PROGRESS AT DOUGLAS ON LAMINAR FLOW CONTROL APPLIED TO COMMERCIAL TRANSPORT AIRCRAFT

ICAS-82-1.5.3

by

W. E. Pearce
Manager – LFC Project
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California

ABSTRACT

Design studies, development efforts and testing related to laminar flow control for subsonic commercial transport aircraft are described in this paper. The paper covers selection of a suitable suction surface, integration of the suction system, and results of LFC aircraft design studies. Current programs which include wind tunnel testing and flight testing are discussed as well as proposed future LFC activities.

INTRODUCTION

The current work at Douglas Aircraft Company on laminar flow control (LFC) is sponsored primarily by NASA under the Aircraft Energy Efficiency (ACEE) program with further support from Douglas-funded independent research and development programs. The investigation started with an evaluation of LFC system concepts in October 1976, and the effectiveness of the systems subsequently developed is now being proved on wind tunnel and flight test programs.

The objective of this effort is to significantly reduce the fuel consumption of future subsonic commercial transport aircraft, provided that they are also competitive economically and are entirely practical for use under environmental conditions appropriate to scheduled airline operation. The LFC programs include design studies; systems analysis; fabrication development; and structural, wind tunnel, and flight testing.

With the wings swept for cruising at high subsonic speeds, transition from laminar to turbulent flow usually occurs very close to the leading edge even with a clean, smooth external surface. The transition can be caused initially by instability of the spanwise flow of the boundary layer along the attachment line at the leading edge. This is adversely affected by increased bluntness of the leading edge and increased sweep. The next dominant cause of laminar boundary layer instability is a cross flow condition resulting from a chordwise pressure gradient combined with isobar sweep. Tollmien Schlichting instability then tends to occur further aft on the surface, particularly with adverse pressure gradients.

Fortunately, the removal of only a small fraction of the boundary layer by suction at the surface can counteract these influences. The boundary layer stability provided by suction can also provide increased tolerance to slight surface imperfections. The use of suction on an airfoil having an acceptable pressure distribution was therefore the LFC method selected.

LFC SUCTION SURFACE

Selection of a satisfactory LFC suction surface was the first consideration. Preceding LFC studies had concentrated on the use of multiple suction slots, resulting in an extensive data base being available for this approach. For this investigation at Douglas, however, it was decided to also pursue the alternative possibilities of using porous or perforated surfaces and to take full advantage of any useful recent developments in technology, although this would require additional development work.

Following an initial survey of practical porous and perforated materials, a number of surfaces were tested in the Douglas wind tunnel, in Long Beach, California. Test panels were inserted in a flat panel model, as shown in Figure 1. As an initial screening process, the extent of laminar flow was measured as influenced by the level of

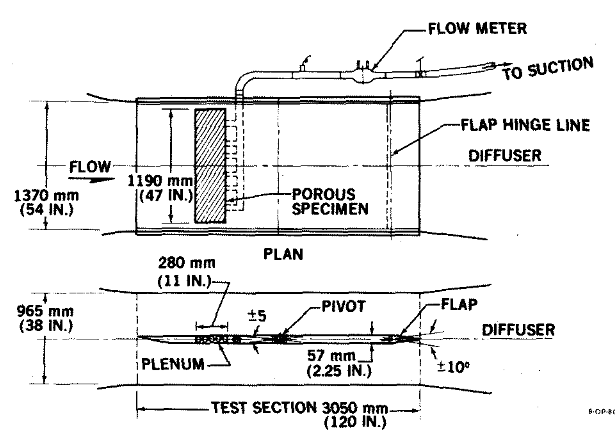

FIGURE 1. WIND TUNNEL MODEL TEST FOR LAMINAR FLOW WITH VARIOUS SUCTION SURFACES

suction through the surface, and the results were compared with those of a nonporous surface at Reynolds numbers up to 11 x 10^6. Some typical results are shown in Figure 2. The alternative surfaces selected subsequently for further consideration were a slotted surface, porous "Dynapore," electron beam perforated titanium, and strip porosity variations of the latter two, all of which performed satisfactorily during wind tunnel testing.

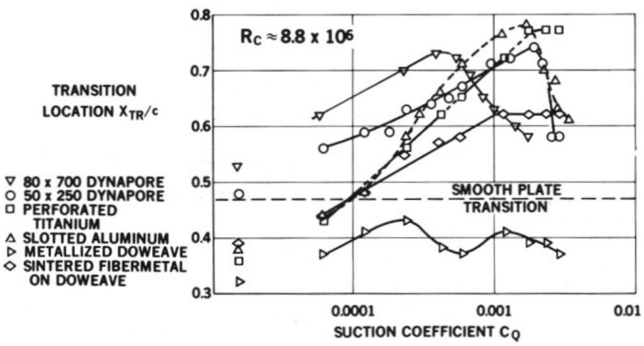

FIGURE 2. COMPARATIVE EFFECTIVENESS OF LAMINAR FLOW CONTROL SURFACES

The slotted surface posed a number of practical difficulties.

