THE RIGHT WING
OF THE
L.E.F.T. AIRPLANE

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ABSTRACT

The NASA Leading-Edge Flight Test (L.E.F.T.) program addressed the environmental issues which were potential showstoppers in the application of Laminar Flow Control (LFC) to transport aircraft. These included contamination of the LFC surface due to dirt, rain, insect remains, snow, and ice, in the critical leading-edge region. As part of NASA contract NAS1-16220, Douglas Aircraft Company designed and built a test article which was mounted on the right wing of the NASA C-140 Jetstar aircraft. (The Lockheed test article, installed on the left wing, will not be discussed in this paper.) The Douglas test article featured a retractable leading-edge high-lift shield for contamination protection and suction through perforations on the upper surface for LFC.

Following a period of developmental flight testing, the aircraft entered simulated airline service, which included exposure to airborne insects, heavy rain, snow, and icing conditions both in the air and on the ground. During the roughly 3 years of flight testing, the Douglas test article has consistently demonstrated laminar flow in cruising flight.

This paper briefly summarizes the Douglas experience with the L.E.F.T. experiment, with emphasis on significant test findings. The following items are discussed:

- Test article design and features.

- Suction distribution.

- Instrumentation and transition point reckoning.

- Some problems and fixes.

- System performance and maintenance requirements.

- Conclusions.

FOREWORD

This paper highlights the design and analyses detailed in References 1 and 2, performed by the Douglas Aircraft Company, McDonnell-Douglas Corporation, under the NASA contract entitled, "Laminar Flow Control Leading-Edge Glove Flight Test Article Development." The program was administered through Langley Research Center under the direction of NASA Laminar Flow Control project manager, Mr. R. D. Wagner. The L.E.F.T. project technical manager was Mr. M. C. Fischer, and more recently, Mr. D. V. Maddalon.

Flight testing was conducted by NASA Ames/Dryden Flight Research Facility staff. The flight test project manager was Mr. R. S. Baron, and more recently, Ms. J. L. Baer-Riedhart. The principal investigator was Mr. D. F. Fisher, and more recently, Mr. L. C. Montoya. Special thanks goes to Mr. J. A. Thelander at Douglas, who patiently analyzed the data.

The ultimate acceptability of laminar flow technology to airplane operators depends critically on the level of additional maintenance required and the ability to achieve laminar flow reliably on a daily basis. Surface erosion and contaminant accretion are known to be almost exclusively confined to the wing leading-edge region. This region is the most critical for wing laminarization.

The NASA Leading-Edge Flight Test was conceived as a critical test of LFC contamination-avoidance technologies. Douglas Aircraft Company (DAC), under contract to NASA, designed and built a leading-edge test article which was flown on the starboard wing of NASA's C-140 Jetstar aircraft (Figure 1). The DAC test article featured a retractable leading-edge high-lift shield for contamination protection, and suction through perforations on the upper surface for laminar flow control.

Earlier DAC system studies suggested that a high-lift shield, deployed from the wing undersurface, could protect the LFC leading edge from airborne contamination and allow higher lift coefficients for takeoff and landing. Although the shield may prevent lower surface laminarization, the reduction in wing size allowed by the higher maximum lift coefficient, along with the simplification of the LFC suction systems, makes this a favorable trade.
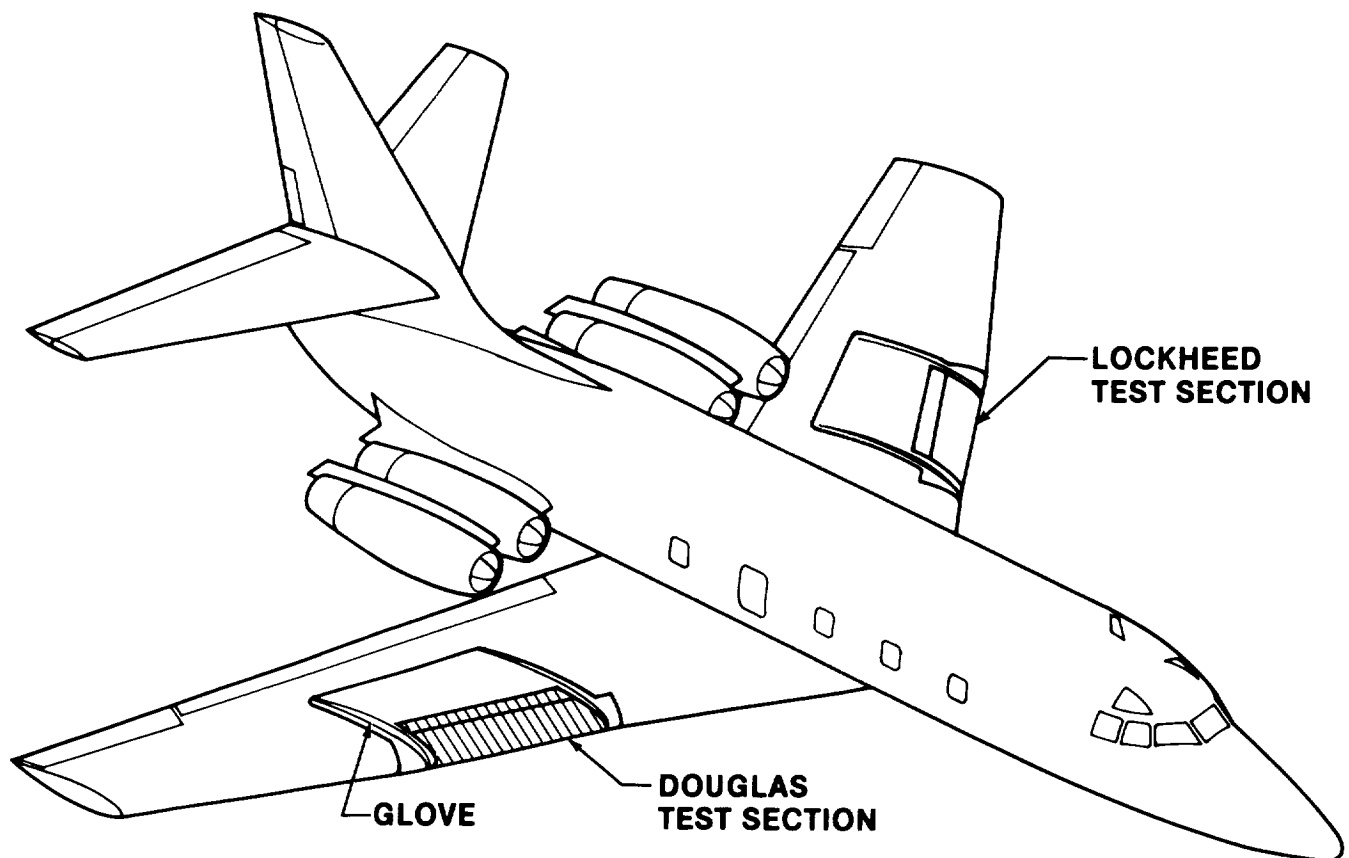

