroughly studied, since a fleet of LFC aircraft would operate throughout the world at a variety of climates, altitudes, and weather conditions.

Insect impacts in the leading-edge region are a particular concern, since surface residue can prevent attainment of laminar flow during cruise. Some preliminary answers to the insect contamination question were provided by NASA flight tests early in the LFC program with the NASA Jetstar aircraft (ref. 7). These tests also evaluated the effectiveness of superslick surface coatings and a liquid spray washing system for preventing or minimizing insect contamination. An outboard wing leading-edge test panel (with four chordwise strips of different surface coatings) was equipped with upper surface total head tubes to detect transition in the leading edge, and with lower surface water spray nozzles to coat both upper and lower surfaces with protective fluid film. Airline-type flights conducted at major U.S. airports (with no protective spray) indicated that insects can contaminate the wing leading edge and prevent laminar flow. Surface coatings (Teflon tape and spray-on, organo-silicone, and radome rain repellant) were not effective in preventing contamination. Degree of contamination experienced was seasonal and dependent on geographical location (ref. 8). Flights in agricultural areas heavily populated with insects showed that water spray injection which maintained a wet surface was effective in preventing leading edge insect contamination. This preliminary work indicated that a prudent course would be to develop and test a practical anti-contamination system.

Laminar flow impact on aerodynamic performance is given in figure 2 for a transport aircraft designed for a speed of $M = 0.75$, a Reynolds number of about 27 million, and a sweep of 27.5 degrees (ref. 9). If laminar flow extends over the entire wing section, more than an 80 percent profile drag reduction is possible -- with two-thirds of the reduction resulting from the upper surface. NASA-sponsored work by aircraft manufacturers quantified the effect of laminar flow loss on aircraft performance. Some results for aerodynamic efficiency, $M(L/D)_{MAX}$, are given in figure 2. Aerodynamic efficiency increases from 16 to over 20 for the full-chord laminar flow case. Conversely, should operations result in laminar flow loss, performance deterioration will be equally dramatic -- but acceptable. Maximum range is reduced from 6500 nmi to about 5200 nmi (fig. 3) for a Lockheed-Georgia-designed 400-passenger, $M = 0.80$ aircraft (ref. 8). Detection of laminar flow loss and flight management will be necessary in such circumstances.

LAMINAR FLOW CONTROL SYSTEMS

Prevention of laminar flow loss will depend heavily on the systems provided by the designer. Over the course of the ACEE program, NASA worked with industry to develop such systems and to incorporate them into both perforated and slotted LFC wing structure designs (fig. 4).

In the Douglas Aircraft Company (DAC) LFC concept (ref. 9), the main wing box covers are internal blade-stiffened G/E skin panels. Perforated suction panels are gloved to the main wing box, and suction air collection is external to the wing box. Suction panels are attached to generally chordwise oriented blades on the wing box cover outer surface. The blades form shallow ducts for suction air collection into trunk ducts in the leading-edge box. This collection scheme is advantageous over spanwise air collection because air flow quantity and collection distance are such that ducts can be very shallow and wing structural depth loss is minimized. Behind the rear spar and in the leading-edge box, air collection is in spanwise ducts. Suction is applied only on the upper surface wing, and a leading-edge Krueger flap is used. Acceptable low-speed aircraft performance is achieved with a small trailing-edge flap system which allows laminar flow to 85 percent chord on the wing upper surface in cruise. If suction is desired on the lower surface, the Krueger flap would not be used because of surface smoothness concerns in the stowed condition. In this instance, a powerful 30 percent chord trailing-edge flap and larger wing are required to meet acceptable low-speed performance. The trailing-edge flap limits laminar flow to 70 percent chord and the larger wing degrades cruise performance. Douglas trade studies show that upper surface laminarization is the most effective LFC suction application. Upper surface suction also provides practical solutions to potential manufacturing and maintenance concerns. The wing assembly can be accomplished from the lower surface using internal fasteners that do not penetrate the upper wing surface. Maintenance access can be done through the lower surface, and since most ducting is in the leading-edge box, ducting would be accessible by Krueger flap deployment on the ground. LFC impact damage maintenance is minimized since the upper surface is least exposed to foreign object damage. Finally, the Krueger flap can shield the leading edge from insects and debris on takeoff and landing.

Details of the Douglas perforated suction surface are given in figure 5. Surface perforations, drilled by an electron beam into titanium sheet, are finely spaced circular (or elliptic) holes as small as 0.0025 in. in diameter. Holes taper to about twice that size on the opposite surface. Figure 5 shows the remarkable regularity and circularity of the holes which are more than an order of magnitude smaller than the perforation sizes possible with practical manufacturing methods during the X-21 era. At that time, slotted suction surfaces were favored over perforations as wind tunnel and flight tests had shown that unless suction holes were very small, suction-induced flow disturbances would cause premature transition.

The tiny holes used in the DAC design mean that provisions must be made for periodically cleaning the suction surface. A steam-cleaning technique was developed with porosity results given in figure 6, for which the specimen was exposed to an airport environment for approximately 15 weeks. An initial steam-cleaning returned the sample to nearly virgin porosity, and three steam-cleanings returned air passage to the initial ultrasonic cleaning level.

Contamination prevention efforts include use of a cleaning fluid consisting of 60 percent PGME and 40 percent water during takeoff and at low altitudes in both Douglas and Lockheed concepts. Use of cleaning fluid may require purging systems to clear suction ducting. Douglas ground tests show a purging pressure near 1 psig (fig. 7) is sufficient to rapidly clear both suction ducting and surface.

In the Lockheed-Georgia Company concept (refs. 8, 10, 11), the LFC ducting network is integrated into primary structure, and wing surface suction is through spanwise slots (fig. 4). Extensive use is made of graphite-epoxy (G/E) composite material. Primary load-carrying structure is thick G/E wing skin stiffened with G/E hat section stiffeners. Titanium sheet is bonded to G/E wing skins to present a tough, damage-tolerant, noncorrosive surface -- and for lightning protection to the substructure. After bonding, spanwise slots are cut in the titanium sheet with a high-speed steel jeweler's saw. Suction air passes through the slots into small plenums molded into the G/E skins and then through metering holes to spanwise ducts formed by the hat stiffeners. At every other rib station, suction air is metered into ducts formed by rib caps of truss ribs. The rib cap ducts penetrate the front spar web to transfer suction air into trunk ducts in the leading-edge box. Trunk ducts collect suction air into suction pumps driven by independent gas turbine power units; both pumps and power units are located under the wing roots. To evaluate the wing-box design, an extensive fabrication and testing program examined materials, adhesives, cure process variables, structural characteristics, and fabrication techniques. No significant problems were uncovered.

Investigations of laminar flow loss from, for example, leading-edge surface roughness caused by insect impact, were made in wind tunnels by both Douglas and

Lockheed-Georgia. Conditions were representative of the altitude and speed of subsonic transport operations.