1. The slots need to be as narrow as 0.076 mm, (0.003 in.) and are difficult to machine satisfactorily in the tough, corrosion-resistant surface needed.
2. Slot width tolerances would need to be extremely tight in order to avoid significant suction variations along the span.
3. Because the slots are cut after the surface is attached to its supporting structure, the release of any locked-up stresses during fabrication could cause variations in slot width and contour.
4. On tapered wings, the slots, which should follow the isobars to avoid spanwise pressure gradients, tend to be too close at the wing tip unless the number of slots is reduced. Ending a slot along the span could result in transition occurring at that point.
5. Should damage occur during fabrication or in service, the repair and alignment of slots in a repair patch with those already existing would be very difficult.

Because of these known problems, the porous or perforated surfaces were given primary consideration.

A variety of porous surfaces was investigated. The most satisfactory of these was "Dynapore," a finely woven stainless steel material that is calendered to produce a smooth flat surface. Highly magnified photographs of Dynapore material are shown in Figure 3. Without magnification, it is difficult to see any irregularities in the surface, and it performed very well during LFC wind tunnel testing. The problems encountered were mainly structural. Although the weave is locked in place by the calendering process, the elastic strain limit is low. The material is also produced only in an annealed condition, resulting in low impact and rain erosion resistance. It was therefore necessary to structurally support the surface. A diffusion-bonded perforated sublayer was used for this purpose, resulting in increased weight. Some porosity variation was also noticed.

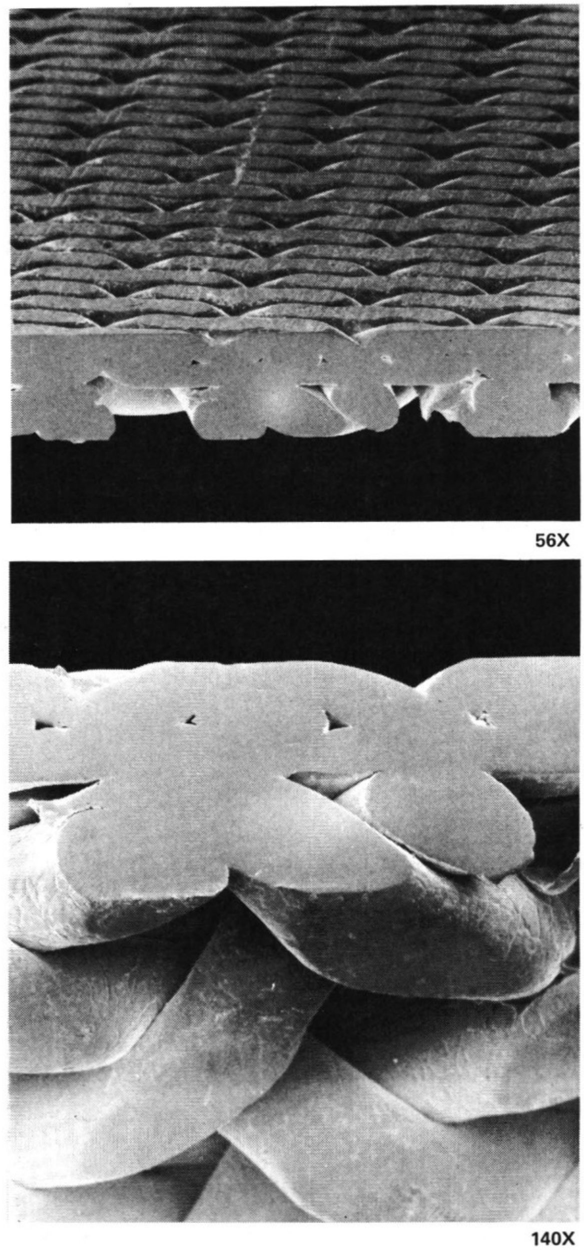

FIGURE 3. 80 BY 700 DYNAPORE SURFACE PLUS DIFFUSION-BONDED 80 BY 80 SUBLAYER

The electron beam (EB) perforated titanium proved to be far more practical than the preceding alternatives. Previous attempts at achieving LFC with perforated surfaces had not been satisfactory because the smallest holes that could be produced economically were too large. The EB drilling process enables the holes to be as small as 1/10 of the material thickness. The holes can be produced rapidly, at a typical rate of about 1200 per minute.* The

