Laminar Flow Control Leading-Edge Systems in Simulated Airline Service

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Achieving laminar flow on the wings of a commercial transport involves difficult problems associated with the wing leading edge. In this program two laminar flow control leading-edge systems were flight tested. One used a perforated titanium-suction surface with approximately 1 million, 0.0025-in.-diam, electron-beam-drilled holes to maintain laminar flow on the wing upper surface to the front spar. This leading edge also had a Krueger-type flap, which served as a protective shield against insect impacts. The second leading edge had suction through a slotted titanium skin with 27 spanwise slots (about 0.004 in. wide) on the upper and lower surfaces to maintain laminar flow on both surfaces to the front spar. Fluid dispensed through some of these slots near the attachment line provided wing-surface wetting to protect against insect impacts. Both leading edges were equipped with anti-icing and fluid-purge systems. The NASA Leading Edge Flight Test Program made major progress in the development of practical systems for laminar flow control commercial aircraft. Both the effectiveness and practicality of the candidate laminar-flow, leading-edge systems were proven under representative airline service conditions.

Introduction

PREVIOUS laminar flow control (LFC) flight tests, such as the X-21, removed any doubt that extensive laminar flow could be achieved in flight (see Refs. 1 and 2). These flight tests did not, however, resolve concerns relative to the practicality of producing surfaces sufficiently smooth and wave free and of maintaining the required surface quality during normal service operations. In the late 1970s, with the progress made in the development of new materials, fabrication techniques, analysis methods, and design concepts, a reexamination of these issues appeared warranted.

The leading-edge region of a laminar-flow wing presents difficult problems associated with possible foreign object damage, insect impingement, rain erosion, icing, and other contamination. In addition, anti-icing, anticontamination, suction, and perhaps purge systems must all be packaged into a relatively small leading-edge box volume. Most of these problems are common to all of the concepts under consideration for the achievement of extensive laminar flow on aircraft wings; solutions are needed to establish the practicality of this technology for various types of aircraft.

In 1980, NASA initiated the Leading Edge Flight Test (LEFT) Program as a flight validation of LFC leading-edge systems under development by NASA and U.S. airframe manufacturers. Program objectives were to 1) demonstrate that the required leading-edge systems could be packaged into a wing representative of a subsonic commercial transport and 2) demonstrate the performance of these systems in representative operational conditions. To accomplish these objectives, the wings of a Lockheed JetStar aircraft were modified. Complete LFC leading-edge systems were installed in both the left and right wings, and flight tests were performed to gain operational experience to assess the effectiveness and practicality of each (see Fig. 1). References 3–11 provide a detailed description of the flight program. Herein, we will provide a program overview. Design, fabrication, and flight experiences will be discussed to provide an appraisal of the systems tested including their performance in a simulated airline environment.

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Aerodynamic Design

The aerodynamic design of the modified JetStar wing was subject to several constraints. Test articles were installed in the leading-edge opening created by removal of auxiliary fuel tanks on the basic wing. The planform of the modified wing is shown in Fig. 2. The modification spanned about 7 ft of the wing with the suction articles about 5 ft in span. The sweep of the basic wing limited the sweep of the test articles. Outboard and inboard, the sweep of the basic JetStar wing is 33 deg; the test articles were swept 30 deg. To produce the desired pressure distribution, the wing section required extensive modification in the test area. Wing contour to the rear spar on the upper surface and to the front spar on the lower surface was changed with installation of the test articles and fiberglass fairings over the wing box and at the extremities of the test article. The gloved wing was significantly thicker than the basic JetStar as the inserts in Fig. 2 indicate—particularly in the outboard region of the glove. The resultant test articles were dimensionally about equivalent to the leading-edge box of a DC-9-30 at the mean aerodynamic chord. Thus, the volume of the leading edge available for system installation was representative of a small commercial transport.

The design pressure distribution is shown by the solid lines in Fig. 3. The design goal was a pressure distribution in the test region that would be characteristic of a future LFC transport, a roof-top pressure distribution with supercritical flow over the wing box. The flight data confirmed that this was achieved over the expected range of JetStar cruise conditions.

