NASA TM-84518

NASA Technical Memorandum 84518

NASA RESEARCH ON
VISCOUS DRAG REDUCTION

NASA-TM-84518 19820025468

RICHARD H. PETERSEN
AND
DAL V. MADDALON

AUGUST 1982

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

NASA RESEARCH ON VISCOUS DRAG REDUCTION

R. H. Petersen and Dal V. Maddalon
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

Abstract

Current NASA research points toward exciting opportunities for large reductions in viscous drag. Research is underway on natural laminar flow, laminar flow control by suction, and turbulent drag reduction. Preliminary results suggest that a significant amount of natural laminar flow can be achieved on small, straight-wing airplanes. On larger, swept-wing aircraft, laminar flow control by distributed suction is expected to result in significant fuel savings. The area over which laminar flow control is applied depends on tradeoffs involving structural complexity, maintenance, and cost. Several methods of reducing turbulent skin friction by altering the turbulence structure itself have shown promise in exploratory testing. This paper reviews the status of these technologies and indicates the benefits of applying them to future aircraft.

Introduction

From 1960 to 1972, jet fuel prices paid by U.S. airlines were nearly constant at about 10¢ per gallon. After the Arab oil embargo of 1973, however, domestic fuel prices increased by over an order of magnitude to the present level of about $1.05 (fig. 1). During this time, the annual U.S. airline fuel bill rose from 1 billion dollars to over 11 billion dollars. The percent of airline direct operating cost due to fuel increased from 24% to a staggering 60% and inevitably fares -- on average -- rose. The impact of these cost increases has been significant. Major changes occurred in the kind of airline service offered. More seats were added to aircraft, fare incentives were given to increase airplane use, design range was better matched to route structure, and drag cleanup operations were performed wherever possible. A major improvement in fuel efficiency resulted with traffic increasing from 162 billion passenger miles per year in 1973 to 254 billion passenger miles per year in 1980 while fuel burned in moving this traffic was reduced from about 10.7 million gallons annually to only 10.2 million gallons, yielding a 65% improvement in the passenger miles obtained per gallon of fuel used. Further improvements, however, depend primarily on vehicle and system technology advances. Airlines responded by placing orders for an entirely new generation of fuel-efficient jet transports, the 767 and 757. The 767 begins scheduled service this year and the 757 enters service in early 1983. In addition, many new fuel-efficient models of existing aircraft were (or will be) introduced (i.e., L-1011-500, DC-9 Super 80, and the A-310). For all such aircraft, however, the present state-of-the-art is for airplane designs based on turbulent flow with the attendant penalty for viscous drag.

Viscous drag represents approximately half of the total drag and fuel burn for a long-range commercial transport aircraft and results in about a third of its direct operating cost. Achieving all-laminar flow on such an aircraft would reduce viscous drag by nearly 90%, fuel burned almost 45%, and direct operating cost about 27%.

Military transport aircraft would show the same drag and fuel reductions, but less relative cost savings. For military aircraft, laminar flow offers the advantage of tremendous increases in range and payload capability[1].

NASA responded to the increased fuel prices by giving much more emphasis to research which improved aircraft fuel consumption characteristics. Payoffs from such research were identified in references 2 and 3. Through the Aircraft Energy Efficiency (ACEE) Program, NASA focused aircraft fuel conservation technology development in the discipline sciences of aerodynamics, structures, materials, controls, and propulsion[4] -- and much was accomplished with this program. However, it is expected that fuel prices will continue to increase in the future and there is still a lot that can be done. We therefore plan to build on our previous efforts in these basic disciplines. This paper will cover NASA research in just one area, that of viscous drag reduction. Here, particularly, current efforts indicate exciting possibilities for large drag reductions because of technological advances in, for example, new materials, fabrication techniques, stability theory, and airfoil and wing design methodology. Specific areas of research to be addressed are natural laminar flow, suction-controlled laminar flow, and turbulent skin friction reduction. This paper reviews the status of these technologies, how they might be integrated into aircraft, and the potential benefits that might be realized.