The Douglas approach used the Krueger high-lift flap as a protective shield against insect impact. Tests (ref. 9) in the NASA Lewis Icing Research Tunnel (fig. 8) evaluated Krueger effectiveness in protecting the leading edge from insect contamination. These tests (supported by trajectory analysis) demonstrated that the Krueger flap serves as an effective line-of-sight shield for heavy insects (fig. 9) and suggest that a supplemental spray might be necessary to protect against possible impingement of lighter insects in some wing areas. In particular, wing twist can result in direct impacts in the outboard region, and high inboard lift can deflect lighter insects onto the wing.

The Lockheed approach injects cleaning fluid through slots above and below the attachment line. Concept feasibility was verified during wind tunnel tests in their low-speed wind tunnel facility (ref. 8). A partial-span full-scale leading-edge section was subjected to insects injected in the tunnel free stream at number densities much higher than expected at actual flight takeoff and landing conditions. Cleaning fluid injected through leading-edge slots completely covered and protected upper and lower surfaces. Insects did not adhere to the wet surface.

Together, the Douglas and Lockheed tests show that although the need for an active "anti-contamination" system is not conclusive, the prudent course would be to develop potential systems and assess their need in actual operations.

LEADING-EDGE FLIGHT TEST OPERATIONS

Integration of either the Douglas or Lockheed concepts with insect protection, leading edge anti-icing, and suction systems is a formidable design challenge. Indeed, most difficult problems in achieving laminar flow on commercial transports are associated with the leading edge. Practical solutions to these problems will remove many laminar flow concerns. A laminar flow control Leading-Edge Flight Test (LEFT) was therefore begun to evaluate the effectiveness of integrated leading-edge LFC systems. Under NASA contract, both Douglas and Lockheed designed, fabricated, and installed on a Jetstar aircraft LFC leading-edge test articles (fig. 10) which demonstrate that these systems can be packaged into a leading-edge section representative of future LFC commercial transport aircraft. A further purpose was to show that these systems can operate reliably with minimum maintenance in an airline-type flight environment.

The Douglas leading-edge concept (fig. 11) consists of an electron-beam perforated (EBP) titanium sheet bonded to a fiberglass sandwich substructure which forms a removable suction panel (refs. 12, 13) attached to ribbed supporting substructure. Areas where the EBP skin bonds to the corrugated substructure are impervious to flow. Thus, suction is through perforated strips. Alternate substructure flutes are used for suction air collection. Suction is applied only on the upper surface from just below the attachment line to the front spar. The Krueger-type flap protects against insect impact. Supplemental spray nozzles on the underside of the Krueger flap coat the leading edge with a fluid freezing point depressant to guard against impingement of lighter insects. In icing conditions, the Krueger flap serves as the primary leading-edge anti-icing protection system -- supplemented as required with spray nozzles. The shield leading edge is equipped with a commercially available ice protection system. As previously discussed, a system for purging fluid from the suction flutes and surface perforations is provided.

The Lockheed leading-edge concept is illustrated in figure 12 (ref. 14). The leading-edge box structure is of sandwich construction with 0.016-in. thick titanium outer sheet bonded to a substructure of graphite-epoxy face sheets with a Nomex-honeycomb core. Suction is through fine spanwise slots (0.004-in. width) on both upper and lower surfaces and extends to the front spar. Suction flow is routed through the structure by a combination of slot ducts, metering holes, and collector ducts embedded in the honeycomb. The insect protection system is integrated with the anti-icing system and dispenses a cleaning/anti-icing fluid over the surface through slots above and below the attachment line. Slots which provide suction to achieve laminar boundary layer flow at cruise are purged of fluid during climbout. Actual fabrication of this configuration presented some extremely difficult problems that led to a suction surface only marginally acceptable in meeting LFC smoothness and waviness criteria (see ref. 14).

Flight acceptance testing on the LEFT aircraft began in late 1983 at the NASA Ames-Dryden Flight Research Facility. Figure 13 shows the aircraft in flight. Reference 15 contains a detailed program description.

Evaluation and optimization of the individual performance of each Jetstar LFC system are currently underway. The best laminar flow performance has been achieved on the Douglas article, but we are continuing to improve the Lockheed article performance. The aircraft will soon be placed in the simulated airline service flight testing phase wherein the aircraft operates out of "home base" areas throughout the Unites States (fig. 14). Plans are to fly two or more flights daily with test article condition and laminar flow results documented after each flight. These simulated airline service flights are designed to provide operational experience with LFC systems operated in a "hands off" mode, so that a maintenance and reliability data base can be established. In the Jetstar flight testing, the DAC test article purge begins before takeoff and continues until an altitude of about 23,000 ft is reached (fig. 15). The Lockheed slotted design also uses purging system air but only from about 6,000 to 23,000 ft. For both test articles, suction system operation begins at 32,000 ft with the surface clear of fluids.

ICE PARTICLE DEGRADATION OF LAMINAR FLOW

Laminar flow is usually lost in visible cloud penetrations. To determine visible cloud encounter probability along various airline routes, a program was initiated to study how cloud frequency varies with altitude, latitude, longitude, and season (ref. 16). Cloud-encounter data were available from the NASA Global Atmospheric Sampling Program (GASP) archive (ref. 17). In the GASP program, meteorological and trace-constituent measurements of ambient atmospheric conditions were taken worldwide aboard four Boeing 747's during routine commercial service to obtain detailed measurements of the upper troposphere and the lower stratosphere. Measurements made from 1975 to 1979 on some 3,000 flights included about 88,000 cloud encounters. Using this data, an analysis was made of LFC loss due to visible cloud encounters on major airline routes (fig. 16). Calculations assumed that all cloud encounters result in laminar flow loss and that no cloud avoidance measures (flight management) were taken. Using these conservative assumptions, results show that laminar flow should be lost at most about 8 percent of world-wide flight time (fig. 16). Hence, although infrequent, visible cloud encounters are not negligible and some flight management to avoid clouds could be desirable. This seems practical since at cruise altitudes these clouds usually occur in thin strata only a few thousand feet in depth.