A typical suction distribution for the upper surface is shown in Fig. 4. Suction levels were selected to be representative of that required in the leading-edge box on an LFC wing with

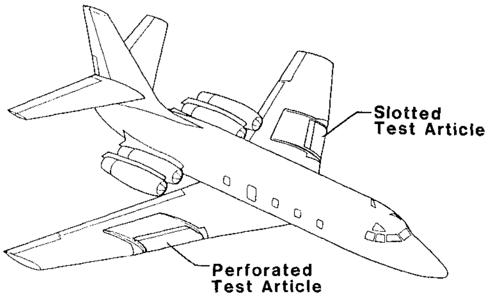

Fig. 1 NASA leading-edge flight test JetStar aircraft.

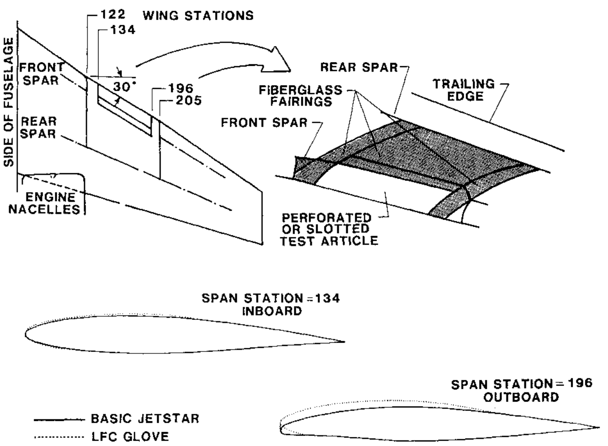

Fig. 2 LEFT JetStar planform and wing sections.

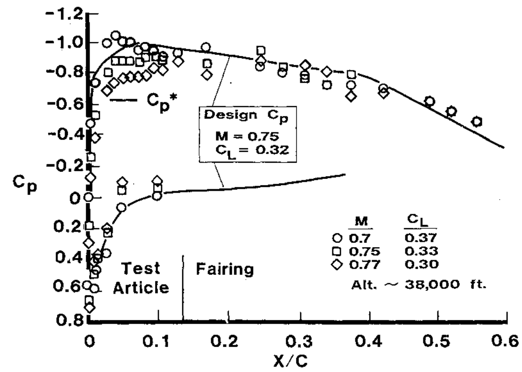

Fig. 3 Design and flight pressure distributions.

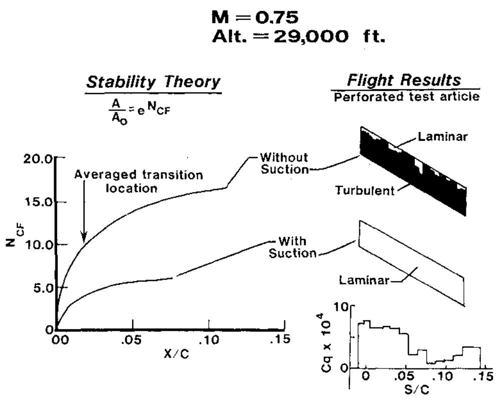

Fig. 4 Effect of suction on stability and transition.

near full chord, laminar flow; that is, more suction than would be required to get laminar flow to just the front spar. This was done so that the suction ducting volume requirement would be representative of future extended-chord applications. High initial suction levels were required to control cross flow in the leading edge. Beyond x/c greater than 0.05, a lower level of Cq was maintained to the front spar, again to be representative of the suction distribution required in an actual application with laminar flow beyond the front spar. Stability calculations were made to determine suction adequacy, and sample results are shown in Fig. 4. Crossflow N factors show that suction was needed to achieve laminar flow ahead of the front spar. Indeed, flight tests with suction blocked by sealing the perforations with wax showed transition to occur from about 2 to 4% chord downstream of the attachment line depending on flight conditions; for the condition given in Fig. 4, the average transition location was about 2% chord. With design suction levels (see Ref. 5), the crossflow N factors were lowered to values consistent with the achievement of laminar flow in the leading edge.