*The EB perforated panels were manufactured by Pratt & Whitney Aircraft to meet Douglas' design requirements using improved techniques that they developed with EB perforating equipment supplied by Steigerwald.

hole pattern tested is shown in Figure 4. It should be noted that the taper resulting naturally from the process should prevent clogging by any particles entering from outside. Figure 5 shows the hole pattern compared with an ordinary paper clip. Figures 6 and 7, of increasing magnification, show the remarkable regularity and circularity of the holes produced. Compared with the preceding alternative suction surfaces, the EB perforated material offers several advantages:

1. Its high strength and stiffness contribute to wing bending and torsional strength and stiffness.
2. Damage resistance is high, no loss of LFC occurred during tests when dents were repaired by filling.
3. Any accumulation of dirt can be removed by simple steam cleaning to restore the original porosity.
4. Porosity is uniform and unaffected by stress and strain.
5. Both weight and cost are lower.

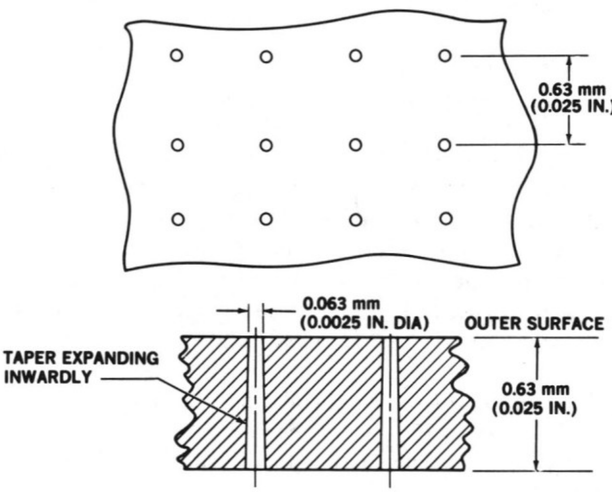

FIGURE 4. ELECTRON-BEAM-PERFORATED TITANIUM SUCTION SURFACE

FIGURE 5. ELECTRON BEAM PERFORATIONS COMPARED WITH ORDINARY PAPER CLIP

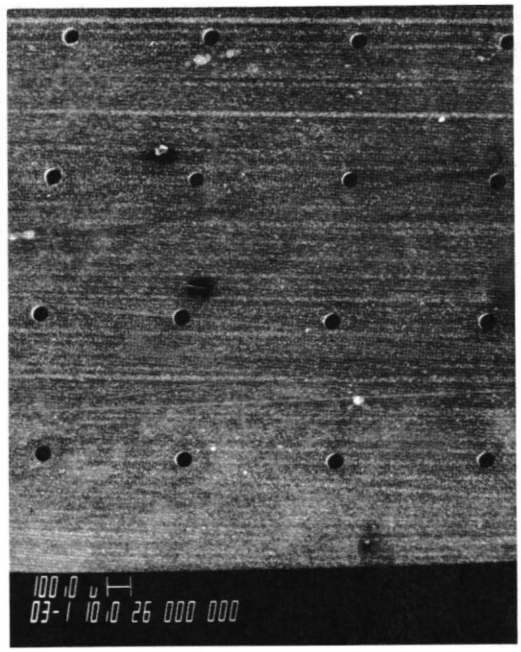

FIGURE 6. REGULARITY OF ELECTRON BEAM PERFORATIONS 0.025 INCH (0.63 mm) APART

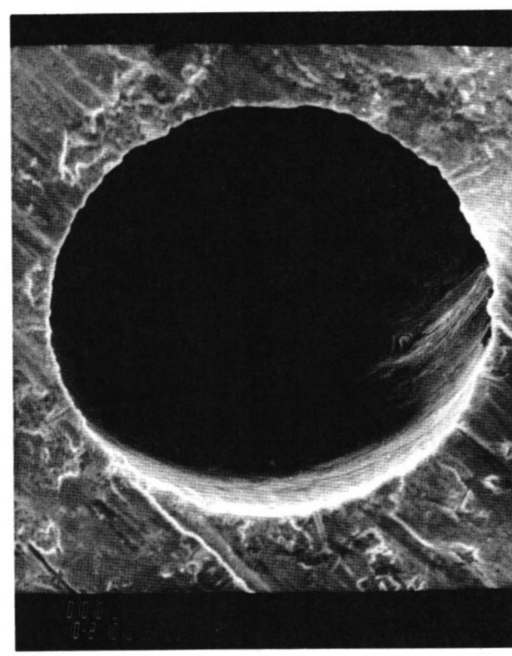

FIGURE 7. SINGLE ELECTRON BEAM PERFORATED HOLE, 0.0025 INCH (0.063 mm) DIAMETER

LFC GLOVE PANEL

The EB perforated titanium surface is bonded to a corrugated composite substructure as shown in Figure 8. Alternate flutes are used to collect suction air from the surface. The porous strip effect obtained was found to have no adverse effects on LFC performance.