During the X-21 program, it was found that high altitude ice particles could promote laminar boundary layer transition when either visible or invisible cirrus clouds were encountered. To help explain these results, Hall developed a theory to predict the effect of ice particle encounter on laminar flow (as discussed in ref. 16). Hall's theory assumes turbulent vortices shed in the wake of ice particles entering the laminar boundary layer will trigger transition (fig. 17). Key factors that determine whether a given cloud ice particle encounter will cause total, partial, or no loss of laminar flow are particle size, concentration, and residence time in the boundary layer. The theoretical analysis indicated that, for $M = 0.75$ and 40,000 ft altitude, particles smaller than 4 microns (μm) length will not impinge on the airfoil surface since aerodynamic forces predominate over inertia forces and particles follow streamlines which do not enter the boundary layer. As the ice particles become large, they penetrate the laminar boundary layer but do not cause a breakdown to turbulent flow until some critical size is attained. Concentration of particles of this critical dimension or larger will determine the persistence of boundary layer transition. Even with visibility as great as 50 miles, partial loss of laminar flow is predicted by the Hall criteria (fig. 18). This concentration certainly does not constitute a visible cloud and this suggests that the ice cloud problem is more extensive than suggested by the visible cloud analysis from the GASP program. In the X-21 program, erratic achievement of laminar flow was observed in light haze conditions, qualitatively verifying the Hall prediction. Pfenninger (ref. 18) has suggested that this effect is strongly dependent upon wing sweep. F-94 aircraft flights with a laminar flow control glove and 10 degrees of leading-edge sweep showed no evidence of erratic laminar flow due to ice crystals. (The X-21 had 33 degrees of leading-edge sweep.) To assess the ice particle problem, Jetstar flights include cloud measurements using a Knollenberg probe mounted on a pylon on the aircraft fuselage (fig. 18). Small ice particle concentrations due to cirrus conditions are monitored. These data will be correlated with the degree of laminar flow achieved.

A charge plate particle detector mounted on the leading edge of the Jetstar fuselage upper surface pylon (fig. 18) is also used to determine when ice particles impact the surface (by way of the aircraft charge produced). In earlier LFC flights, a similar device (ref. 4) detected clouds and laminar flow loss. Successful further development of this device may provide a low cost means of cloud identification and resultant laminar flow loss (for future aircraft use).

The influence of sweep will also be evaluated as part of a flight program to provide a transition data base for laminar flow wing designs (also, see ref. 19). An F-14 aircraft with variable wing sweep capability is being modified with full-span gloves to produce a range of upper wing surface pressure distributions (fig. 19). The gloves are constructed of foam and fiberglass (no suction provisions) gloved onto the existing wing surface. Gloves extend from below the attachment line to the upper surface rear spar (≈60 percent chord). The first glove is a simple fiberglass cover of the basic wing (which was a strong favorable pressure gradient). The fiberglass cover gives the wing a smooth, nearly wave-free surface which meets laminar flow criteria. Current plans are to begin flight testing of the basic wing glove in mid-1985. As part of the flight test, the Jetstar aircraft with mounted Knollenberg probe and charge patch (fig. 13) will be flown with the F-14 to allow correlation of cloud particulate size and concentration with the amount of natural laminar flow achieved (at different wing sweep angles).

CONCLUDING REMARKS

The NASA Jetstar laminar flow control leading-edge flight test program will soon provide day-to-day operational experience on laminar flow reliability and maintenance. Leading-edge suction concepts are being evaluated to resolve industry concerns about laminar flow practicality. Efforts such as the variable sweep transition flight test will provide additional insights with regard to laminar flow flight operations. Potential benefits from transport laminar flow operations are great. Accomplishments to date show that they may be achieveable.

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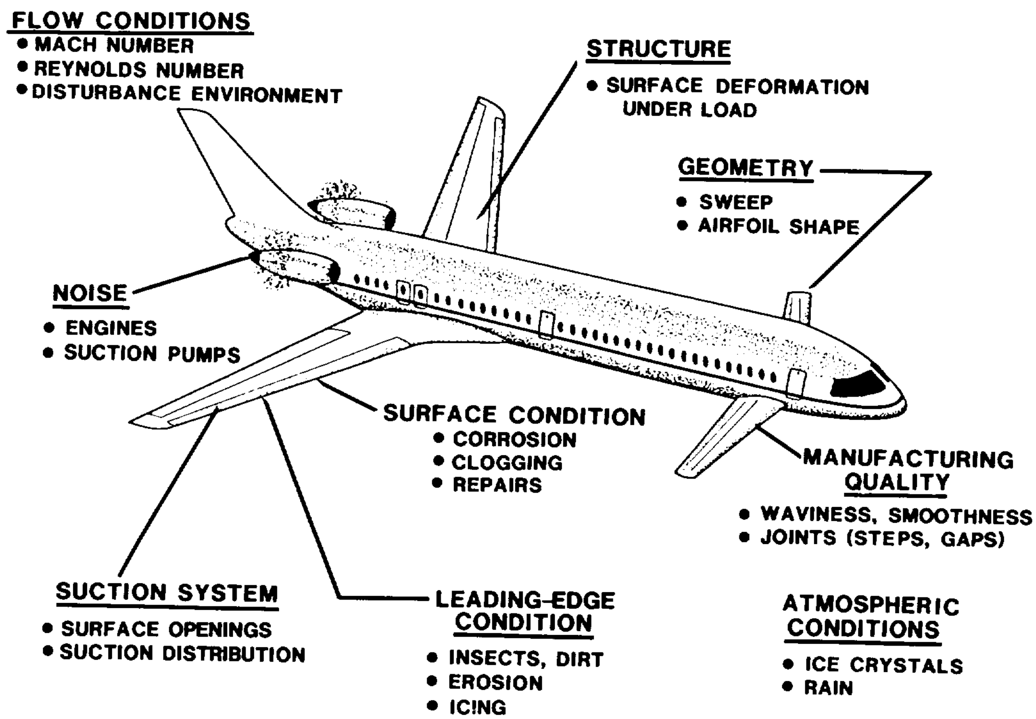

Figure 1.- Factors affecting laminar flow in flight.

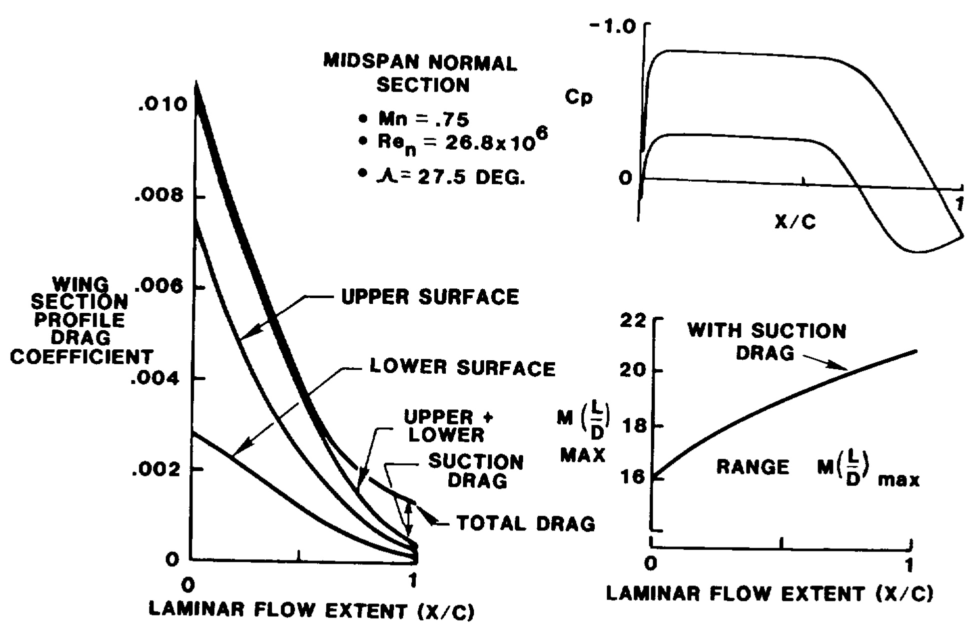

Figure 2.- Wing performance versus extent of laminar flow.