Leading-Edge Systems Design

Detailed descriptions of the leading-edge systems flown on the JetStar are provided in Refs. 4 and 5. Each system was complete in that it included all of the subsystems necessary to provide all of the functions required for an LFC aircraft, although different subsystems were used in each wing. The system on the right wing was installed in a structure consisting of a sandwich panel supported by ribs attached to the front spar (see Fig. 5). The outer suction surface face sheet of the panel was titanium, 0.025-in. thick, perforated with over 1 million holes about 0.0025 in. in diameter and drilled by an electron beam with 0.035-in. spacing between centers. Panel core and inner face sheet were constructed of fiberglass. The core was corrugated to form flutes for subsurface suction air collection. Bond areas between the perforated surface and the core were impervious to flow; thus, suction on the surface was along spanwise perforated strips spaced about 0.65 in. apart. Suction was applied to just the upper surface back to the front spar. No attempt was made, with either leading edge, to achieve laminar flow beyond the front spar. The perforated leading edge housed a Krueger-type leading-edge device that deployed to provide the main wing with line-of-sight protection against insect impacts during takeoff and landing. The Krueger had a glycol fluid anti-icing system, a commercially available system which dispensed a freezing point depressant fluid through a porous strip along the Krueger leading edge. The Krueger also had a spanwise row of spray nozzles that dispensed a 60/40 mixture of propylene glycol methyl ether (PGME), a freezing-point depressant, and water. These nozzles provided icing protection for the main wing and also could be used to wet the wing on takeoff or landing to supplement the insect protection of the Krueger. A system was also provided to purge the wing ducts and perforated surface of any fluids that might be ingested. This was simply a pressurized air source, which produced a positive 0.5 psi pressure differential across the suction surface. Use of the shield precluded attainment of laminar flow on the lower surface of the perforated article. The practical advantages of such an approach may more than compensate for the turbulent drag of the lower surface as discussed in Ref. 6.

The leading-edge system with the perforated suction surface presented no difficult fabrication problems. Indeed, a major outcome of the LEFT program is the emergence of perforated titanium as suction surface material that can be worked with practical fabrication methods to meet the stringent, laminar-flow surface quality requirements.

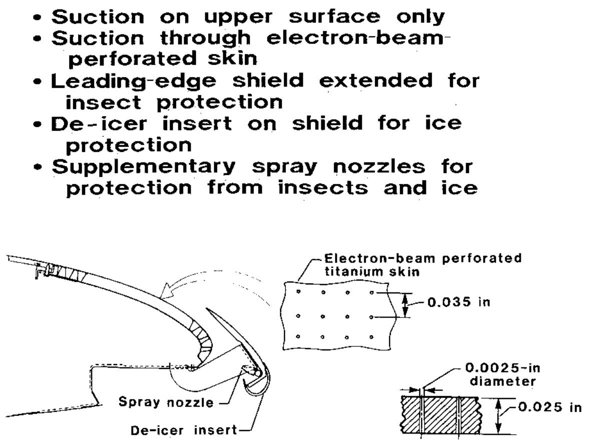

Fig. 5 Cross section of the perforated test article.

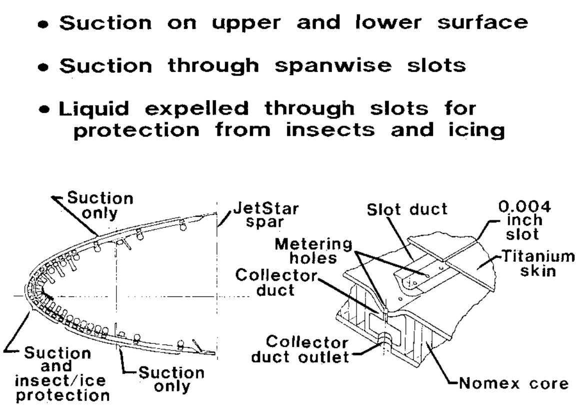

Fig. 6 Cross section of the slotted test article.