The glove panel is attached to the basic wing structure as indicated in Figure 9. The attachment to the external wing stiffeners creates integral suction ducts that collect suction air from the glove panel flutes through holes metered as necessary to control suction distribution. The primary wing box skin forms a reliable barrier between the suction air and the integral fuel tank.

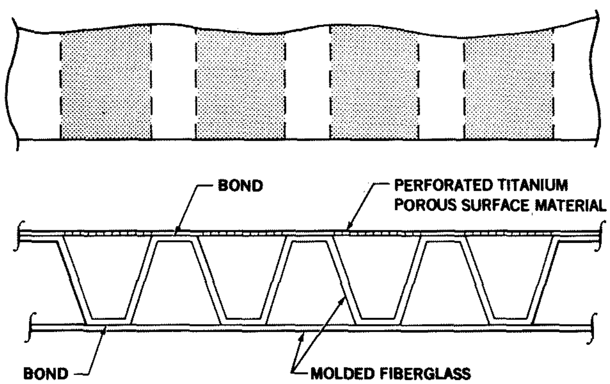

FIGURE 8. LFC GLOVE PANEL STRUCTURE

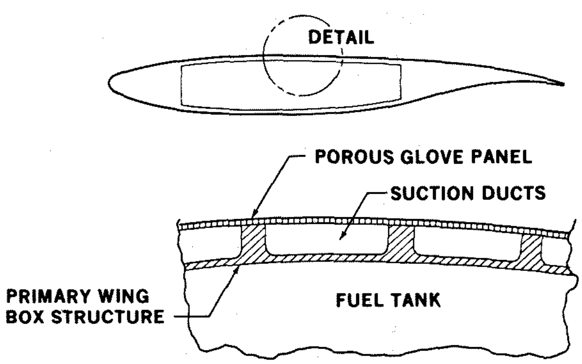

FIGURE 9. LFC POROUS SUCTION GLOVE

SWEPT WING LFC WIND TUNNEL TESTING

After the initial wind tunnel testing to compare alternative suction surfaces, LFC capability needed to be demonstrated under the cross-flow conditions resulting from wing sweep. Low-speed wind tunnel testing was done at Douglas. The model and test result are illustrated in Figure 10.

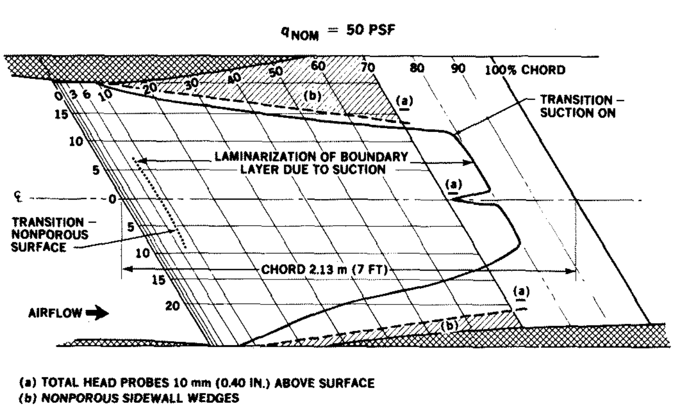

FIGURE 10. EFFECT OF SUCTION TO 70-PERCENT CHORD ON TRANSITION

The model chord was 2.13 meters (7 feet), and the tunnel walls were modified to simulate an infinite 30-degree swept wing. The maximum Reynolds number was 4.11 x 10^6 per meter (1.35 x 10^6 per foot), compared with 4.87 x 10^6 per meter (1.6 x 10^6 per foot) for an aircraft flying at a Mach number of 0.75 at 38,000 feet. Laminar flow was achieved satisfactorily back to 80 percent chord, using suction to 70 percent chord.

LFC AIRCRAFT DESIGN STUDY

Comprehensive preliminary design studies were conducted to assess the possible benefits of LFC applied to commercial transport aircraft. The selected aircraft mission is listed in Table 1.

TABLE 1
AIRCRAFT DESIGN STUDY MISSION

RANGE	5,000 N MI
PAYLOAD	69,000 LB (300 PASSENGERS PLUS CARGO)
CRUISE MACH NO.	0.8
APPROACH SPEED	130 KEAS
FIELD LENGTH	10,000 FT

Because of the unusual wing construction, the study included strength, flutter, and aeroelastic analyses for a range of aspect ratios. Advanced technology appropriate to a 1995 time frame was utilized and included a graphite-epoxy composite basic wing structure.