FIGURE 1. NASA JETSTAR AIRPLANE

The test article and glove were designed to give a chordwise pressure distribution that would be representative for both surfaces of a full-chord LFC wing. Douglas and Lockheed worked together to arrive at a suitable glove shape. The proximity of the engine nacelles caused a perturbation to the glove pressure distribution, which was accounted for by incorporating incremental nacelle pressures from a high-speed wind tunnel test of the LFC configuration. Figure 2 shows the test article planform, the changes to the wing geometry at the inboard and outboard glove stations, and the resulting chordwise pressure distribution in the glove midspan region.
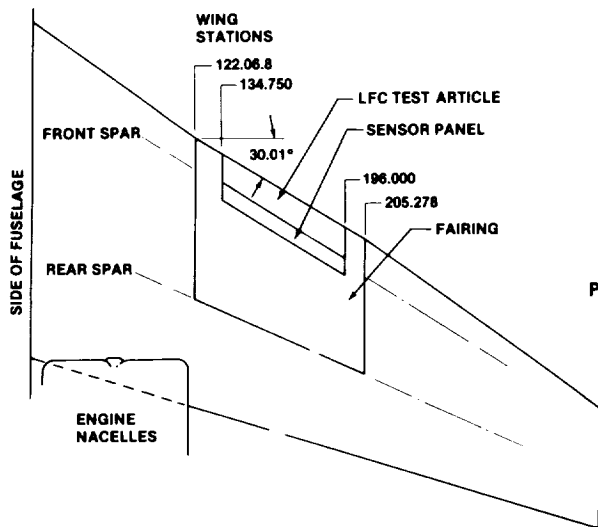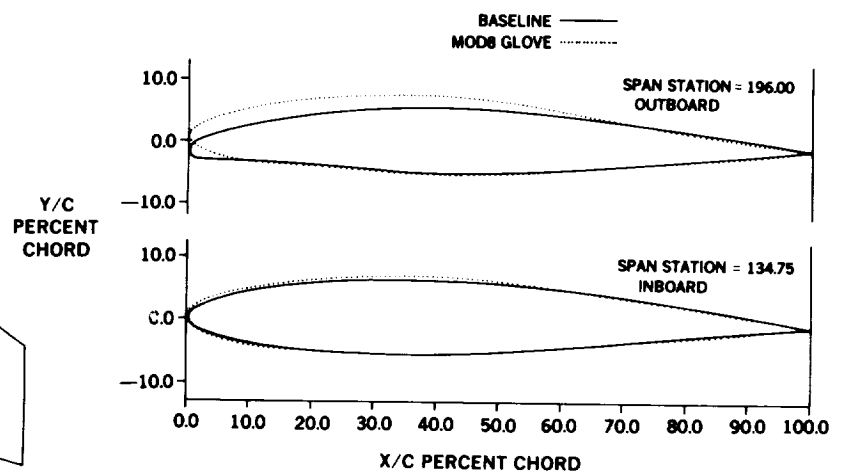
FIGURE 2A. JETSTAR LFC TEST
ARTICLE PLANFORM

FIGURE 2B. COMPARISON OF JETSTAR AND LFC
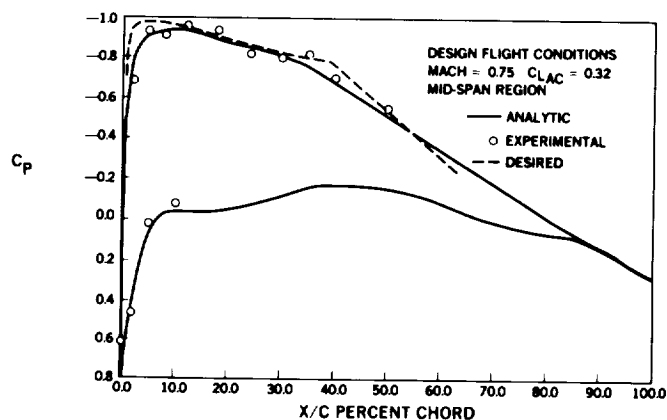GLOVE DEFINING AIRFOIL SHAPES

FIGURE 2C. COMPARISON OF PREDICTED DISTRIBUTION WITH JETSTAR MODEL
TEST DATA AND DESIRED LFC PRESSURE DISTRIBUTION

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The contamination-avoidance and ice-protection systems are shown in Figure 3. The primary component of these systems is the shield, which physically blocks contaminants from impacting on the leading edge. A propylene glycol methyl ether (PGME) spray system, located behind the shield, provides capability for de-icing after flight into icing conditions and was intended to augment the shield by wetting the LFC surface so any contaminants getting past the shield would not stick to it. (Despite its small size, the shield has proven so effective for contamination avoidance that the spray system was sealed off for summer operations.) Freezing-point depressant liquid (FPD) or rainwater is prevented from entering the perforated LFC surface by maintaining a small positive pressure differential across the porous surface. This is set by surface tension considerations at about 0.5 psi. Shield de-icing is provided by a woven stainless-steel insert on the shield leading edge which oozes FPD liquid.
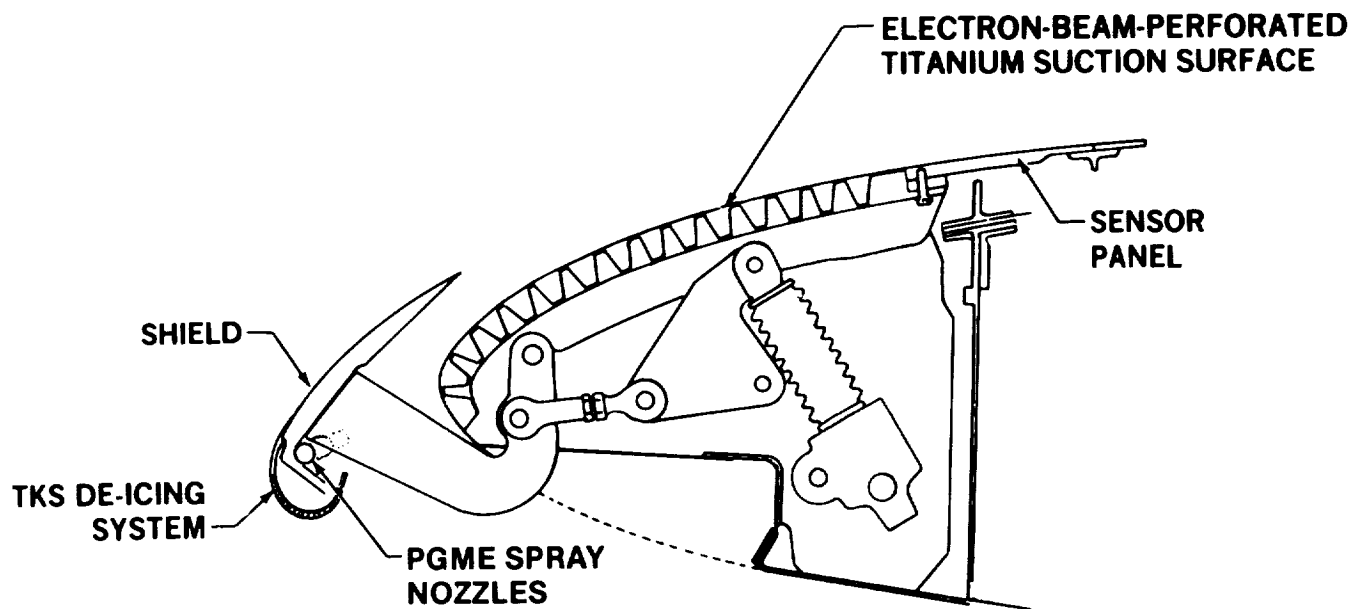