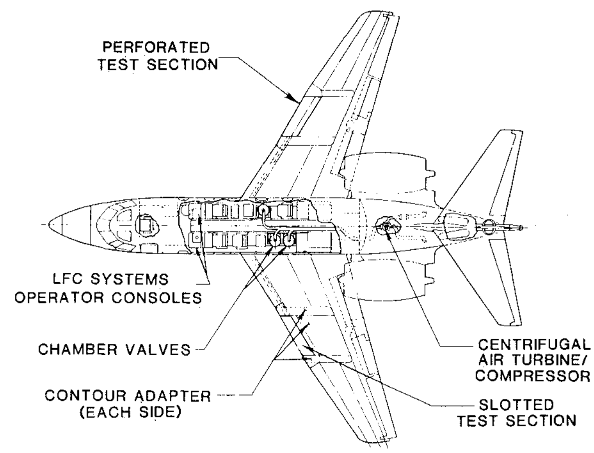

Fig. 7 Modified JetStar LEFT configuration.

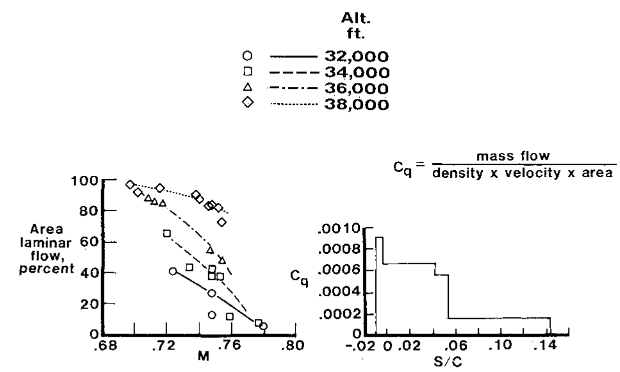

Fig. 8 Percent areal laminar flow—initial flights.

The leading-edge system with the slotted suction surface is illustrated in Fig. 6. The leading-edge box structure is of sandwich construction. A 0.016-in. thick titanium outer sheet is bonded to a sandwich of graphite-epoxy face sheets with a Nomex honeycomb core. Suction is accomplished through fine, spanwise slots (0.004 in. wide) on both the upper and lower surfaces to the front spar. Suction air 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 protection system. A 60/40 mixture of PGME and water is dispensed through slots above and below the attachment line. Fluid wets the surface to provide anti-icing or insect protection; previous flight and wind tunnel tests have shown that insects do not adhere to a wet surface. These slots are purged of fluid after climbout through a system of check valves; suction is applied to the slots at cruise. Purge pressure can also be applied to the slots.

Fabrication of the slotted leading edge presented formidable problems. Spring back of the initially roll formed outer titanium sheet was experienced when the slots were cut. To circumvent this problem, the skin was hot formed to stress relieve the skin in the desired contour. Bonding the skin to the substructure then became a problem because of the precision needed to minimize bond lines and adhesive flow into metering holes and ducts. Alignment of slot ducts with slots was also difficult because of the small duct dimensions and precision required. Two articles were built to flight standards. The first was considered to be flawed and was used for structural integrity tests. In spite of the lessons learned on the first article, the second article also experienced flaws that required extensive repair and then only marginally met laminar flow surface quality criteria. Funding constraints prevented further attempts to improve the article.

Surface pitots were used to determine if laminar flow existed at the front spar and to locate the approximate transition location ahead of each tube. Pitots were flight calibrated for transition location by placing transition strips at known locations on the test surface (see Ref. 9).

Aircraft Modifications

A schematic of the JetStar modified for the LEFT program is presented in Fig. 7. A centrifugal air turbine compressor, a modified AiResearch turbocompressor originally designed for the air-conditioning system on the Boeing 707, was used as a suction pump. The compressor is located in the unpressurized rear fuselage compartment. To permit optimization of the systems, each of the 15 suction flutes on the perforated test article and each of the 27 slots on the slotted test article have individual flow control. This is accomplished through the use of chamber valves in the fuselage cabin. Flow control valves were for research purposes only and were not used during the simulated airline service flights.

A pylon on the fuselage was used as a mounting for a Knollenberg probe to measure ice particle size and count during ice cloud penetrations. The pylon also housed a charging patch for measurement of aircraft charge buildup during cloud encounters (see Ref. 9).