The initial LFC configuration, shown in Figure 11, was laminarized to 70 percent chord on both upper and lower wing surfaces. The suction pump and drive systems were mounted under the wing near mid-semispan to reduce suction duct sizes. The propulsion engines were located on the aft fuselage to reduce engine noise effects on LFC.

Figure 12 shows a competitive turbulent flow configuration designed for the same mission and with the same level of advanced technology except for LFC.

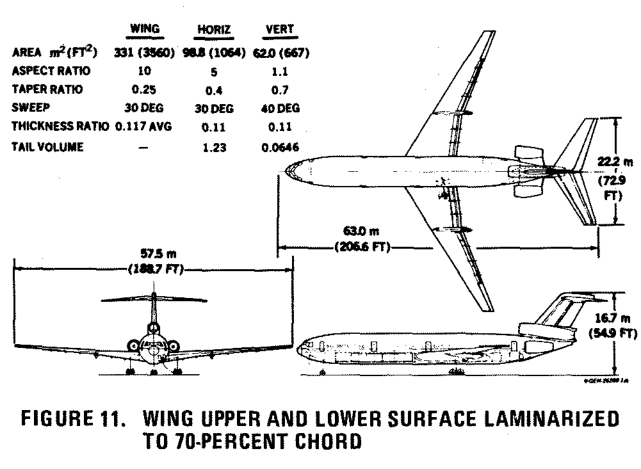

FIGURE 11. WING UPPER AND LOWER SURFACE LAMINARIZED TO 70-PERCENT CHORD

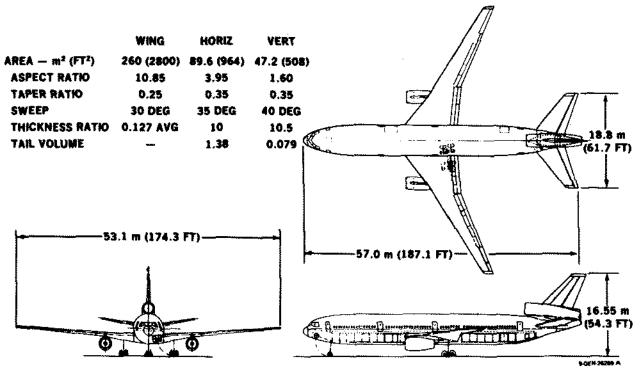

FIGURE 12. ADVANCED TURBULENT FLOW AIRCRAFT

A performance comparison showed that the LFC airplane would require 22 percent less fuel for the same mission, allowing for 2 percent fuel used in providing suction.

Further consideration of the initial LFC configuration disclosed a number of concerns:

1. Positive protection of the wing leading edge would be required to avoid insect impingement – insect debris as small as 0.1 mm (0.004 inch) above the surface could cause a trailing wedge of turbulence.
2. Access to wing systems would be difficult with LFC on the lower surface.
3. The sensitive lower LFC surface would be vulnerable to damage from debris thrown up from the runway.
4. A comparison of wing areas showed the LFC wing area to be 27 percent greater than the turbulent wing area due to its relatively poor maximum lift capability without a leading edge device.

It became obvious that a leading edge shield could be shaped to also provide increased lift and could be retracted into the lower surface when not in use. A device of this type is shown in Figure 13. With such a device, laminarization of the lower surface would be impossible due to surface irregularities at the interfaces. However, removal of LFC from the lower surface would overcome the vulnerability and access problems.

LFC is more effective on the upper surface, so an extension of laminar flow to 85 percent chord on the upper surface was considered as possible compensation for the loss of LFC on the lower surface. The effect of this is shown in Figure 14. The small increase in drag coefficient could be more than compensated by the simpler LFC system, the more efficient wing structure, and the improved wing lift system. Figure 15 shows that even with a smaller flap aft, the wing with a leading edge device is able to provide a 24 percent increase in maximum lift coefficient.