Discussion

Background

Figure 2 displays the fuel efficiency that might be attained on a 1990 technology level, four-engine, long-range transport airplane. This reference aircraft is fabricated of composite materials, utilizes supercritical airfoil

N82-33344 #

technology, has an aspect ratio 12 wing, and uses an active control system featuring relaxed static stability. It is designed to carry about 500 passengers and 43,000 pounds of cargo to a range of about 5000 n.mi. Aircraft characteristics are summarized in Table 1. The resulting seat-miles per gallon (smg) at cruise is about 112, almost double the 60 smg possible with current long-range aircraft. Also shown in figure 2 is the performance possible with the 1990 airplane if laminar flow could be attained over all of the aircraft's surfaces. Such an all-laminar airplane would achieve 225 smg, a 275% increase over the base aircraft's performance and a 100% increase over the 1990 advanced technology airplane.

Attainment of laminar boundary layer flow in day-to-day airplane operations with the resulting reduction in skin friction has long been the dream of the aerodynamicist. To appreciate the potential problems associated with this very difficult task, consider the physical parameters which affect laminar flow. Figure 3 lists the most important. Most fundamental, of course, is 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 a significant part of its chord. If the airplane is also designed for high speed, weight considerations usually dictate that the wing have a significant degree of sweep -- thus greatly complicating the basic task of preventing transition. Sweep introduces cross-flow boundary layer disturbances that may amplify, interact with Tollmien-Schlichting waves, and cause transition. Airfoil geometry determines the extent of the favorable pressure gradient and suction requirements needed to help stabilize boundary layer fluctuations. Ideally, new laminar flow wing designs should achieve drag divergence Mach numbers attainable with turbulent supercritical wing technology. At the present time, however, little information is available for application to practical transonic laminar flow aircraft wings. NASA is committed to providing such fundamental data.

New aircraft structures such as graphite-epoxy composite materials offer the promise of airfoils of nearly perfect shape, tolerance, and smoothness at reasonable cost. When such structures are fabricated or undergo deformation under load, surface deviations must be kept small to prevent the occurrence of local pressure waves[5] which can cause transition. Leading-edge roughness caused by contaminants such as insects, dirt, erosion, or foreign object damage must be minimized or turbulence will result. Suction systems used to stabilize airplane boundary layers typically have very fine surface openings that must be easy to clean and repair while also resistant to clogging and corrosion. Noise from the propulsion system can amplify boundary layer disturbances and cause premature transition. Finally, atmospheric conditions can profoundly influence the performance of a fleet of aircraft designed for low viscous drag -- since these aircraft would operate throughout the world at a variety of altitudes and weather conditions. NASA is now actively researching these potential barriers to laminar flow flight.

Natural Laminar Flow

Natural laminar flow (NLF) both in flight[6] and in wind tunnels[7] was achieved over 35 years ago under very limited conditions on certain airfoils. Wind tunnel tests yielded transition Reynolds numbers as high as 14 million[7] for natural laminar flow, under essentially ideal conditions of wing smoothness, two-dimensional flow (no cross-flow disturbances), favorable pressure gradient, and very low tunnel turbulence level. However, extensive regions of natural laminar flow were never achieved on general aviation or transport airplanes in routine operations because of the practical constraints of large Reynolds numbers, high speed, and rough wing finishes. The wing size and the sweep angle associated with a modern transport airplane may preclude extensive use of NLF on such aircraft in the foreseeable future. General aviation business and commuter aircraft, however, are much smaller and usually free of complex leading-edge flaps. Further, general aviation aircraft typically fly at lower speeds and do not require the large wing sweep angles which can introduce cross-flow instabilities and span-wise contamination. Achieving NLF on such aircraft is therefore greatly simplified. Furthermore, composite materials have already been introduced into general aviation aircraft on a limited basis. Such materials offer surfaces which are very smooth and which may eventually offer low manufacturing costs. These aircraft are promising candidates for NLF applications.