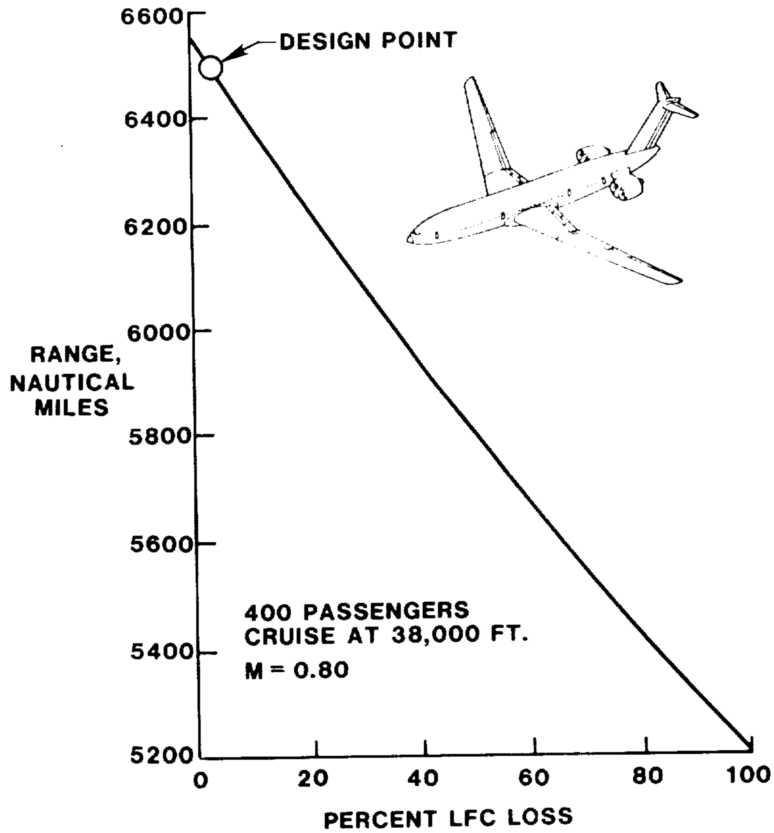

Figure 3.- Effect of laminar flow control system loss on range capability.

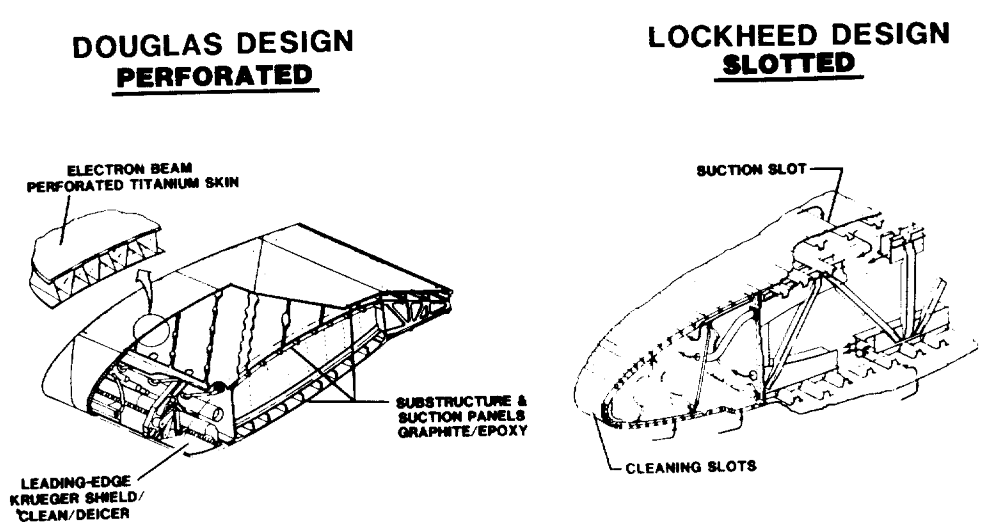

Figure 4.- Laminar flow control structural development.

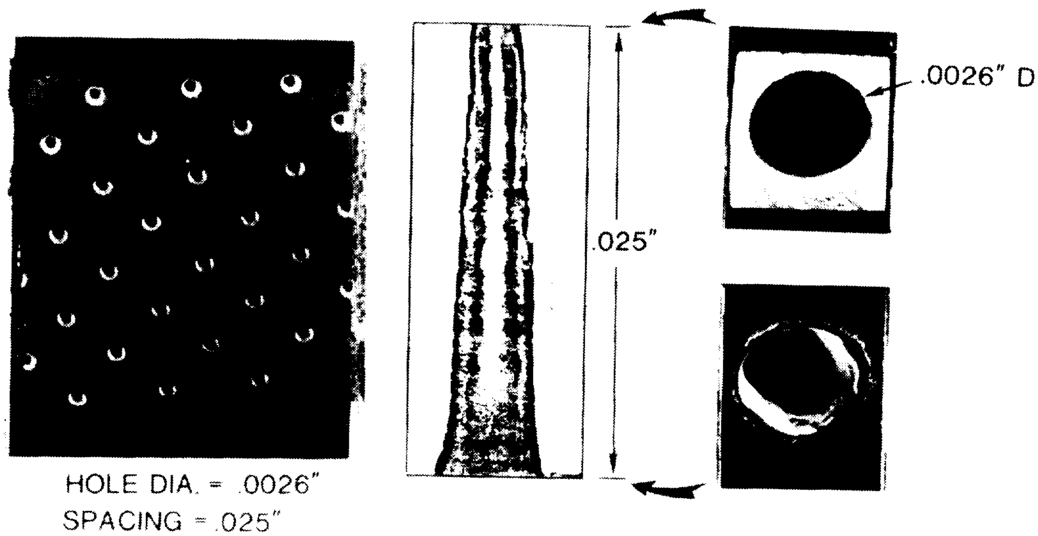

Figure 5.- Microphotograph of electron beam perforated holes.