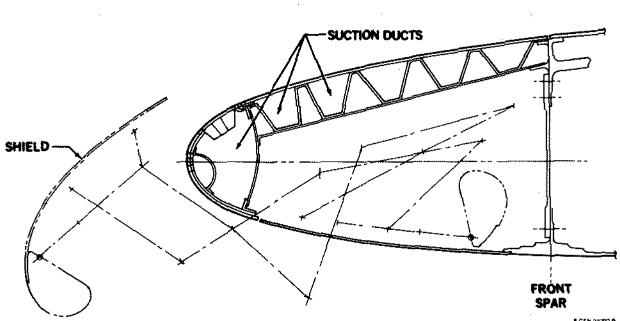

FIGURE 13. LEADING EDGE DESIGN WITH UPPER SURFACE SUCTION

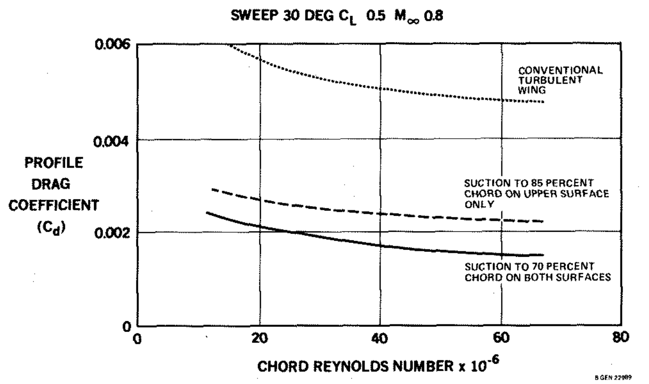

FIGURE 14. EFFECT OF LFC EXTENT ON WING PROFILE DRAG

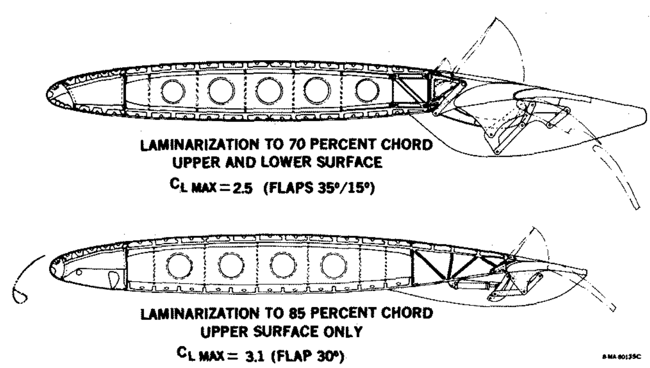

FIGURE 15. COMPARISON OF LFC WING SECTIONS

A wind tunnel test in the NASA-Lewis icing tunnel (Figure 16) confirmed the shielding effect of the leading edge device and provided data for use in analyzing insect trajectories based on existing programs developed for ice accumulation.

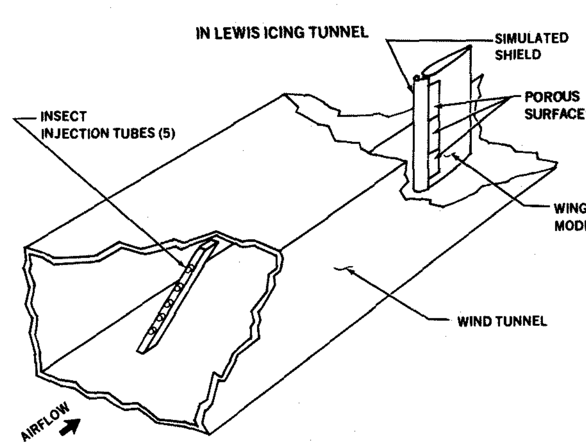

FIGURE 16. INSECT IMPINGEMENT TESTS CONDUCTED IN NASA-LEWIS ICING TUNNEL

The revised LFC configuration with suction only on the upper wing surface to 85 percent chord is shown in Figure 17. The improvements over the previous LFC configuration are presented in Table 2. From every aspect considered, the configuration with LFC on the upper wing surface only (USO) was superior. The practical design objectives of reduced vulnerability to both insect contamination and foreign object damage plus normal wing access to systems were obtained. The effect of LFC on direct operating cost (DOC) is shown as a function of fuel cost in Figure 18. Based on recent fuel prices, the DOC of the USO aircraft would be 6 to 8 percent less than with suction on both surfaces (U + L), and the USO aircraft is again superior.

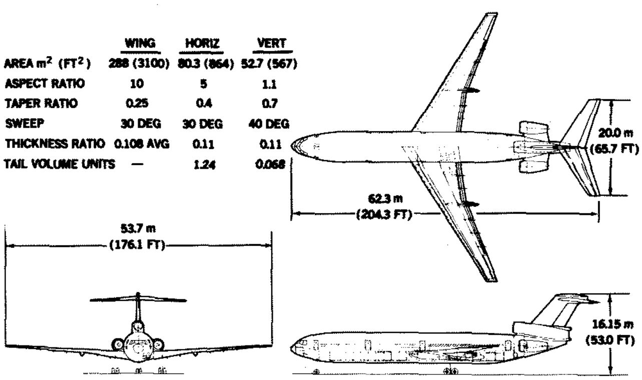

FIGURE 17. UPPER AIRFOIL SURFACE LAMINARIZED TO 85-PERCENT CHORD

TABLE 2
LFC AIRCRAFT CONFIGURATION SUCTION ON UPPER WING SURFACE TO 85-PERCENT CHORD

		LFC ON BOTH WING SURFACES TO 70% C	LFC ON UPPER SURFACE ONLY TO 85% C	CHANGE (%)
WING AREA	m² (FT²)	331 (3,560)	288 (3,100)	−13.0
WEIGHT (OEW)	kg (LB)	97,900 (215,830)	93,690 (206,550)	− 4.3
THRUST/ENG SLS	kn (LB)	145.4 (32,690)	139.8 (31,430)	− 3.9
FUEL BURNED	kg (LB)	49,745 (109,670)	49,260 (108,600)	− 1.0
INITIAL COST	($ MILLION)	48.39	46.52	− 3.9