Recent development of improved NLF airfoils at Langley has led to a new look at NLF technology[8]. Elements of the NASA NLF flight program[9] are illustrated in figure 4. During 1981 and early 1982, test flights were made on the following aircraft: T-34C (modified), Vari-Eze, Long-Eze, a biplane racer, Skyrocket II, Beech Sierra, Cessna P-210, and a Learjet. For most airplanes, transition was detected by use of sublimating chemicals such as naphthalene, diphenyl, acenaphtene, and fluorene. These chemicals evaporate as a function of local shear stress and heat transfer thus providing a visual indication of laminar flow breakdown.

Natural laminar flow flight tests on two canard configurations (Vari-Eze and Long-Eze) showed large effects on airplane performance and stability and control when laminar flow was lost. Wind tunnel tests with simulated rain on one canard airplane (Vari-Eze) confirmed loss of laminar flow due to rain. Future flight tests on smooth airplanes capable of supporting laminar flow should therefore include fixed transition testing as well as free transition tests. Finally, tests on one configuration (Skyrocket II) showed extensive laminar flow in the propeller slipstream.

Maximum transition Reynolds number observed was about 11 million (fig. 5), an expected result to researchers familiar with the early work on smooth wings[7] but nonetheless a dramatic surprise to those who had always assumed turbulent flow (based on experience with rough aluminum wings). The significance of this work is that it demonstrates that NLF can indeed be obtained in flight on modern production quality aircraft wings, for the case of low Reynolds number, smooth wing, low cross-flow disturbances, to a chord location of about 30-50%, in a favorable pressure gradient.

We plan to extend these studies by measuring transition locations on a NLF glove installed on the T-34 aircraft wing using thin film gages to correlate the transition results with the chemical tests. A study of several different types of porous leading edges (perforated titanium and composites) which can both wet and de-ice the airfoil surface will also be done in the Langley Research Center Low Turbulence Pressure Tunnel and the Langley 4- by 7-Meter Tunnel. The latter tests will determine if natural laminar flow can be retained after insects impact the wet model surface, an important consideration since residue resulting from bug impact with an aircraft's leading edge can cause an effective roughness which trips the boundary layer and initiates a "wedge" of turbulent flow. Future investigation of propeller slipstream effects are planned, as are studies to determine the practical upper Reynolds number limit for achieving laminar flow on modern production quality wings. Studies of passive surface coatings to protect NLF leading edges are also planned.

In addition, an initial flight investigation of the effect of sweep on natural laminar flow has been recently accomplished with a "glove" airfoil mounted on a variable-sweep F-111 airplane(10). Results indicate that extensive regions of natural laminar flow cannot be obtained for leading-edge wing sweeps greater than approximately 16 degrees. Linear boundary-layer stability theory is currently being applied to these data in order to quantify the effect on position of transition of the interaction between cross-flow instabilities due to sweep and Tollmein-Schlichting instabilities. Quantification of this interaction effect is the key to natural laminar flow wing design and must be based on experimental data. Plans are being made to obtain the required additional data.

Laminar Flow Control

Natural laminar flow may not be practical on modern long-range transports except for limited applications such as the outboard wing region and low Reynolds number tail regions. To achieve extensive regions of laminar flow on transport aircraft characterized by large size, Reynolds number, and wing sweep, a suction system is required to remove a small part of the airfoil's boundary layer. Partial boundary layer removal stabilizes (reduces disturbance growth rate to an acceptable level) the boundary layer and keeps it laminar (fig. 6). The LFC concept is applicable to all airplane surfaces, but work to date has generally been limited to studies of wings. Virtually all available reports on LFC can be found in references 11-14. An LFC system requires a perforated or slotted surface, internal ducting to suck air from different sections of the airfoil, and a compressor to expell the air. Suction power requirements are small compared to the reductions obtained in propulsive power enabled by the very large reduction in skin friction drag. LFC, therefore, can provide major benefits in reduced fuel use, lower operating costs, and increased range -- as shown in NASA-sponsored industry studies(15-17).