FIGURE 3. DOUGLAS CONTAMINATION-AVOIDANCE
AND ICE-PROTECTION SYSTEMS

The NASA MARIA code (Reference 3) was found to be a convenient tool for evaluating the effectiveness of various trial suction distributions. Although the computations are done in an approximate way, and the code only computes the amplifications of zero-frequency cross-flow waves, it has the ability to quickly compute and present the amplifications of a wide spectrum of wavelengths. This allows the effects of many trial suction distributions to be viewed in a short time. The code also does an excellent job of identifying critical wavelengths for corroborative analyses using the SALLY or COSAL codes. Figure 4 illustrates the effectiveness of suction application at the attachment line (trial distribution Number 3). This result would not have been expected using the X-21 cross-flow transition criterion, but has been verified using the SALLY code and by test data. Trial distribution Number 3 became the basic suction distribution.
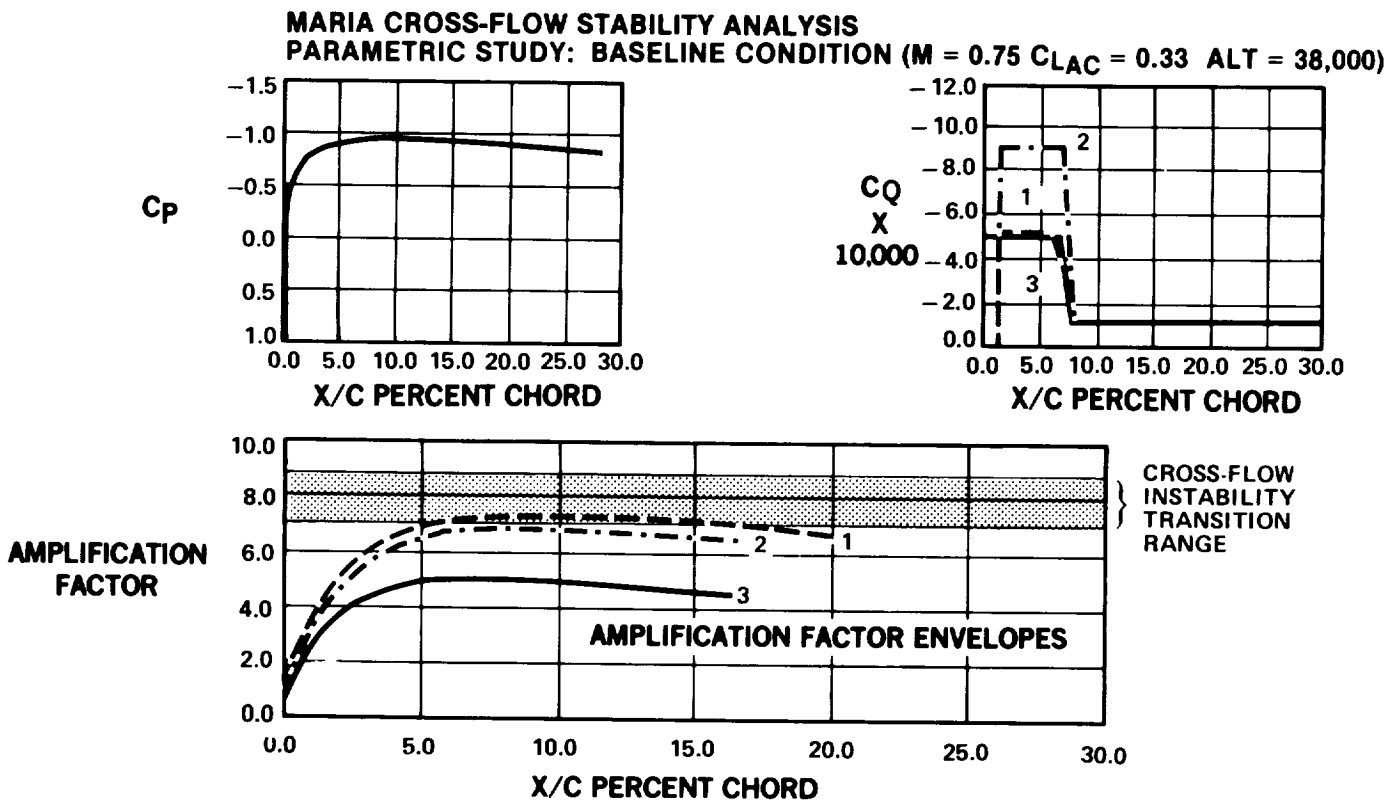
MARIA CROSS-FLOW STABILITY ANALYSIS
PARAMETRIC STUDY: BASELINE CONDITION (M = 0.75 C_{LAC} = 0.33 ALT = 38,000)

FIGURE 4. EFFECT OF SUCTION DISTRIBUTION ON CROSS-FLOW INSTABILITY

The basic and nominal suction distributions are shown in Figure 5. The basic suction distribution was developed based on MARIA and SALLY analyses of stationary cross-flow disturbance amplifications, taken at a computational station near the glove centerline. Cross-flow amplification factors were held at conservative levels of around five. Tollmien-Schlichting (T-S) amplifications were checked and found not to be critical. Using known external pressures and porous surface characteristics, required flute pressures were obtained. Analysis of spanwise and chordwise external pressure variations over the porous leading edge indicated the necessity of slightly higher suction levels in order to ensure that all span stations would have at least the basic suction levels. This defined the nominal suction distribution. The apparently higher suction level on flute Number 1 is only a consequence of the way in which the nonporous area is accounted for. The suction system was designed to allow at least a 50-percent oversuction capability from the nominal.
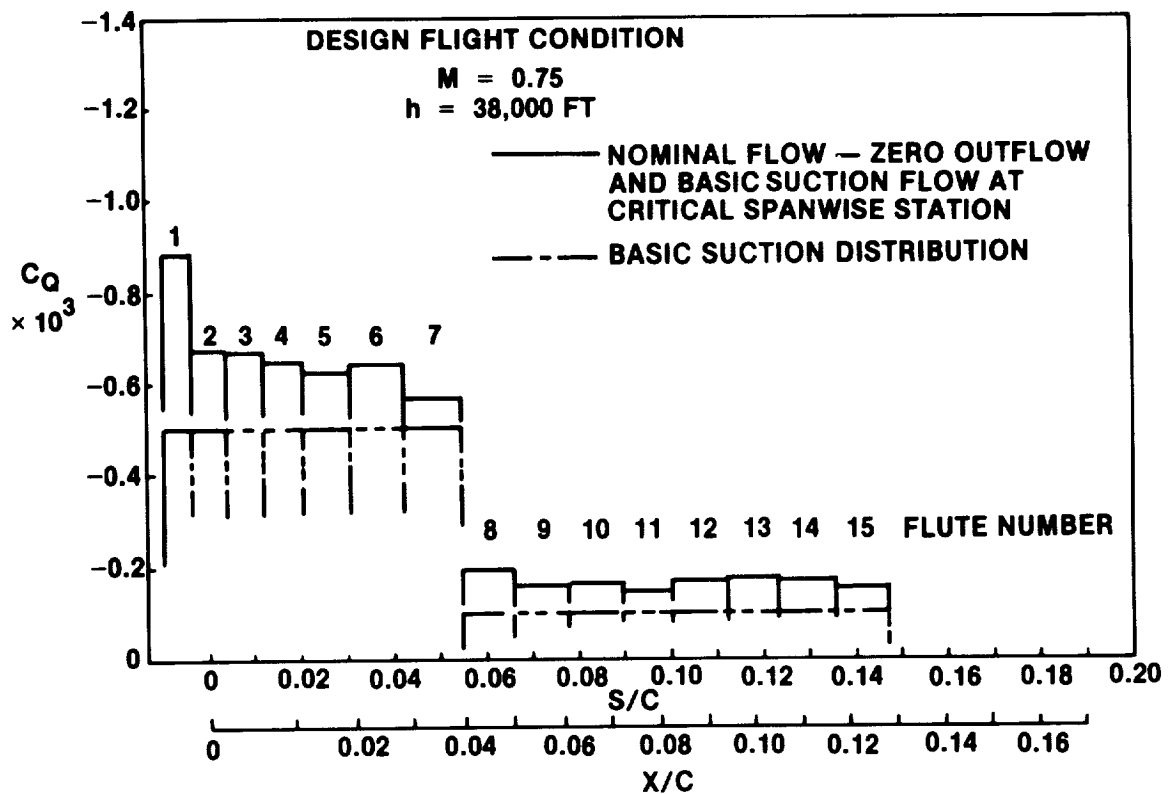