Initial Flight Results

Extensive flight testing was first performed at the NASA Ames-Dryden Flight Research Facility to optimize the performance of the systems on the flight articles. Initial flight test results for the perforated test article are shown in Fig. 8, which illustrates the laminar flow area on the test article as a function of the Mach number at various altitudes in clear air. Most laminar flow was obtained at the lowest speeds and highest altitudes (i.e., the lowest Reynolds number). Conversely, lowest altitudes and highest speeds (the highest Reynolds number) resulted in the least laminar flow. At the design point, $M = 0.75$ and 38,000 ft. approximately 83% of the test article was laminar. At the off-design point of $M = 0.705$ and 38,000 ft, this value was only 7 or 8%. Calculations indicated that this poorer performance at higher Reynolds number was caused by spanwise turbulence contamination (see Ref. 8) from the fuselage and inboard wing.

As seen in the right part of Fig. 9, the transition front moved from inboard to outboard as altitude was reduced and Reynolds number increased. Approximate values of the attachment line momentum thickness Reynolds number critical value exceeded $Re_\theta \approx 90$–100 (see Ref. 1) over the range of flight conditions; movement of the transition front is consistent with the increasing values of Re_θ. Initial findings from the perforated test article are replotted in Fig. 9 as a function of the momentum thickness Reynolds number. As Re_θ is reduced to values near 90–100, the extent of laminar flow approached 100%.

Several approaches to control spanwise turbulence contamination were examined. A Gaster bump (see Ref. 12) was first attempted, but the best results were obtained with an integral notch bump in the inboard leading edge. This configuration allowed the achievement of nearly full laminar flow over the entire perforated test article (to the front spar) at the conditions tested (see Fig. 10). Some modification of the design suction distribution contributed to this improved performance. Suction was increased in the aft flutes. In general, the area where laminar flow was lost was believed due to locally poor isobar patterns or surface imperfections due to instrumentation installations. There was also some evidence of laminar boundary-layer separation at higher speeds and altitudes. With the improved configuration, at the design condition $M = 0.75$ and an altitude of 38,000 ft, the test article was 96% laminar. Areas of laminar-flow loss were turbulent wedges near the front spar.

The slotted test article with the notch bump did not maintain laminar flow as consistently as the perforated article (see Fig. 11). Near the design conditions, the test article surface varied between 80 and 94% laminar. At other Mach numbers and altitudes, the data were scattered without a clear indication of why the performance was poorer. These effects are probably the result of the poorer surface quality of the slotted article compared to the perforated article. It was felt, however, that the performance was not so unrepeatable as to invalidate the simulated airline service performed later in the program.

Flights were also made to optimize the performance of the fluid wetting systems of both test articles. Actual functional performance for insect protection or anti-icing was not evaluated; this was accomplished in the simulated airline service to be discussed later. Initially, only a good wetting of the suction surfaces was a goal. Wetting of both surfaces was good with flow rates of about 1.5 and 1.0 gallons/min through the slots

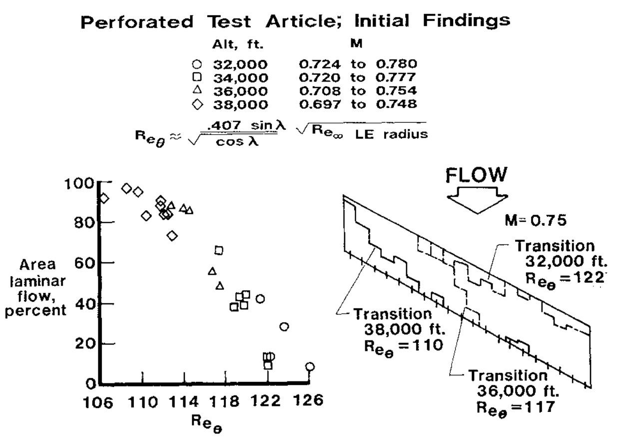

Fig. 9 Percent laminar flow vs momentum thickness Reynolds number.