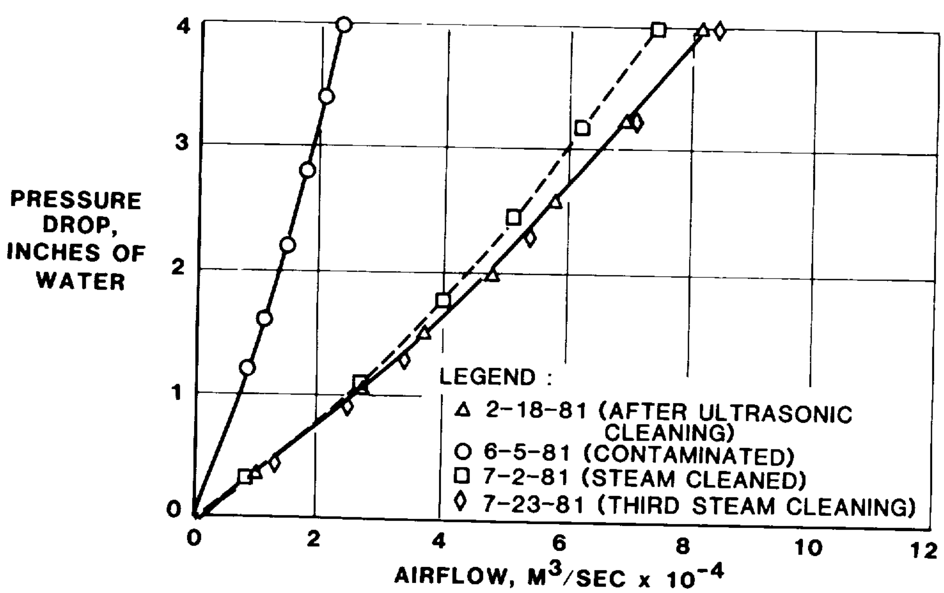

Figure 6.- Electron beam perforated titanium cleaning techniques.

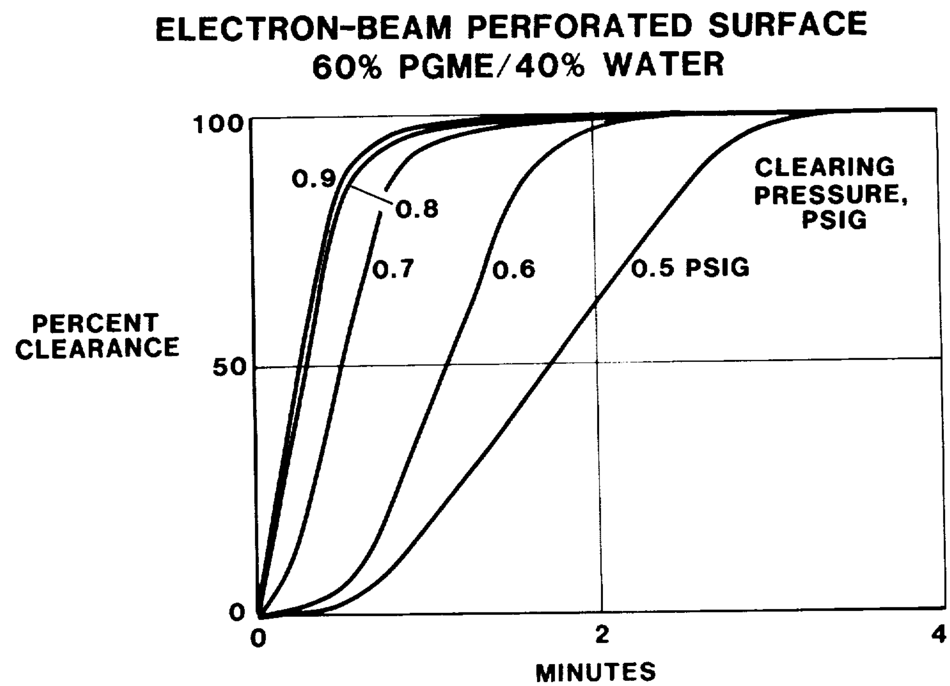

Figure 7.- Electron beam perforated surface purging system results.

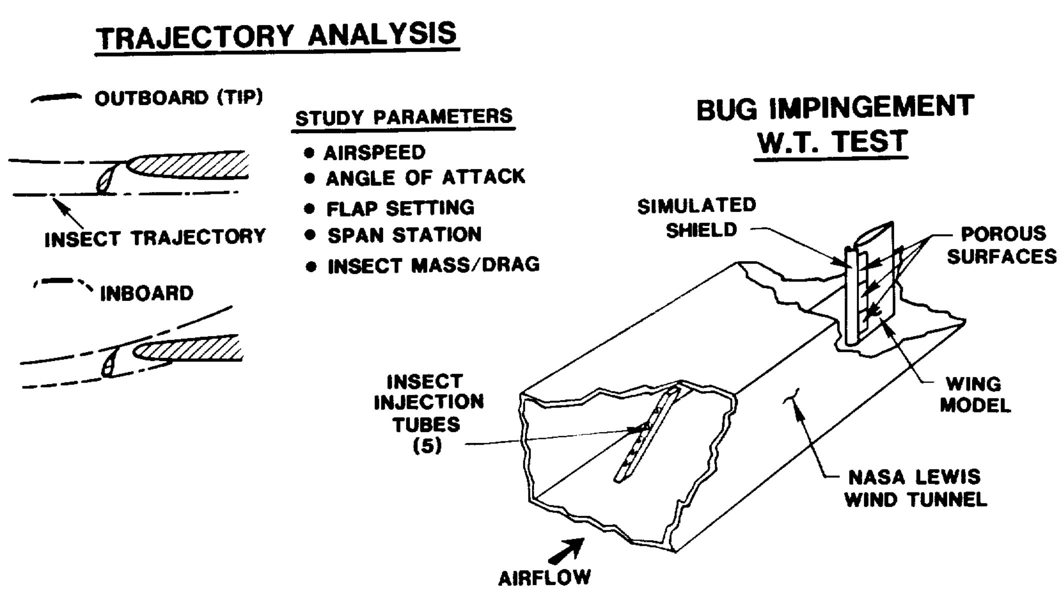

Figure 8.- Douglas Krueger shield insect trajectory analysis and wind tunnel test.