FIGURE 5. BASIC AND NOMINAL SUCTION DISTRIBUTIONS

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The surface waviness criterion for the LFC leading edge was based on available X-21 results (Reference 4) and is shown in Figure 6 for M = 0.75, at 30,000- and 38,000-foot altitudes. Waviness measurements of the LFC leading-edge suction panel, after bonding the perforated titanium skin to the fiberglass substructure, are plotted in the figure. These measurements were all within the limits specified, and encompass the entire span of the suction panel. Observance of waviness criteria is a simplified approach to avoiding laminar separations, excessive growth of T-S waves, and critical amplification of Görtler vortices, which might not be accounted for otherwise. Aerodynamic and boundary layer stability analyses of the actual measured surface are the alternative.
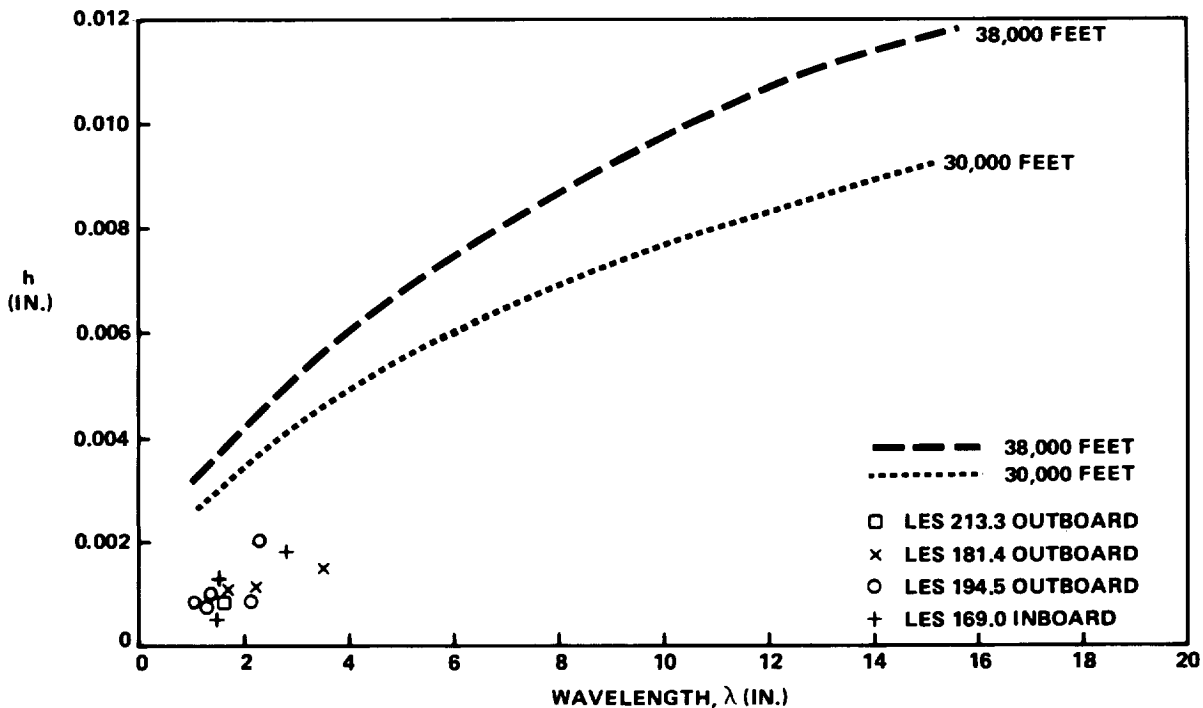

FIGURE 6. LFC FLIGHT TEST ARTICLE WAVINESS VERSUS MULTIPLE-WAVE CRITERION

The surface instrumentation layout is shown in Figure 7. It consists of three chordwise rows of static pressure taps, a leading-edge-normal row of hot film sensors, and a row of 20 boundary layer Pitot tubes mounted on a sensor panel just aft of the perforated LFC surface. It was important that the static pressure taps not trip the flow so the existing electron beam perforations were used where possible. The static pressure taps were placed in the inactive areas between the suction flutes. In locations where adhesive bonding had blocked the holes, a Number 80 drill was used, and was found sufficiently small so as to not disturb the flow. The centerline row consisted of 16 taps, and the two side rows had 8 taps each. The flute pressures were also monitored.
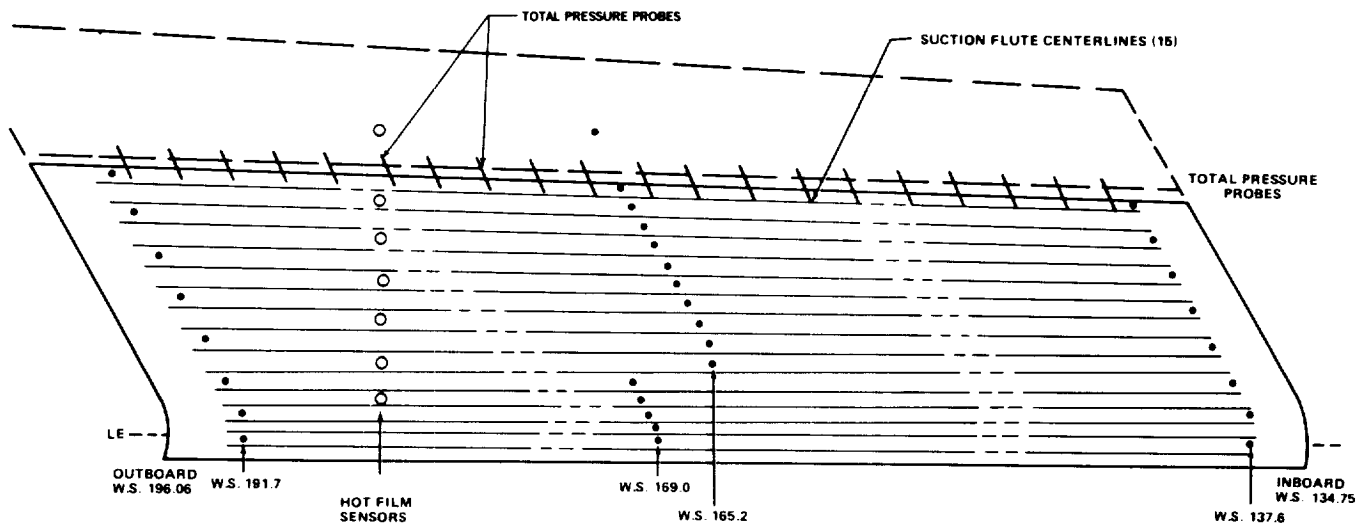
FIGURE 7. TEST ARTICLE SURFACE INSTRUMENTATION

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A series of boundary layer Pitot tubes, mounted on the sensor panel aft of the suction surface, as shown in Figure 7, were used for determining whether or not the boundary layer is locally laminar, and for reckoning the transition point upstream. Two Pitot tubes located well above the boundary layer measured free-stream total pressure. Other tubes were located at 0.060 inch above the surface, just above a laminar boundary layer, but within a turbulent boundary layer. Total pressure deficit is used to determine transition location. Boundary layer computations were made, based on measured pressure distributions, for various altitudes at Mach 0.75 (Figure 8a) over a range of transition locations. A set of curves (Figure 8b) was constructed showing the total pressure deficit as a function of chordwise transition location for each altitude. Note that laminar separation is predicted for the 38,000- and 40,000-foot altitudes. This is due to a local compression in the chordwise pressure distributions near flutes 13 and 14 at these altitudes.
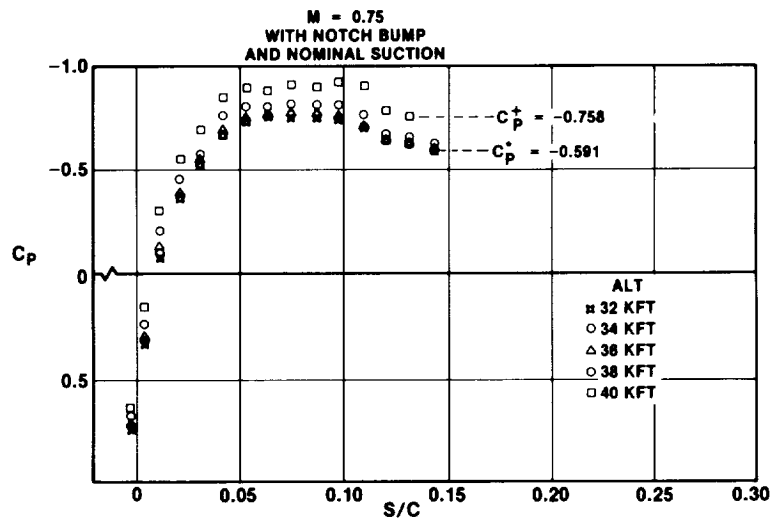