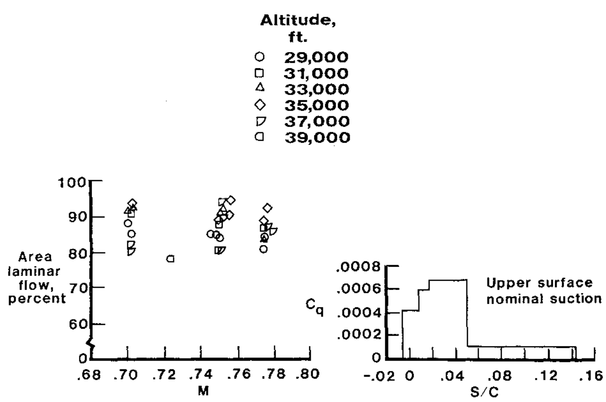

Fig. 11 Slotted percent areal laminar flow with notch/bump.

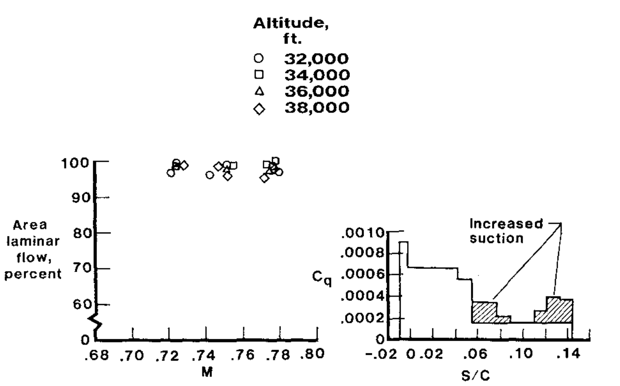

Fig. 10 Perforated percent areal laminar flow with notch/bump.

	TIME ELAPSED, MIN.	SLOTTED	PERFORATED
Takeoff	0	Liquid on	Shield extended Liquid on
1,000 ft.	1	Liquid off Purge on	Liquid off Purge on
4,000 ft.	2		Retract shield
20,000 ft.	8	Suction pump start	Suction pump start
23,000 ft.	10	Purge off	Purge off
32,000 ft.	15	Beginning of suction on test article	Beginning of suction on test article

Fig. 12 LEFT operations and in-flight leading-edge washing.

or spray nozzles, respectively. The operation sequence for the fluid, purge, and suction systems is illustrated in Fig. 12.

Simulated Airline Service

To evaluate the effectiveness and practicality of the laminar-flow, leading-edge systems in representative airline service, a series of simulated airline flights were made. The aircraft operated out of three major airports (Atlanta-Hartsfield, Greater Pittsburgh International, and Cleveland Hopkins International) to other airports in the United States. One to four flights per day were made from the home base airport; a total of 62 flights were made to 33 different airports in the United States. Flights were made from Atlanta in July 1985, from Pittsburgh in September 1985, and from Cleveland in February 1986. Thus, the weather conditions experienced varied from extreme summer to severe winter conditions.

Simulated service flights were made as similar to commercial transport operations as was possible. This included scheduled takeoffs and landings; queuing up with the commercial airliners in the flight line; use of air traffic control of vector, altitude and speed; and operation at various times of day including peak traffic hours. Before, during, and after flights, the aircraft was exposed to the airline environment and was parked overnight on the apron. LFC systems were operated in a handsoff mode; no adjustments were permitted in flight, and the same suction control settings were used for all flights, i.e., the systems were operated in an on/off mode.

Evaluation of LFC Systems

All subsystems of the perforated and slotted laminar-flow control systems were evaluated during the simulated service flights. The suction system was operated on all flights and the other subsystems used as weather or environmental conditions required.