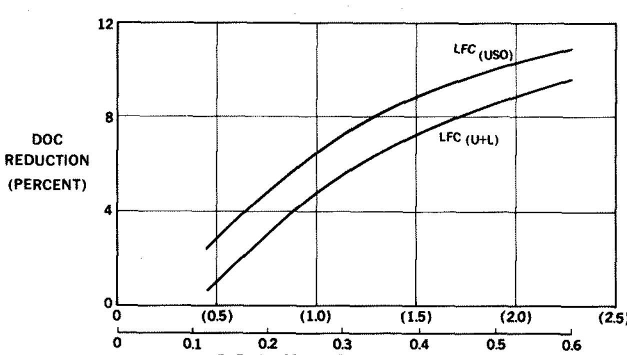

FIGURE 18. REDUCTION IN DOC DUE TO LFC

LFC LEADING EDGE FLIGHT TEST

The leading edge region of the wing is most critical under adverse environmental conditions. To test the effectiveness of the LFC surface protection systems, a Douglas LFC leading edge is to be installed on the NASA JetStar aircraft and tested in 1983. The test section, as shown in Figure 19, is located within a glove fairing designed to provide a pressure distribution similar to that desired for LFC. The protective shield uses only a simple hinge, as shown in Figure 20, and is designed to avoid significant asymmetric lift when extended only on one side of the aircraft. The relatively small shield is equipped with a supplementary spray system to provide additional protection for the upper surface, if necessary.

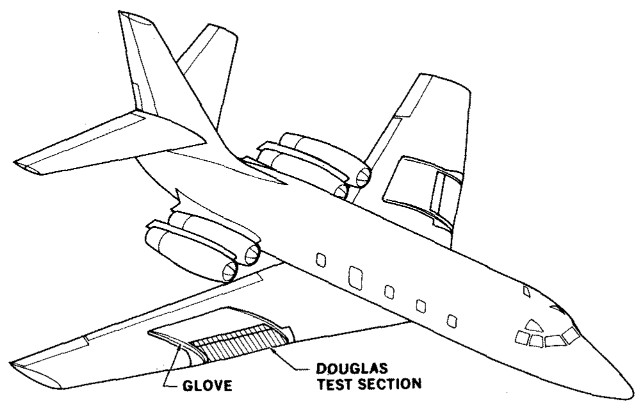

FIGURE 19. NASA JETSTART LFC TEST AIRPLANE

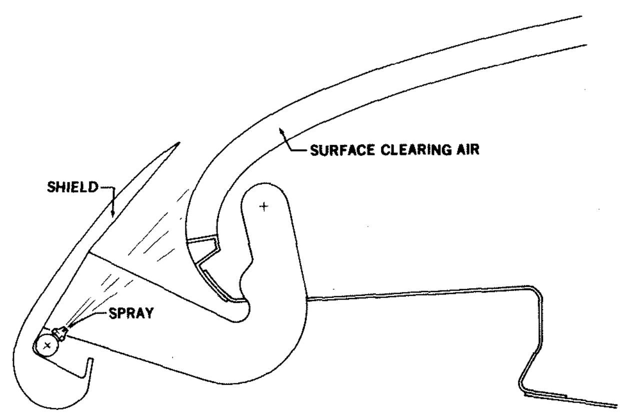

FIGURE 20. CONTAMINATION AVOIDANCE CONCEPT

LFC HIGH-SPEED SWEPT WING WIND TUNNEL TEST

The Douglas LFC system is to be tested on a 2.14 meter (7-foot) chord swept wing model. Tests will be made in the NASA Langley 2.44 meter (8-foot) pressurized tunnel at a Mach number of 0.82 and at Reynolds numbers ranging from 8 x 10^6 to 40 x 10^6.

Perforated suction glove panels will be installed on the upper surface, in place of previously tested slotted panels, to test their effectiveness for achieving LFC over the full chord length.

PROPOSED FOLLOW-ON LFC PROGRAMS

Before going ahead with an LFC commercial transport aircraft, a more complete LFC system must be demonstrated in flight on a sufficiently representative aircraft.