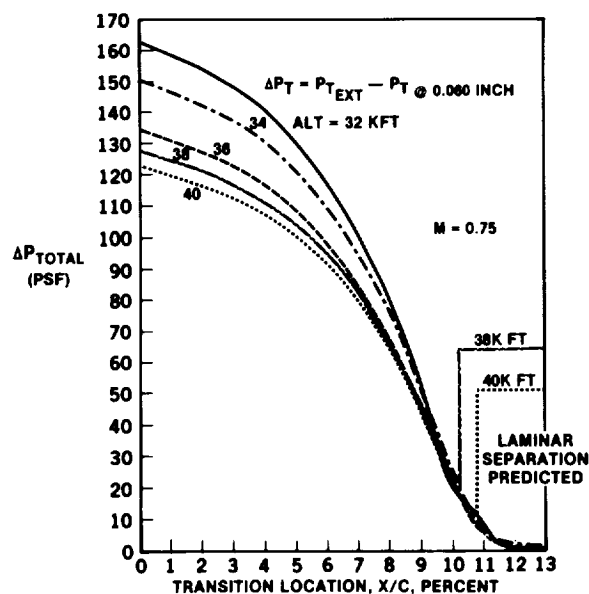**FIGURE 8A. MEASURED CHORDWISE PRESSURE DISTRIBUTIONS**

FIGURE 8B. PREDICTED BOUNDARY LAYER TOTAL PRESSURE DEFICIT VALUES

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Figure 9 shows the boundary layer total pressure deficits on the test article for the first design-point test of the suction system. Except for a problem inboard, attributable to spanwise turbulence transfer along the attachment line onto the LFC test article, and a couple of small turbulent wedges, the test article succeeded in achieving laminar flow. The turbulent area inboard was later cured by the application of a passive turbulence diverter (Gaster bump or notch/bump). The pressure deficits further outboard occurred only at the higher altitude, where laminar separation was predicted.
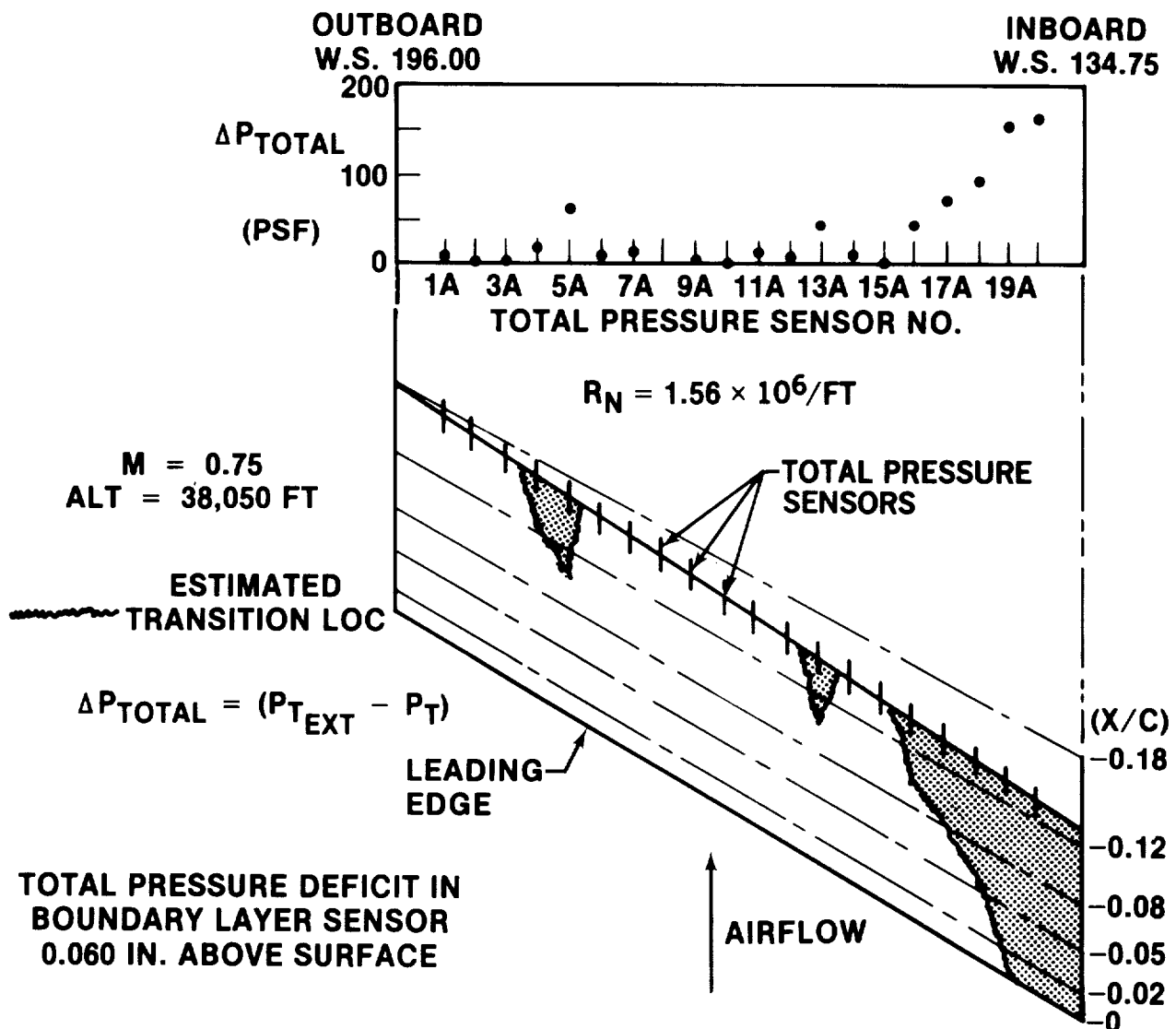
FIGURE 9. INITIAL TRANSITION PATTERN BEFORE INSTALLING NOTCH BUMP

A number of data points were taken at different flight conditions -- and different unit Reynolds numbers -- before the turbulence diverter was installed. The cases shown in Figure 10 are all for nominal suction. Of interest is the distance along the test article the turbulence was able to propagate at different unit Reynolds numbers. The attachment line momentum thickness Reynolds numbers are also shown in parentheses, and tend to confirm the lower critical value of around 100. The application of a turbulence diverter (notch/bump in this case) to the inboard end of the test article is seen to affect a cure. According to Reference 5, if the attachment line can be kept free of supercritical excrescences by the use of the shield, laminar flow is possible with attachment line momentum thickness Reynolds numbers up to approximately 240. Since the attachment line Reynolds number varies roughly with the square root of leading-edge radius, the successful functioning of the leading-edge shield as a protection device allows application of LFC to large aircraft.
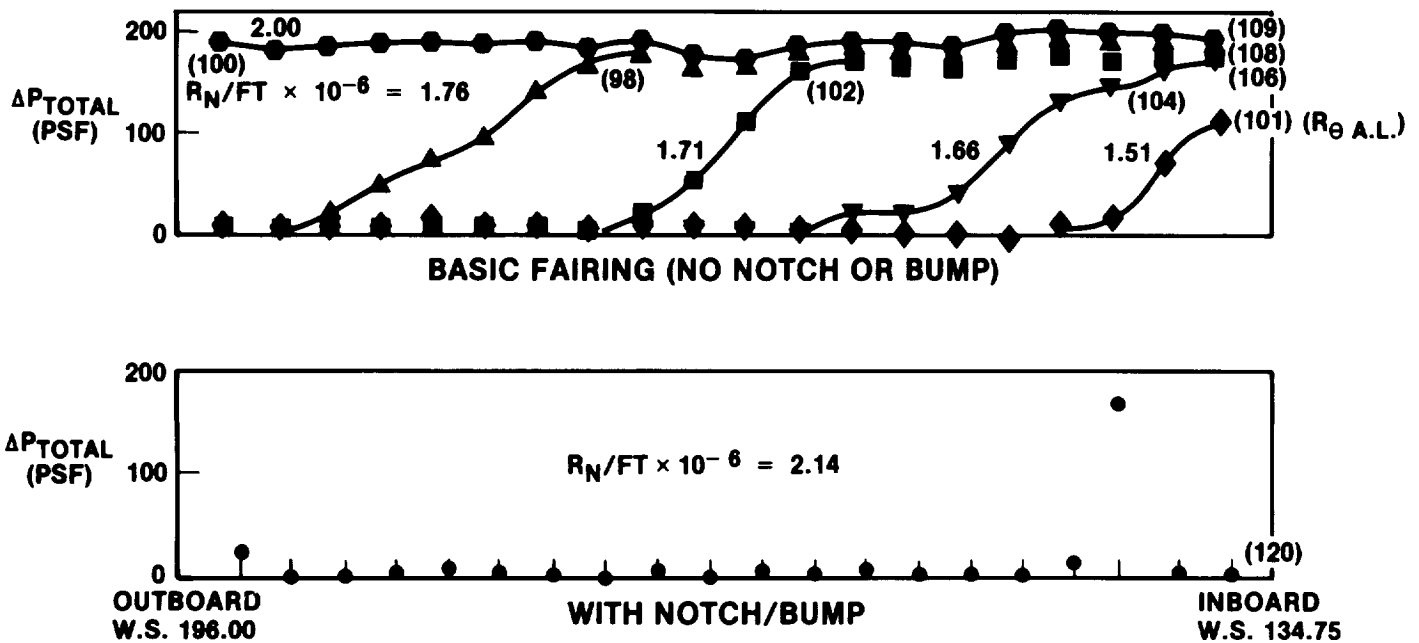