A typical flight profile with laminar flow obtained with the perforated article is shown in Fig. 13. These data are for a flight from Atlanta to Atlantic City on February 20, 1986. The laminar flow achieved was steady over long periods during the flight through clear air. At three times during the flight, high altitude ice clouds were encountered and loss of laminar flow was experienced. Cloud penetrations were indicated by the charging patch instrumentation on the pylon. The insert in Fig. 13 shows how the laminar flow was distributed across the span before, during, and after a cloud penetration. Prior to the cloud entry, 100% laminar flow was registered on the leading edge to the front spar. In the cloud, the transition front was nearly uniform across the span at about 5% chord. Note, however, that good performance was restored after passing through the cloud. This was typical of cloud effects on the extent of laminar flow. Experience showed that ice cloud encounters at altitude were infrequent; less than 7% of the accrued cruise time was in clouds. Laminar flow was usually obtained to the front spar for clear-air cruise flight. Exceptions involved adverse effects such as rare insect impacts, surface icing due to inadvertent nonuse of pertinent subsystems, off-design flight, and icing damage to the notch bump.

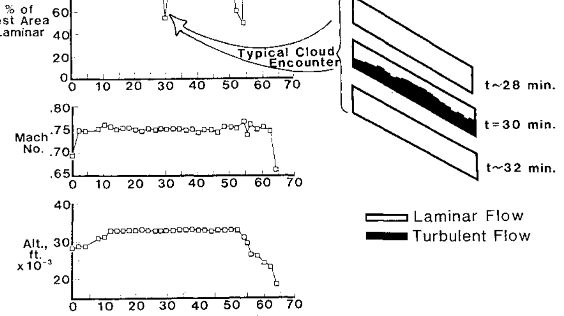

Fig. 13 Typical flight profile.

Examination of Fig. 13 also shows that in descent, appreciable amounts of laminar flow were obtained at lower than cruise altitudes. In fact, laminar flow was obtained at altitudes as low as 10,000 ft with no adjustment of the suction settings.

There appeared to be no appreciable degradation of the suction surfaces with service time. In particular, the perforated suction surface showed no tendency to clog; the porosity did not change over the flight-test program. Degradation of the slotted surface was more difficult to monitor because of the overall poorer performance due to the surface imperfections previously mentioned, but in general clear-air cruise performance did not deteriorate with time.

Both subsystems for insect contamination performed well during the simulated airline service. In the service operations out of Atlanta and Pittsburgh, insect contamination was evident on the slotted leading edge upon landing. These insect deposits were believed due to impacts during descent. The insect protection system was not used during landing on the slotted test article for the following reasons: 1) the long approaches to landing would require a considerable amount of fluid to be carried throughout the flight; 2) purging the liquid from the slots and ducts after landing requires high-power settings of the engines, and the resulting noise level would be very undesirable; and 3) postflight cleaning could be accomplished simply; and and most effectively by the ground crew. Visual observations of the leading edge during climbout and cruise indicated that the fluid wetting system did keep the slotted leading edge clean for those portions of the flights. Between flights, a damp cloth was used to clean the slotted leading edge. Cleaning of the perforated leading edge between flights was not necessary. The Krueger shield was used on both takeoff and landing and was almost completely effective in eliminating insect deposits.

Severity of potential insect contamination is illustrated in Fig. 14. Results of a postflight inspection of the leading edges after a flight from Boston to Pittsburgh in September 1985 are shown. The upper surface of the slotted leading edge after nonuse of the fluid-injection system revealed a great number of insect deposits, many of sufficient height to cause boundary-layer transition at cruise conditions. Two insect deposits were observed on the inboard end of the perforated leading edge. Occasional deposits that occurred in this area were a consequence of the shield design, which did not provide protection at the inboard edge. It was noticed that this insect debris tended to erode away in subsequent flights, and that passage through ice particles provides a natural cleaning of the surfaces. Midway through the simulated service, it was found that the shield alone was sufficient to protect the leading edge from insect impacts; use of the supplemental spray was then discontinued.

The system for purging the fluids from the air passages operated satisfactorily in flight and on the ground in winter or summer operations. During the simulated service in Atlanta, while on the ground, the aircraft was exposed to a heavy rainfall of over 1.3 in. in a short time. The next morning, rain water which had seeped into the ducting was easily purged from the ducts, slots, and perforations. With the purge system, accumulation of ground anti-icing fluids in the ducts, etc., also presented no problems.

In-flight icing was encountered in the winter simulated service from Cleveland in February 1986. Although these encounters were quite limited, visual observations indicated both anti-icing systems were effective. Subsequent laminar flow monitoring in high-altitude cruise indicated no apparent problems with fluid runback and refreezing on the suction surfaces.