The technical validity of a laminar flow control (LFC) system has been demonstrated in both wind tunnels and flight, the most notable example being the X-21 research program conducted between 1962 and 1965(18-23). This effort was terminated because the Air Force had more urgent priorities and lacked an aircraft program that required this technology. Further, at that time, fuel was readily available and of low cost. In 1965, the main technical problem was the difficulty in achieving and maintaining very smooth surfaces between metal joints and gaps. Today, new materials and fabrication techniques make this considerably easier. Many technical problems were resolved during the X-21 tests. After several years of diligent effort, laminar flow was repeatedly achieved over almost all of the intended laminar upper wing area(24) to Reynolds numbers of about 20 million. Laminar flow was also achieved on a non-routine basis to Reynolds numbers as high as 47 million. The main problem in retaining laminar flow was the increased importance of surface roughness at these higher Reynolds numbers. The spanwise contamination problem was identified and largely resolved; the solution being to suck the leading edge and/or minimize the leading edge radius. Unresolved at the time the X-21 was cancelled was the economic feasibility of an LFC system including unknowns such as system reliability, maintenance requirements, and cost. NASA's efforts in resolving these uncertainties began in 1976. We have studied the aerodynamics, materials, structures, systems, and operational problems associated with a laminar flow control system. Recent progress has been impressive.

Stability codes have been developed(25&26), compared to experiments(26), and found to accurately predict boundary layer fluctuation growth. An advanced LFC airfoil incorporating the latest supercritical technology has been designed(26) and is now being tested in the Langley 8-Foot Transonic Pressure Tunnel (fig. 7). The airfoil design pressure distribution permits a drag divergence Mach number comparable to that obtained with the latest supercritical turbulent airfoils. Significant regions of supercritical flow will exist on the upper and lower surfaces. The leading edge has a small nose radius which helps to stabilize boundary layer cross-flow disturbances and reduce the amount of suction needed. The model (fig. 8) has a 7.07-foot chord, 23 degrees sweep, a thickness ratio of 13%, a design point chord Reynolds number of 20 million, and a predicted lift coefficient of 0.55 at the design Mach number of 0.755 (normal to the leading edge). A flap extends over the rearward 10.9% of the chord (for pressure distribution control at off-design conditions). Spanwise suction slots range from 0.0025 to 0.006 in. in width, and are spaced 0.12 to 1.7 in. apart. Slots cover nearly all of the upper surface and about 85% of the lower surface, and can be individually controlled.

The tunnel wall has been faired with a liner that produces an infinite swept-wing flow over the model surface[27]. Extensive flow quality improvement modifications to the tunnel plenum chamber include the addition of a honeycomb screen and five wire mesh screens that reduce the tunnel turbulence level to approximately .05%. A two-wall choke between the model and diffuser prevents diffuser noise from propagating upstream and tripping the model boundary layer. Tests will determine the effect of flow quality, optimum suction arrangement, unit Reynolds number, flap angle, angle of attack, and roughness. Initial test results on this model were obtained earlier this year.

When the tests on the slotted model are complete in early 1983, the upper surface of the model will be replaced with a perforated titanium surface (fig. 9) fabricated by the Douglas Aircraft Company (DAC). The porous design incorporates electron beam drilled holes with diameters of approximately .0025 in. at the skin surface and twice that at the back of the .025 in. thick skin. Holes are spaced about .025 in. apart. A fiberglas "hat" structure supports the porous skin and blocks about one-third of the suction holes. The model can therefore be more accurately described as a porous "strip" suction design. Each porous strip is approximately 1 in. wide (chordwise). In future tests in the 8-Foot Tunnel, we expect to replace these and other parts of the model so that we can conduct tests of natural laminar flow configurations, hybrid laminar flow airfoils, different nose shapes, and surface roughness. Other wind-tunnel tests to be conducted during 1983 in the Langley 4- by 7-Meter Tunnel will determine the high-lift characteristics and requirements of LFC airfoils[26].