FIGURE 10. EFFECT OF R_N ON TURBULENCE TRANSFER AND NOTCH/BUMP EFFECTIVENESS

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Figure 11 shows a matrix of test conditions varying with Mach number and altitude and showing the corresponding unit Reynolds numbers. To the left of the hatched bar, 100-percent laminar flow was achieved; to the right there was some reduction. It is obvious that this reduction was not caused by increasing Reynolds number or angle of attack and is consistent with being caused by an increasing shock tendency. This was also consistent with the previously discussed laminar separation predicted at higher altitudes and possibly by a local shock condition aggravated by the presence of the Pitot tube assembly and its mounting.
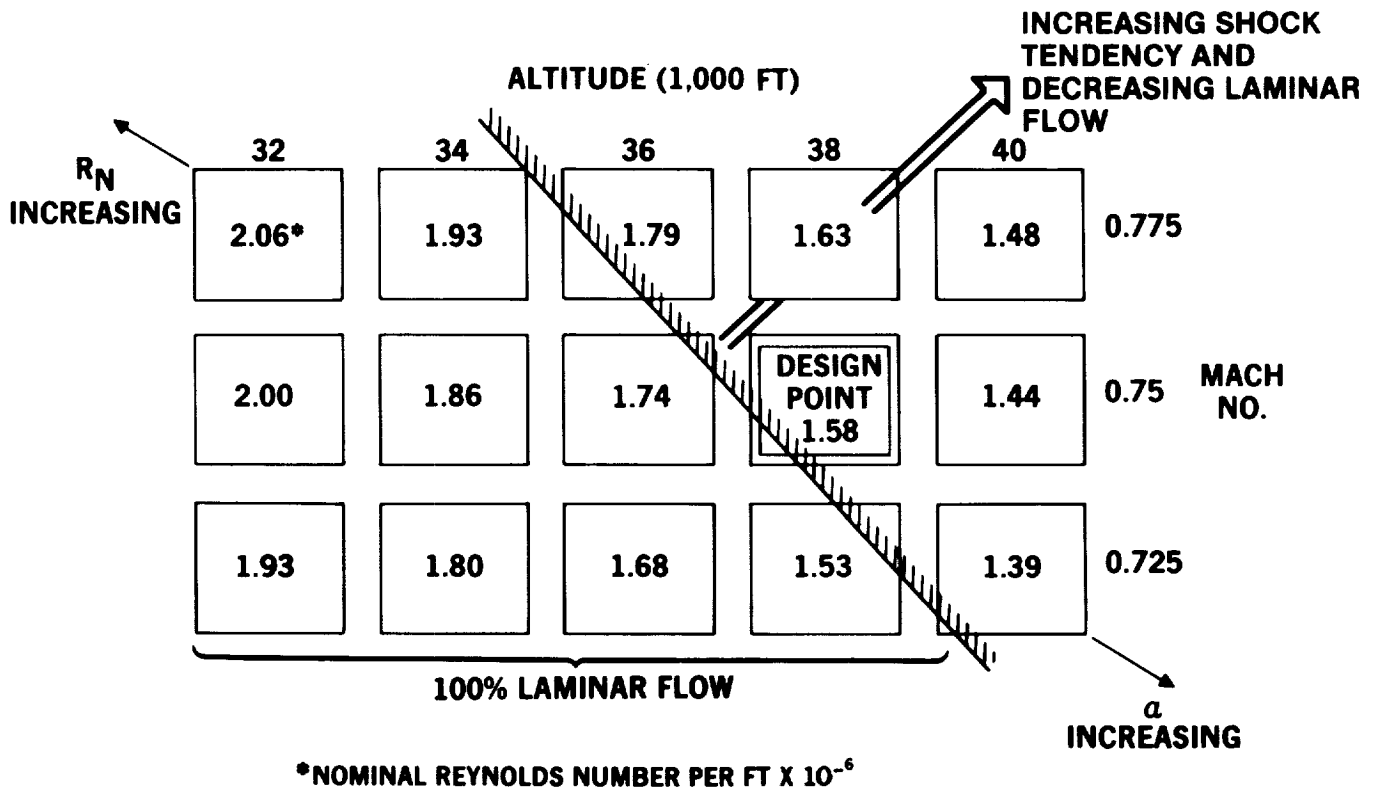

FIGURE 11. FLIGHT TEST MATRIX — SHOCK SENSITIVITY THRESHOLD

There has been concern expressed that high suction flow through a perforated surface might generate a disturbance sufficient to trip the boundary layer, due to vortices trailing off of each suction hole. These vortices are strongest at maximum suction. Suction, up to the level of choking the holes in the porous surface, was achieved when 150 percent of nominal suction flow was demonstrated at design-point flight conditions. For this flight the turbulence diverter was not yet installed, and the test point is within the region where the shock problem exists as shown in Figure 12. Flute Number 3 was choked, as evidenced by the low pressure ratio across the surface (less than 0.528) and the fact that increasing the total suction flow did not increase the suction coefficient. No adverse effect of the oversuction or even choking is seen; in fact, the oversuction has apparently reduced the extent of turbulence along the test article leading edge.
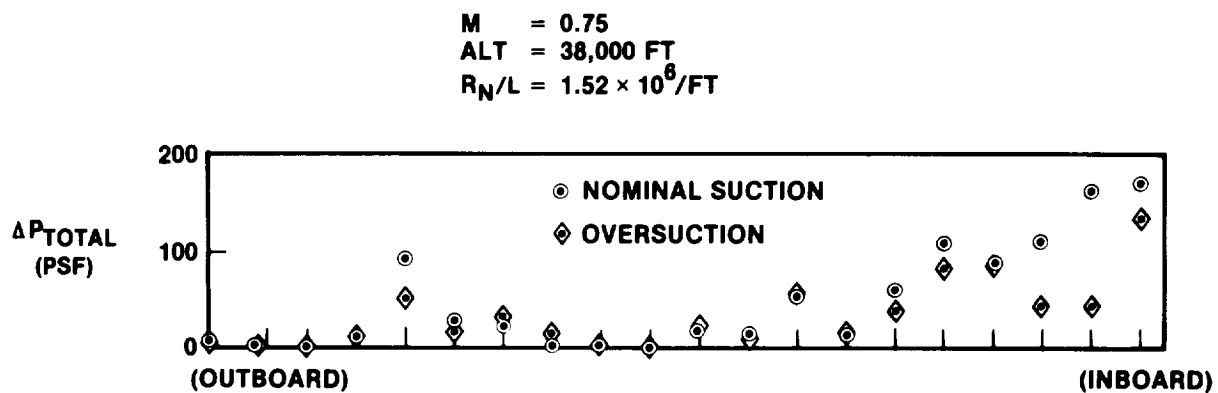
$$M = 0.75$$
$$ALT = 38,000 \text{ FT}$$
$$R_N/L = 1.52 \times 10^6/\text{FT}$$

FIGURE 12. EFFECT OF OVERSUCTION AT DESIGN POINT

Goldsmith's single-row hole flow correlation (Reference 6) is the only guideline currently available for allowable hole parameters. Physically, the question of whether or not the boundary layer is tripped reduces to whether or not the trailing vortices created by the flow into the holes have an opportunity to interact in a destructive way before being damped out by viscosity. Transition is correlated to the equivalent disturbance-height Reynolds number, and a ratio of hole spacing to sucked streamtube height. The correlation is shown in Figure 13. The flute 3 choked-flow data point is shown. Since the boundary layer was not tripped, one can conclude that if a similar correlation curve exists for multiple hole rows, it lies to the right of the data point. It also appears highly probable that holes smaller than 0.0025 inch are not necessary.