Quite severe winter weather was experienced in the Cleve-

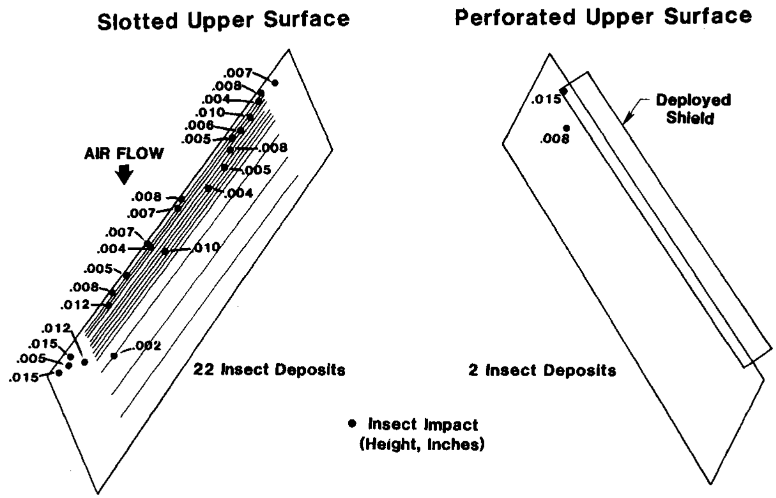

Fig. 14 Typical insect contamination.

land operations. Severe snow and ice accumulation on the aircraft occurred on the ground. With conventional hand-held deicing equipment, snow and ice was as easily removed as is currently accomplished for turbulent commercial aircraft. The purge system then removed any fluids in the perforations, slots, or ducts.

Concluding Remarks

Much progress has been made in the development of practical systems for laminar flow control commercial aircraft. Systems that provide practical solutions to the difficult problems associated with the leading-edge region were demonstrated in flight under representative airline service conditions.

References

[1]Pfenninger, W., "Laminar Flow Control Laminarization," AGARD Rept. No. 654, June 1977.

[2]Edwards, B., "Laminar Flow Control—Concepts, Experiences, Speculations," AGARD Rept. No. 654, June 1977.

[3]Wagner, R. D., Maddalon, D. V., and Fischer, M. C., "Technology Developments for Laminar Boundary Layer Control on Subsonic Transport Aircraft," AGARD Rept. No. 365, 1984.

[4]Etchberger, F. R., "Laminar Flow Control Leading Edge Glove Flight—Aircraft Modification Design, Test Article Development, and Systems Integration," NASA CR-172136, 1983.

[5]Douglas Aircraft Company Staff, "Laminar Flow Control Leading Edge Flight Test Article Development," NASA CR-172137, 1984.

[6]Douglas Aircraft Company Staff, "Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft," NASA CR-159251, 1983.

[7]Fischer, M. C., Wright, A. S., Jr., and Wagner, R. D., "A Flight Test of Laminar Flow Control Leading Edge Systems," NASA TM-85712, 1983.

[8]Fisher, D. F., and Fischer, M. C., "The Development Flight Tests of the JetStar LFC Leading Edge Flight Experiment," NASA CP-2487, 1987.

[9]Davis, R. E., Maddalon, D. V., Wagner, R. D., Fisher, D. F., and Young, R., "Evaluation of Cloud Detection Instruments and Performance of Laminar-Flow Leading-Edge Test Articles During NASA Leading-Edge Flight Test Program," NASA TP-2888, 1989.

[10]Powell, A. G., and Varner, L. D., "The Right Wing of the LEFT Airplane," NASA CP-2487, 1987.

[11]Maddalon, D. V., Fisher, D. F., Jennett, L. A., and Fischer, M. C., "Simulated Airline Service Experience with Laminar Flow Control Leading-Edge Systems," NASA CP-2487, 1987.

[12]Gaster, M., "A Simple Device for Preventing Turbulent Contamination on Swept Leading Edges," *Journal of the Royal Aeronautical Society,* Vol. 69, 1965, p. 788.