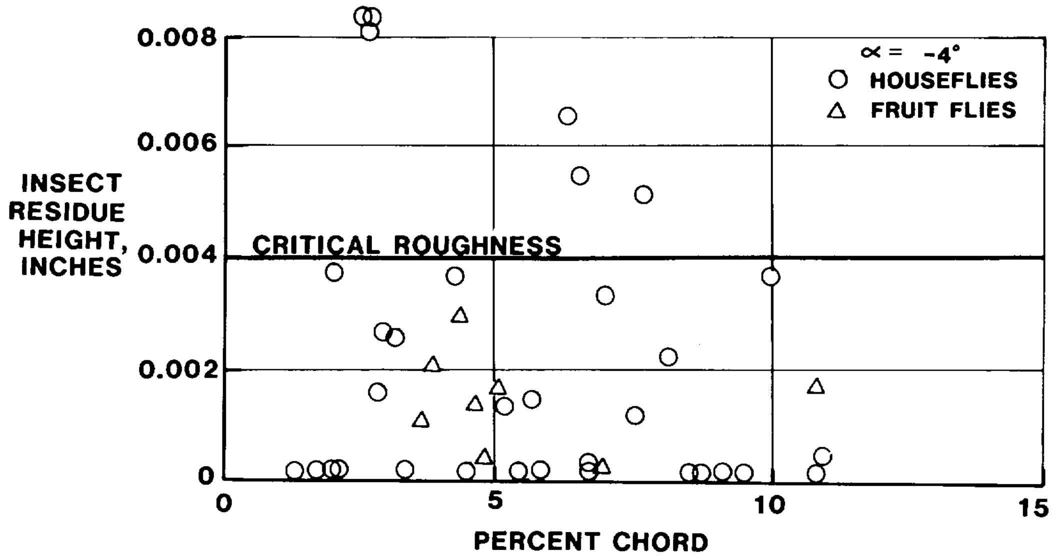

Figure 9.- Douglas insect residue wind tunnel test results.

OBJECTIVE: DEMONSTRATE THE EFFECTIVENESS AND PRACTICALITY OF L.E. SYSTEMS IN MAINTAINING LAMINAR FLOW UNDER REPRESENTATIVE FLIGHT CONDITIONS

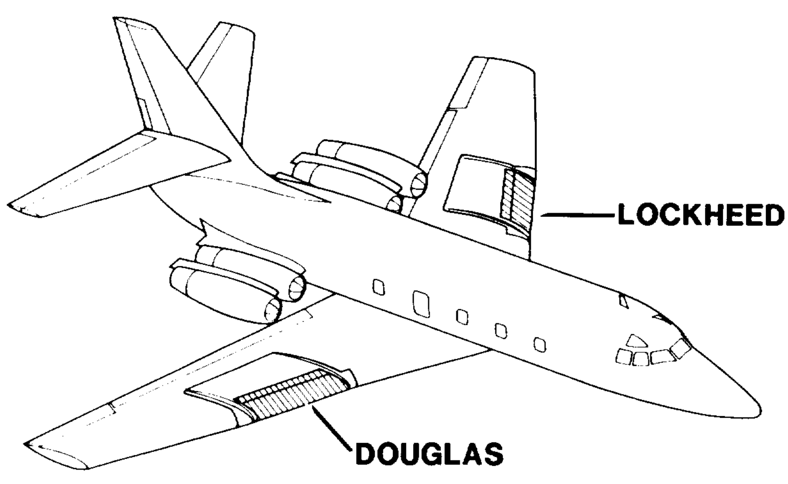

Figure 10.- Leading-edge flight test Jetstar configuration.

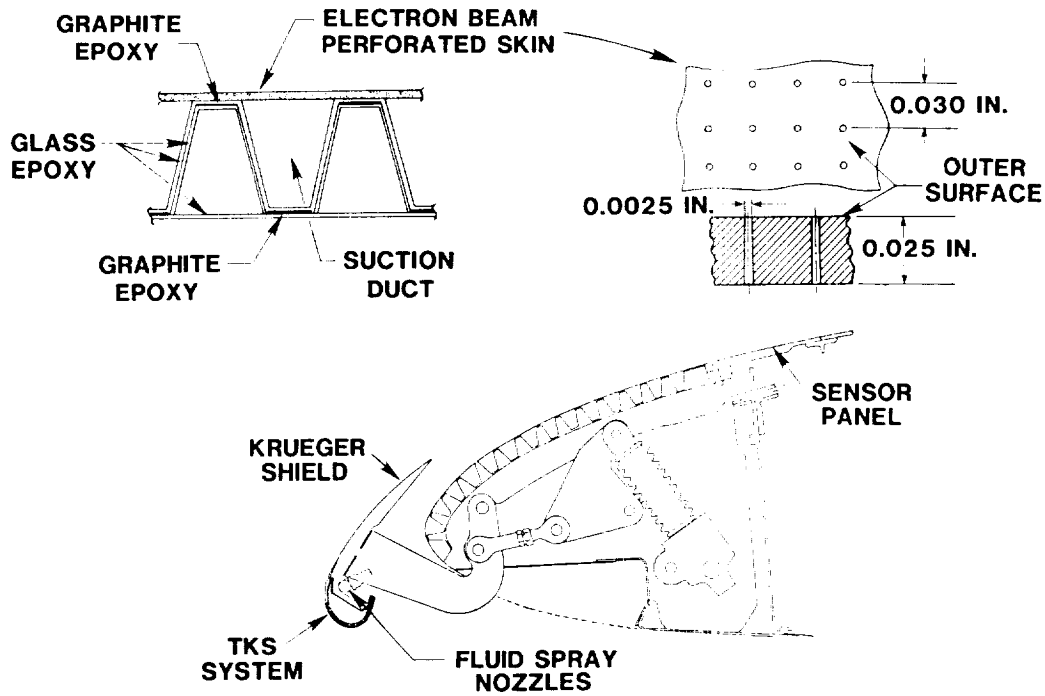

Figure 11.- Douglas leading-edge flight test article.

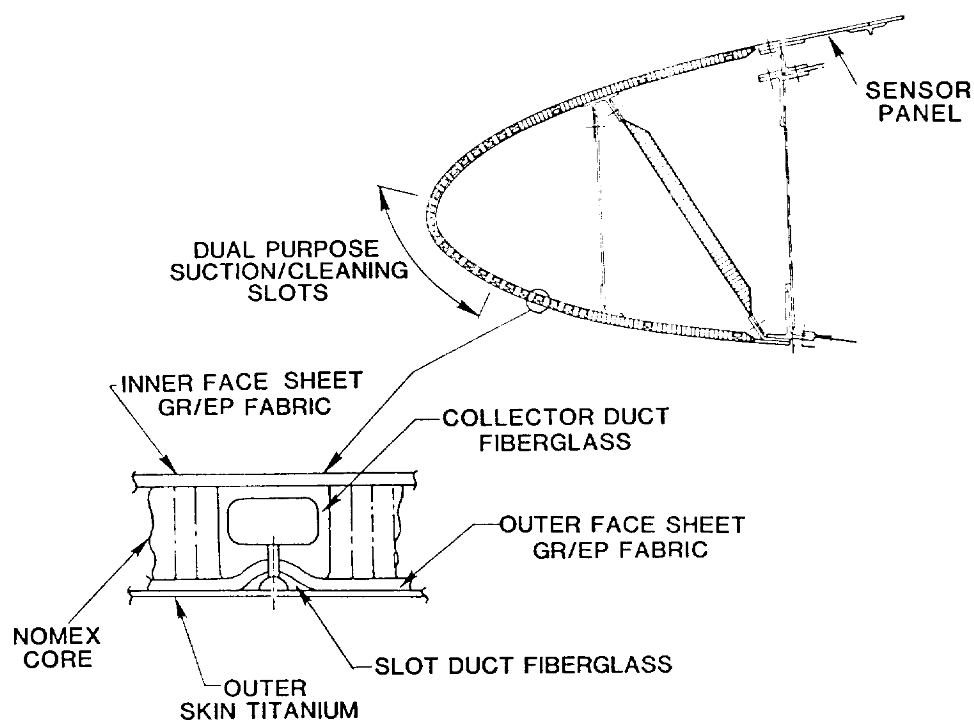

Figure 12.- Lockheed leading-edge flight test article.