Design studies have shown than an LFC glove could be installed on a DC-9 wing, as illustrated in Figure 21. To reduce ducting problems, the LFC test regions could be distributed on both wings, as shown in Figure 22. This would allow independent investigation of LFC regions that present different problems. In addition, an LFC system utilizing discrete suction in critical regions could be compared with a full suction system. An example of this is shown in Figure 23 where suction is used only to stabilize the laminar boundary layer at the attachment line and in the forward cross flow region. A favorable gradient is then employed to maintain laminar flow as far back as possible without inducing separation in the aft pressure recovery region.

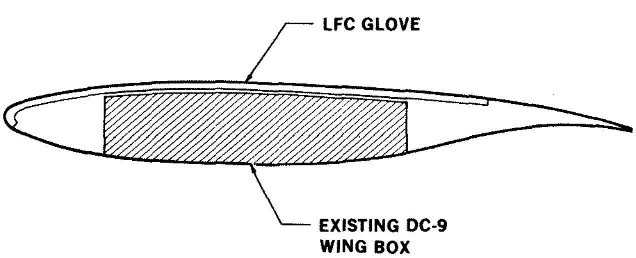

FIGURE 21. PROPOSED LFC GLOVE ON DC-9 WING BOX

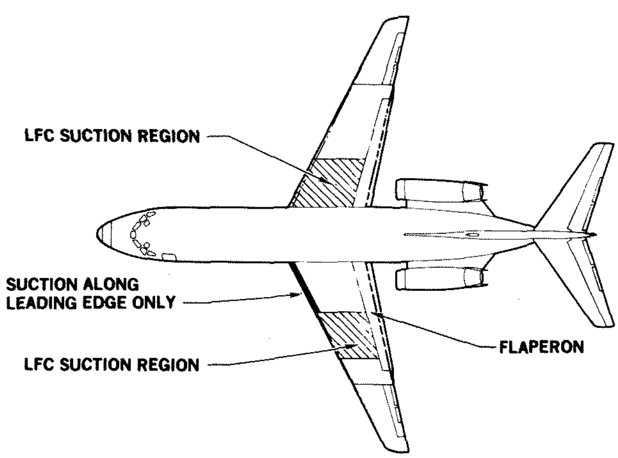

FIGURE 22. LFC WING GLOVE ON DC-9

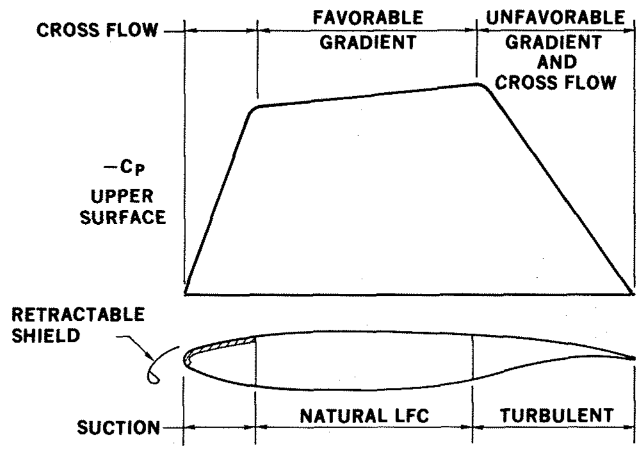

FIGURE 23. NATURAL LFC ON SWEPT WING WITH SUCTION AT LEADING EDGE

The developed LFC system could be demonstrated finally by installing a complete LFC wing on the DC-9 aircraft used previously for LFC system development, as shown in Figure 24. The basic aft fuselage location of the propulsion engines and the clean wing on the DC-9 are ideally suited for this purpose.

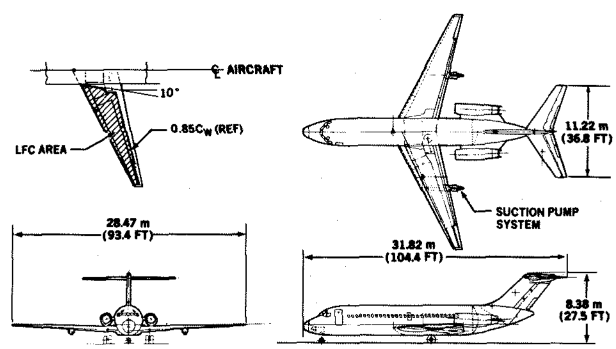

FIGURE 24. DC-9 WITH LFC WING

CONCLUSIONS

The use of a reliable and effective EB perforated suction surface together with the high lift shield and the use of suction only on the upper wing surface may result in the breakthrough needed to make LFC commercial transport aircraft a reality in the near future.