M = 0.75, h = 35,000 FT, FLUTE NO. 3 CHOKED

Δq = VOLUME FLOW PER HOLE

α = CROSS-STREAM HOLE SPACING

$\bar{h}$ = CHARACTERISTIC HEIGHT OF SUCKED STREAMTUBE

$\bar{V}$ = CHARACTERISTIC VELOCITY OF SUCKED STREAMTUBE

$$\bar{h} = \left[\frac{2\Delta q}{\alpha} \bigg/ \left(\frac{\partial u}{\partial y}\right)_{y=0} \right]^{1/2}$$

$$\bar{V} = \frac{\Delta q}{\alpha} \bigg/ \bar{h}$$

$$R_{ek} = \frac{\rho}{\mu} \frac{\Delta q}{\alpha} = \frac{\bar{V}\bar{h}}{\nu}$$

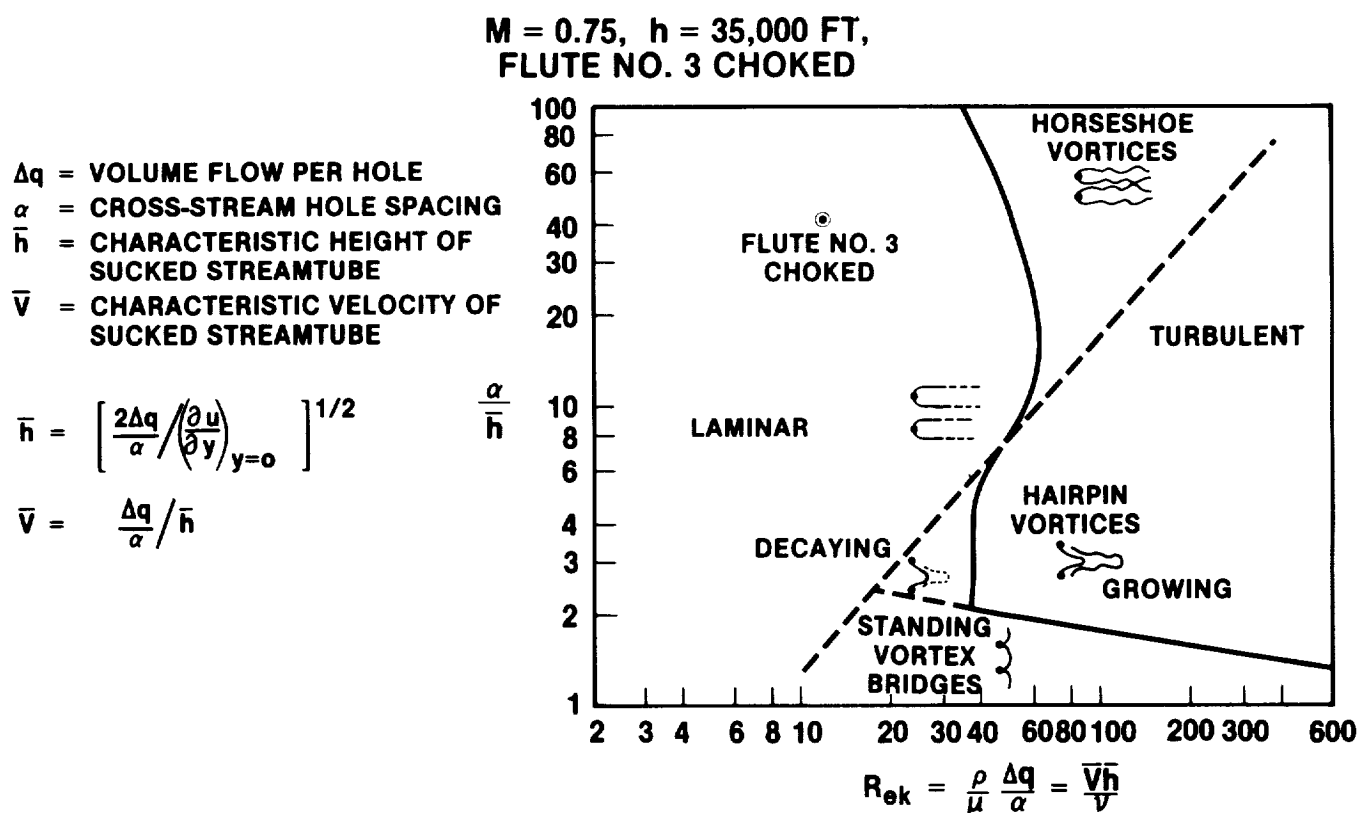**FIGURE 13. CHOKED PERFORATED SURFACE AND GOLDSMITH'S CORRELATION**

The presence of atmospheric ice particles was detected by a charge plate which utilized the triboelectric effect (also responsible for carpet shock). The aircraft was flown through clouds and haze, which at cruise altitude consist of ice particles, and an excellent correlation was obtained between charge plate readings and laminar flow degradation or loss. Figure 14 is a typical result. Laminar flow was always recovered immediately upon exiting airspace where ice crystals were present. One interesting sidenote is that, in at least two instances, ice crystals apparently scoured away a supercritical deposited excrescence. A drop in boundary layer total pressure deficit at one station was observed as a result of an ice crystal encounter, indicating a recovery of laminar flow after the excrescence was removed.
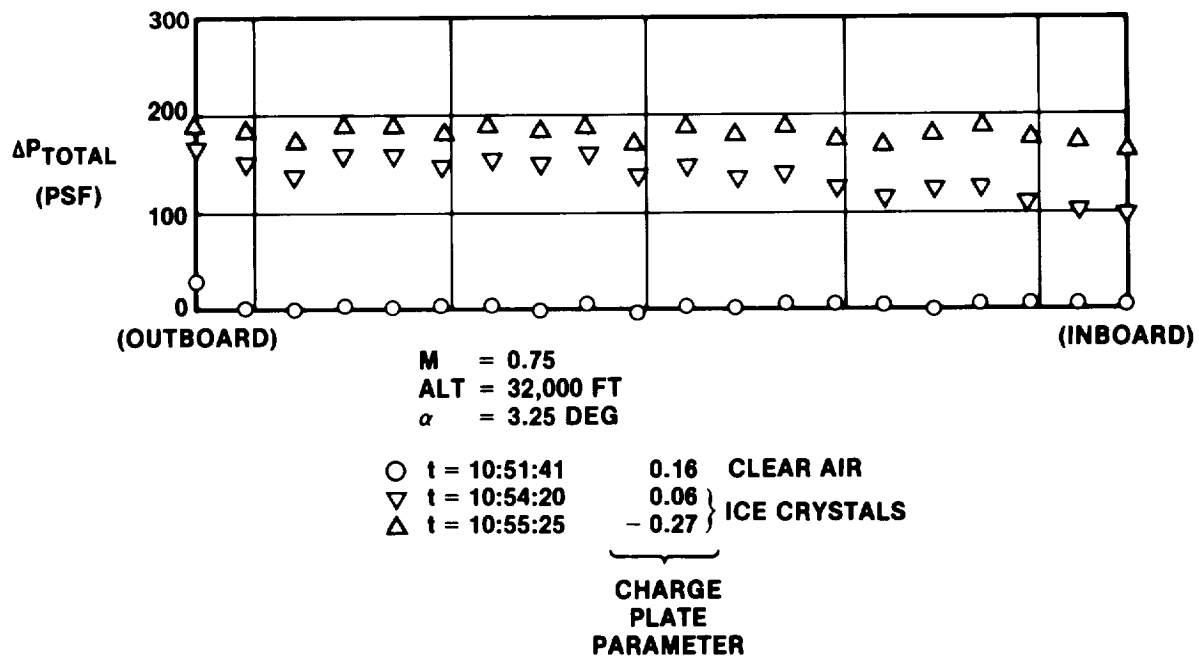

M   = 0.75
ALT = 32,000 FT
α   = 3.25 DEG

○ t = 10:51:41   0.16   CLEAR AIR
▽ t = 10:54:20   0.06 ⎫
△ t = 10:55:25   − 0.27 ⎬ ICE CRYSTALS

CHARGE
PLATE
PARAMETER

FIGURE 14. EFFECT OF ICE CRYSTAL ENCOUNTER

Following more than a year of developmental flight testing, the aircraft was placed into simulated airline service in order to test the effectiveness of the contamination-avoidance and ice-protection systems. This included operation in heavy rain and icing conditions, as well as operation in areas of heavy insect infestation. Despite this intentional exposure to the worst summer and winter conditions, the Douglas test article reliably achieved laminar flow. The performance of the Douglas system in 59 flights from 45 airports is summarized in Figures 15a and 15b.