Under NASA contracts, new structural concepts suitable for actual aircraft wings have been designed, built, and tested. A slotted skin[28] has been developed by the Lockheed-Georgia Company (GELAC) and the same has been accomplished with porous skin[29] by the Douglas Aircraft Company. Perforated skins can now be routinely fabricated with a waviness (due to the "hat" substructure described earlier) of less than 0.001 in. Superplastic--formed diffusion-bonded titanium fabrication processes have been applied to both slotted and porous skin surfaces[30-32].

The culmination of the current NASA laminar flow control program will come with the flight testing of leading-edge flight test (LEFT) articles in late 1982 and 1983. This program involves LFC gloves mounted on the leading edges of an extensively modified JetStar aircraft (fig. 10). Very smooth suction surfaces are integrated with a ducting system in a manner such that cleaning and repair are easily accomplished. The left glove is a slotted GELAC configuration[28]. Surface slots are used not only for suction but also for washing and deicing. Laminar flow is attained on both the upper and lower surfaces; the design does not utilize a leading-edge flap. The right glove is the porous configuration[33] developed by DAC; suction hole diameter and structural configuration are similar to that of the previously discussed wind-tunnel model. The DAC system uses a Krueger flap as both a high-lift device and a bug shield. The flap has a built-in spray nozzle for washing and deicing. This limits LFC to the upper surface of the airfoil (which accounts for nearly two-thirds of the wing drag). Suction systems for both gloves are located entirely ahead of the wing box. The suction system was not extended into the wing box area to keep cost and complexity low. However, the primary problems with a LFC system occur in the leading edge region.

Flight testing will begin in 1983 with initial results available about late summer 1983. The objective is to demonstrate the effectiveness of leading-edge LFC systems in maintaining laminar flow under conditions of varying weather[34], geographical location, and altitude -- to provide the operational data needed for firm analysis of the extremes encountered in actual airline service (fig. 11). Two hundred hours of flight tests are planned. Such data will provide a significant part of the essential information about LFC flight systems that could not be obtained during the X-21 flights.

To date, the NASA LFC program gives promise that the latest structural and material technology may be used to build LFC structures utilizing design and production techniques applicable to modern airplane production lines. Flight quality prototype hardware has been built. Uncertainties regarding LFC application to a transport aircraft wing which revolve around the long-time LFC questions of real-world reliability, maintenance, and cost will be largely answered by the LEFT flight tests conducted under operational airline conditions.

Application of a laminar flow control system to the wing and tail of a 1990 transport airplane would dramatically improve the seat miles obtained per gallon of fuel used. Figure 12 shows an improvement of 25% to 140 smg. These calculations assume either a slotted or porous suction surface (or a combination of the two) used over approximately 75% of the wing and tail area. Such a system would result in obtaining about one-quarter of the benefit possible with the all-laminar airplane.

No effort has yet been made to adapt an LFC system to an aircraft fuselage. Laminarization is especially difficult here since all the boundary-layer stabilization problems encountered on the wing are present plus very high Reynolds numbers; roughness associated with the location of the cockpit, doors, and hatches; and the complicated flow in the wing-fuselage junction. Providing hope for an eventual solution, however, are wind-tunnel tests on a Reichardt body of revolution which have shown the feasibility of using an LFC system to maintain laminar flow to a Reynolds number of at least 58 million[35-37]. Perhaps at least partial fuselage laminarization will eventually be possible. If 75% of the fuselage area could be laminarized on the 1990 airplane, fuel efficiency increases to about 189 smg (fig. 12). Such a large payoff certainly represents a tempting target for future viscous drag reduction.