Figure 13.- NASA DFRF Jetstar in flight.

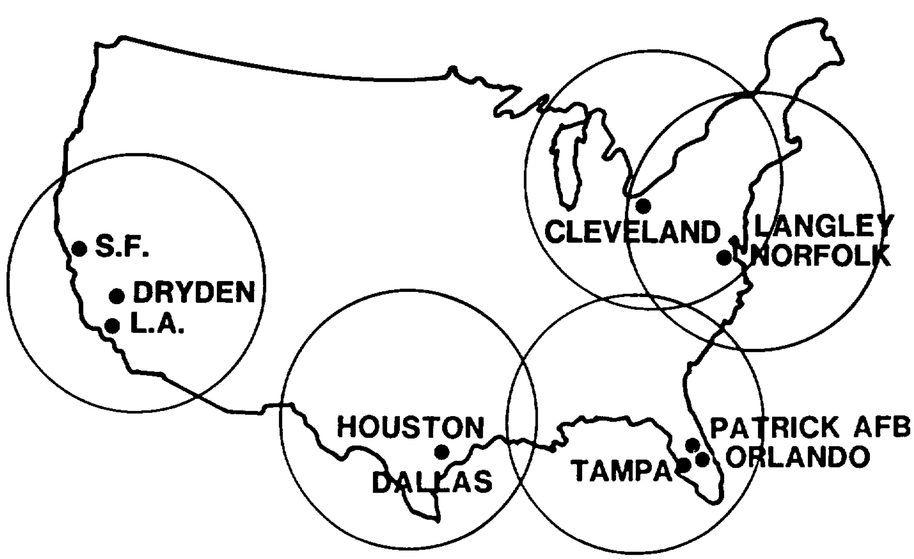

Figure 14.- LEFT simulated airline service homes bases.

	LOCKHEED	DOUGLAS
Takeoff	Liquid on	Shield extended Liquid on Secondary purge on
6,000 ft.	Liquid off Secondary purge on	Liquid off Retract shield Secondary purge on
12,000 ft.	Secondary purge off Primary purge on	Secondary purge off Primary purge on
20,000 ft.	Suction pump start	Suction pump start
23,000 ft.	Primary purge off	Primary purge off
32,000 ft.	Beginning of suction on test article	Beginning of suction on test article

Figure 15.- Leading-edge flight test operations.

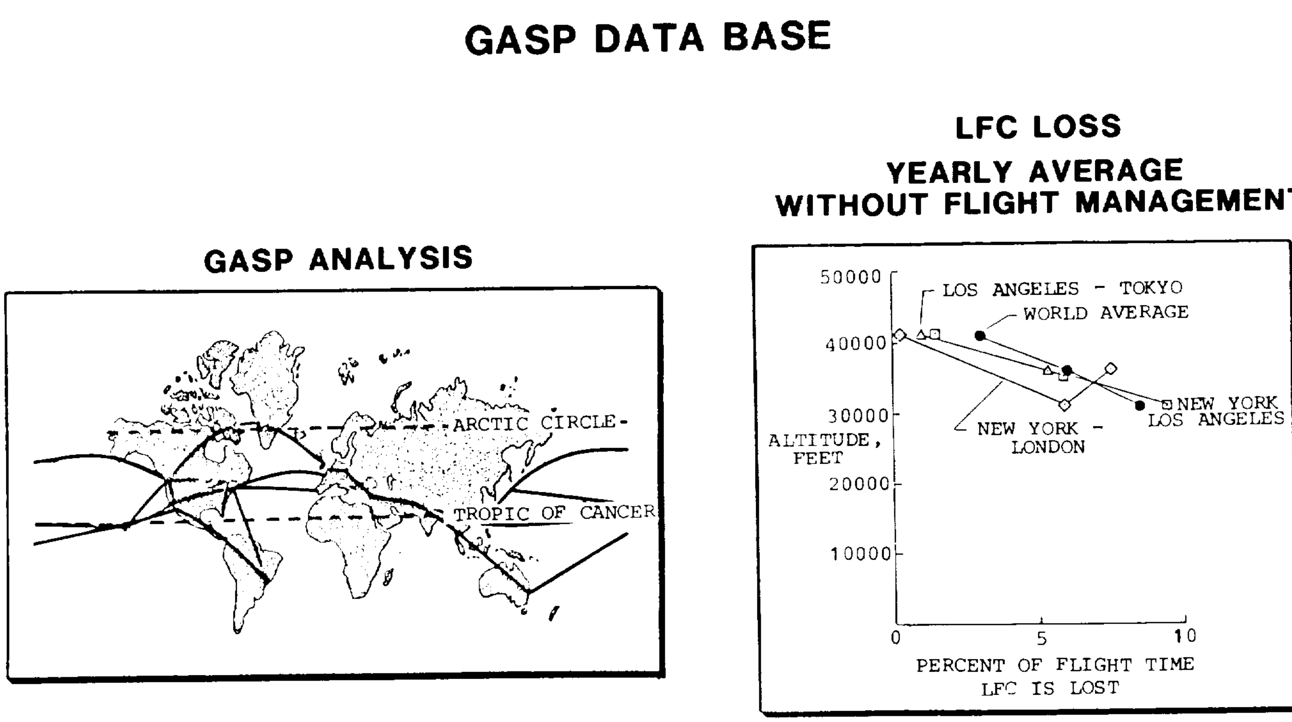

Figure 16.- Cloud particle impact on laminar flow loss from GASP data base analysis.