HOME BASE

☐ ATLANTA
☐ PITTSBURGH
☐ CLEVELAND

DATE

JULY 85
SEPTEMBER 85
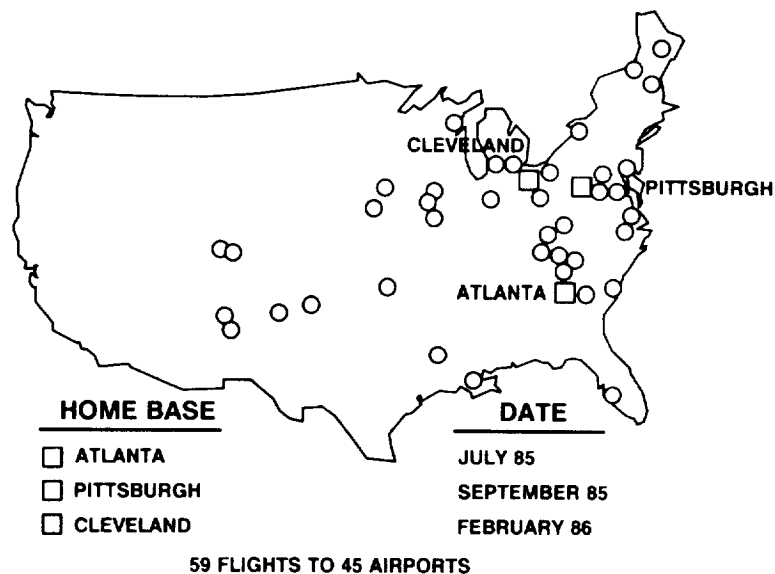FEBRUARY 86

59 FLIGHTS TO 45 AIRPORTS

FIGURE 15A. SIMULATED SERVICE FLIGHT TESTS

- LFC ACHIEVED ON INITIAL TEST FLIGHT
- LFC RECOVERED IMMEDIATELY FOLLOWING FLIGHT THROUGH ICE CRYSTALS
- LFC OBTAINED RELIABLY THROUGHOUT SIMULATED AIRLINE SERVICE FLYING:
  - SUMMER CONDITIONS
    - AIRBORNE INSECT INFESTATION
    - HEAVY RAIN STORMS
  - WINTER CONDITIONS
    - OVERNIGHT EXPOSURE TO ICE AND SNOW
    - IN-FLIGHT ICING CONDITIONS
- NO DETERIORATION OF LFC POROUS SURFACE OR PERFORMANCE IN 3 YEARS OF FLIGHT TESTING

FIGURE 15B. SUMMARY OF DOUGLAS LFC LEADING EDGE PERFORMANCE DURING JETSTAR FLIGHT TESTS

During the year-round simulated airline service, the aircraft was left out overnight in whatever conditions prevailed. Figure 16 shows the typical maintenance procedure for snow and ice removal, in this case after the aircraft was exposed to an overnight snow flurry in Cleveland. It is significant to note that 100-percent laminarization was routinely achieved with no additional maintenance required due to the presence of the Douglas LFC test article. The PGME spray system built into the shield was found to be unnecessary for contamination avoidance and was only used for de-icing. Detailed inspection of the perforated titanium surface after nearly three years of operation revealed no visible wear or erosion, and there has been no deterioration in performance.
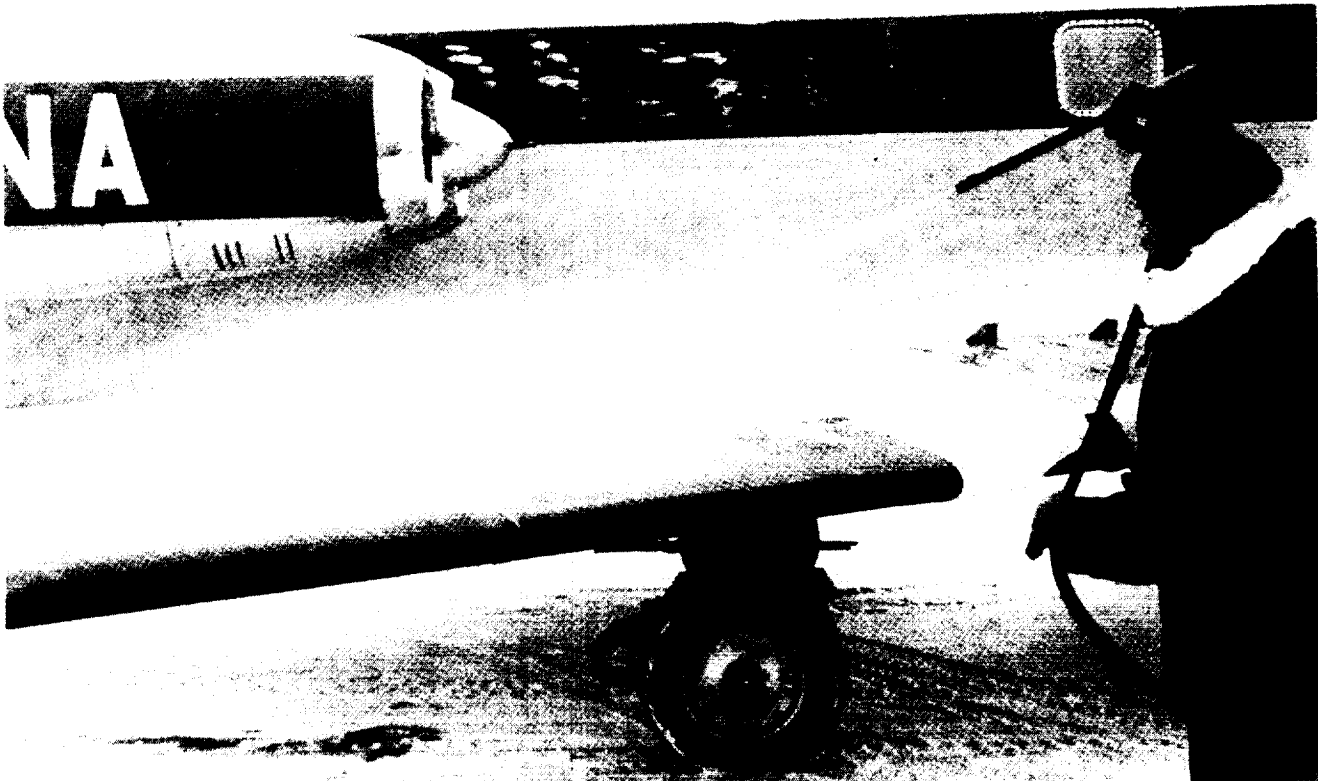
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FIGURE 16. STANDARD SNOW AND ICE REMOVAL PROCEDURE

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CONCLUSIONS

The results of this test program have been extremely encouraging. The success of the Douglas contamination-avoidance and ice-protection systems has established LFC as an attainable drag-reduction technology which would be acceptable to airplane operators. Principal conclusions are listed below.

1. The electron-beam perforated surface provided reliable laminar flow control.

2. The contamination-avoidance/ice-protection system was successful in protecting the LFC leading edge:

    a. The high-lift shield worked very well, despite its small size.

    b. Shield retraction at 5,000 feet AGL was sufficient to avoid insect contamination.

    c. The spray system was only needed for de-icing.

3. The Gaster-bump and notch/bump were successful in preventing the spanwise spread of turbulence along the attachment line.

4. Increasing the level of suction, even to the point of choking the holes, did not trip the boundary layer.

5. Some laminar flow is lost in ice particle encounters, but it is regained immediately in clear air.

6. No additional maintenance was required for the LFC system.

7. No degradation in the LFC surface or its performance was evident after 3 years of flight testing.

8. Laminar flow is attainable on a day-to-day operational basis regardless of environmental factors.

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