Hybrid Laminar Flow Control

As the parameters affecting boundary-layer transition and the criteria for maintaining laminar flow were gradually identified and understood, concepts were developed for using suction in the leading-edge region of the airfoil to maintain laminar flow far downstream of the suction surface. This variation of a LFC system has recently been referred to as a hybrid laminar flow control system (HLFC). Suction is used in the leading-edge region to control the growth of cross-flow instabilities introduced by sweep after which the pressure distribution is "tailored" to control the Tollmien-Schlichting disturbance growth over the wingbox. A HLFC wing would have a supercritical pressure profile perhaps similar to that of figure 13. Pressure distributions on the surfaces of a HLFC airfoil would be favorable over a large region rather than have the nearly constant profile associated with the wingbox region of an advanced LFC wing.

The hybrid approach may provide more extensive laminar flow than possible with NLF on swept wings, but less than that expected with reasonable chordwise extents of LFC. Extensive chordwise suction, however, imposes penalties in weight and systems complexity, especially in the region of the wingbox where fuel is stored. HLFC, therefore, is a compromise between drag reduction and system simplicity that requires evaluation.

A preliminary study of the hybrid concept applied to a transport wing was accomplished by the Boeing Company[38] with NASA sponsorship and indicates significant potential. Laminar flow may occur to approximately 30-60% chord depending on flight altitude, wing surface, and spanwise location. Expected gains for this concept as applied to a transport-size aircraft wing would increase the smg of the 1990 transport airplane by about 12% to about 125 smg, with comparatively little change in the basic design of the aircraft (fig. 14).

The hybrid concept is far simplier than a full laminar flow control system, and should therefore be more reliable. Given these very sizable advantages -- in addition to the relative ease with which such a system could be applied to a production aircraft at reasonable cost, it is likely that a hybrid system will be the first application of laminar flow control to a commercial aircraft wing. For the same reasons, such a system may also be considered in the future for use on a transport aircraft's tail and fuselage.

Turbulent Skin Friction Reduction

The discussion thus far has considered attainment of laminar flow, generally on wings. Another possible approach to viscous drag reduction is to reduce skin friction drag. This concept may hold promise for the fuselage where Reynolds numbers are very high and achieving LFC is difficult. Early exploratory work has suggested that a net drag reduction (after accounting for the drag of the device) may be possible. These gains are attained by altering the scale of turbulence near the wall and in the outer part of the boundary layer. Possible advantages in reducing turbulent drag (versus LFC) include reduced operational sensitivity and therefore increased reliability. Turbulent drag reduction approaches generally involve some type of nonplanar local geometry[39]. More than ten approaches are now under study, but the present discussion is confined to two methods which have indicated possible net drag reductions. Drag reductions observed to date have been measured at relatively low Reynolds number and speed, in a boundary layer that was artificially tripped, and only in a wind tunnel.

In the first approach, called "riblets"[40] the boundary layer structure near the surface is altered by using small flow-aligned grooves on the wall. Some of the configurations tested are shown in figure 15. Riblet heights typically ranged from .025-.050 cm. and spacing varied from .025-.100 cm. Reynolds number is typically about 2 million. The sawtooth geometry provided a 10% net reduction in drag, the most favorable riblet result obtained. In an actual application, the grooves could be manufactured by extrusion molding a thin, low density film with the required geometry; adhesives would be used to apply the non-load carrying film to the surface. Riblet weight estimates applied to a 747 class fuselage indicate a penalty of about 700 pounds, which in the most favorable case could result in an airplane drag reduction of about 2-1/2%.

The second approach[41] involves alteration of the large scales in the outer part of the turbulent boundary layer by inserting a low-drag device within the boundary layer. In effect, the boundary layer is "aged," a phenomena equivalent to an increase in Reynolds number. The basic approach is indicated in figure 16. The vortex from the large-eddy breakup device is used to diminish the boundary layer turbulence structure. Early results indicate that this very simple device can severely alter the outer turbulence scales and provide a net drag reduction, at least for the limited studies completed to date where Reynolds number at the device location is typically about 2 million and about 4 million where drag reductions are measured. At present, it is not known to what Reynolds number the effect may persist. Efficient methods of mounting such a drag reduction device are not yet developed.