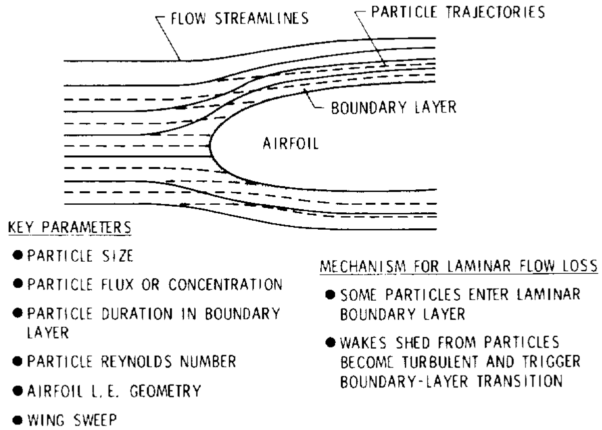

Figure 17.- Ice particle penetration and breakdown of the laminar boundary layer.

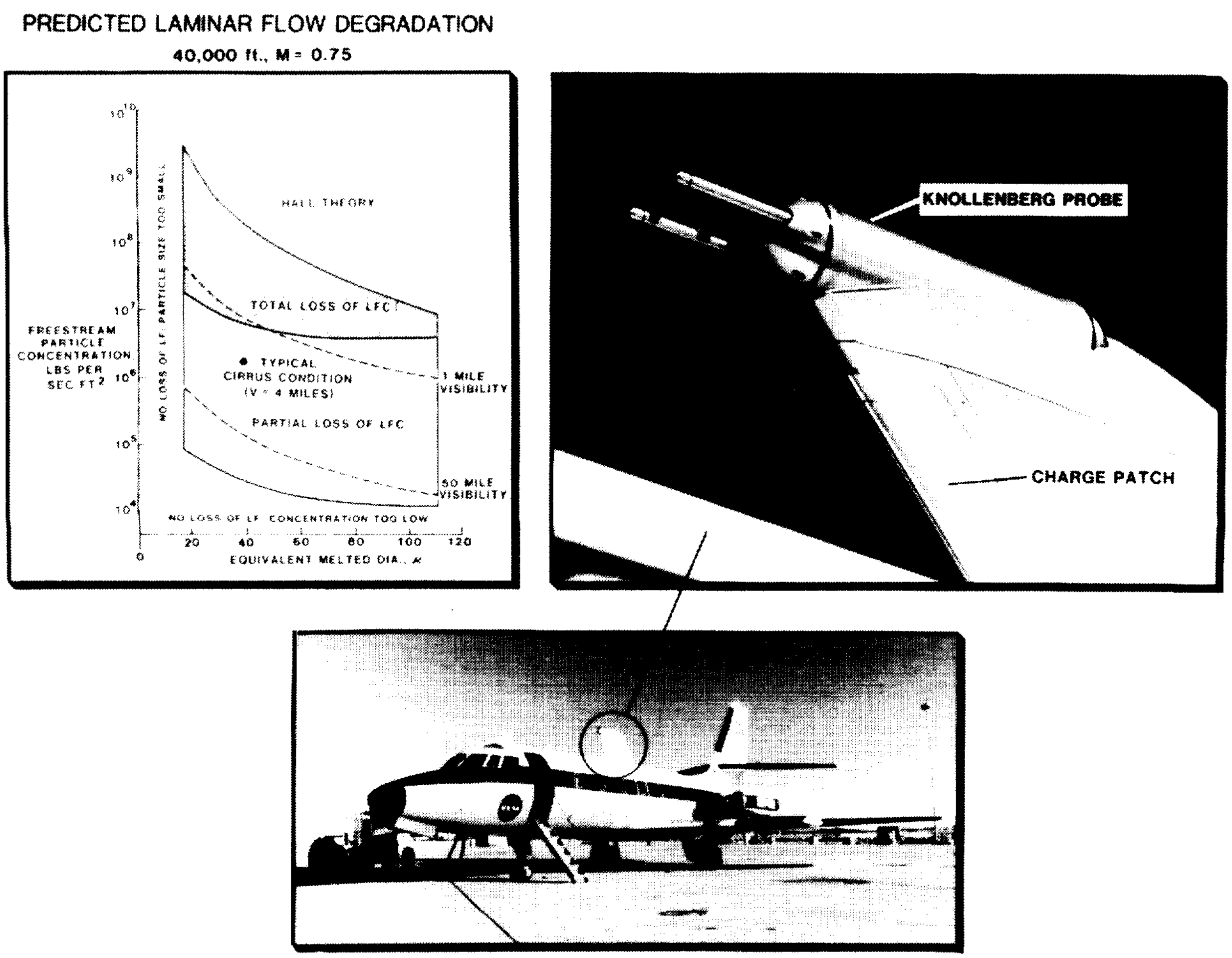

Figure 18.- Instrumentation for measurement of cloud particles and estimates of their effect on laminar flow loss.

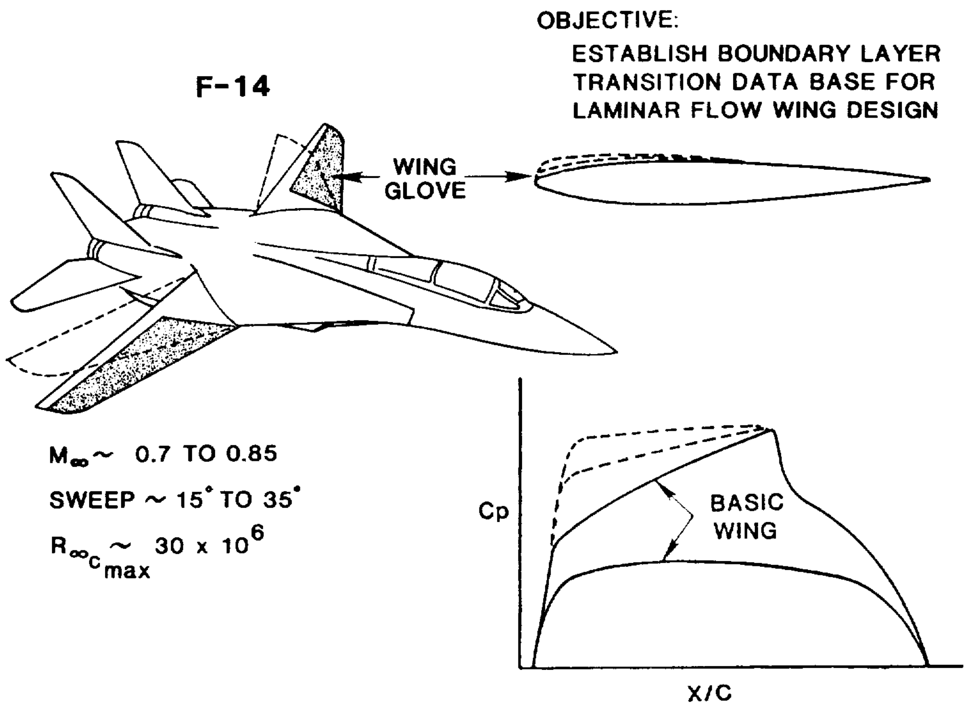

Figure 19.- F-14 variable sweep transition flight experiment.