Early wind tunnel research indicates that both of these mechanisms may accomplish a net turbulent drag reduction. However, the specific processes involved are not well understood. The lack of theory to fully explain such phenomena together with the absence of a significant amount of data with which to optimize these devices mean that future progress will be heavily dependent on the extent and quality of our experimental results. Confirmation of any drag reduction will, of course, await flight test experiments. If these potential benefits could be applied to the fuselage of the 1990 airplane with laminar flow control on the wing and tail, however, a further 7% improvement to 149 smg may be possible (fig. 17).

Concluding Remarks

Great promise exists for reducing viscous drag in the near future. Experimental results, both in wind tunnels and flight, indicate that such technology is rapidly being advanced from the research stage to that of practical application.

As now envisioned, the NASA program in viscous drag reduction is summarized in figure 18. NASA is continuing wind tunnel and flight tests on general aviation aircraft to provide the data base needed to give industry the confidence required to exploit natural laminar flow technology. For transport applications, some form of laminar flow control system will probably be necessary. A sizeable base of fundamental research data on a transonic LFC wing is now being accumulated in ground-based tests. Preliminary structural designs of both slotted and porous suction wings have been accomplished. Actual operation of a LFC airfoil in flight will begin in 1983. Turbulent skin friction reduction is now in an exploratory research stage with only a small amount of experimental ground-based data available.

Taken together, the results obtained to date are very encouraging and offer hope for a future improvement in the performance of most types of aircraft. Such improvement is likely to take the form of large increases in the speed and fuel efficiency of general aviation aircraft, in the fuel efficiency of transport aircraft, and in a dramatic advance in the range and payload capability of military aircraft(42).

References

[1]Nagel, A. L.: Studies of Advanced Transport Aircraft. NASA TM-78697, May 1978.

[2]Nagel, A. L.; Alford, W. J., Jr., and Dugan, J. F., Jr.: Future Long-Range Transports - Prospects for Improved Fuel Efficiency. NASA TM X-72659, February 1975.

[3]Maddalon, D. V.; and Wagner, R. D.: Energy and Economic Trade Offs for Advanced Technology Subsonic Aircraft. NASA TM X-72833, April 1976.

[4]Povinelli, F. P.; Klineberg, J. M.; and Kramer, J. J.: Improving Aircraft Energy Efficiency. Astronautics and Aeronautics (AIAA), Vol. 14, No. 2, February 1976.

[5]Pfenninger, W.; Reed, H. L.; and Dagenhart, J. R.: Design Considerations of Advanced Supercritical Low Drag Suction Airfoils. Viscous Flow Drag Reduction, Vol. 72, Progress in Astronautics and Aeronautics, 1980.

[6]Smith, F.: and Higton, D. G.: Flight Tests on King Cobra FZ-440 to Investigate the Practical Requirements for the Achievement of Low Profile Drag Coefficients on a Low Drag Airfoil. ARC R&M 2375, 1945.

[7]Braslow, A. L.; and Visconti, F.: Investigation of Boundary-Layer Reynolds Number for Transition on an NACA $65_{(215)}$-114 Airfoil in the Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1704, July 1948.

[8]Somers, D. M.: Design and Experimental Results for a Natural-Laminar-Flow Airfoil for General Aviation Applications. NASA TP-1861, June 1981.

[9]Holmes, B. J.; and Obara, C. J.: Observations and Implications of Natural Laminar Flow on Practical Airplane Surfaces. ICAS-82-511, August 1982.

[10]Montoya, L. C.; Steers, L. L.; Christopher, D.; and Trujillo, B.: F-111 TACT Natural Laminar Flow Glove Flight Results. NASA Conference Publication 2208, September 1981.

[11]Bushnell, D. M.; and Tuttle, M. H.: Survey and Bibliography on Attainment of Laminar Flow Control in Air Using Pressure Gradient and Suction - Volume I. NASA RP-1035, September 1979.

[12]Bushnell, D. M.; and Tuttle, M. H.: Survey and Bibliography on Attainment of Laminar Flow Control in Air Using Pressure Gradient and Suction - Volume II. NASA RP-1035, July 1979. Confidential.

[13]Jobe, C. E.: A Bibliography of AFFDL/FXM Reports on Laminar Flow Control. AFFDL-RM-76-26-FXM, U.S. Air Force, March 1976.

[14]Tuttle, M. H.; and Maddalon, D. V.: Laminar Flow Control 1976-1982; A Selected, Annotated Bibliography. NASA TM-84496, 1982.

[15]Anon: Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft. NASA CR-158976, September 1978.

[16]Sturgeon, R. F.; et al: Evaluation of Laminar Flow Control System Concepts for Subsonic Commercial Transport Aircraft-Summary. NASA CR-159254, September 1980.

[17]Pearce, W. E.: Progress at Douglas on Laminar Flow Control Applied to Commercial Transport Aircraft. NAS1-16234, Douglas Aircraft Co. Presented at NASA-Dryden Flight Research Center, September 1981.

[18]Antonatos, P. P.: Laminar Flow Control - Concepts and Applications. Astronautics and Aeronautics, July 1966.

[19]Nenni, J. P.; and Gluyas, G. L.: Aerodynamic Design and Analysis on an LFC Surface. Astronautics and Aeronautics, July 1966.

[20]White, R. C.; Sudderth, R. W.; and Wheldan, W. G.: Laminar Flow Control on the X-21. Astronautics and Aeronautics, July 1966.

[21]Pfenninger, W.; and Reed, V. D.: Laminar-Flow Research and Experiments. Astronautics and Aeronautics, July 1966.

[22]Chuprun, J.; and Cahill, J. F.: LFC on Large Logistics Aircraft. Astronautics and Aeronautics, July 1966.

[23]Anon: Final Report on LFC Aircraft Design Data Laminar Flow Control Demonstration Program. (Contract AF 33(657)-13930 Northrop Corp.) NOR 67-136, June 1967.

[24]Leonard, R. W.; and Wagner, R. D.: Airframe Technology for Energy Efficient Transport Aircraft. Presented at the SAE 1976 Aerospace Engineering and Manufacturing Meeting, San Diego, California. November 29 - December 2, 1976.

[25]El-Hady, N. M.: Hady-1, A Fortran Program for the Compressible Stability Analysis of Three-Dimensional Boundary Layers. NASA CR-3467, September 1981.

[26]Maddalon, D. V. (Editor): Laminar Flow Control - 1981 Research and Technology Studies. NASA CP-2218, March 1982.

[27]Newman, P. A.; Anderson, E. C.; and Peterson, J. B., Jr.: Numerical Design of the Contoured Wind-Tunnel Liner for the NASA Swept-Wing LFC Test. AIAA 82-0568, March 1982.

[28]Anon: Laminar flow Control. Lockheed-Georgia Company (NAS1-16219 and NAS1-16235). Presented at NASA-Dryden Flight Research Center, September 1981.

[29]Anderson, C. B.: Laminar Flow Control Wing Surface Structure Development Program. (NAS1-16234, Douglas Aircraft Co.) Presented at NASA-Dryden Flight Research Center, September 1981.

[30]McQuilkin, F. T.: Study of the Application of Superplastically Formed and Diffusion Bonded (SPF/DB) Titanium Structure to Laminar Flow Control (LFC) Wing Design. NASA CR-158979, December 1978.

[31]Wilson, V. E.: Design Studies of Laminar Flow Control (LFC) Wing Concepts Using Superplastic Forming and Diffusion Bonding (SPF/DB). NASA CR-159220, May 1980.

[32]Douglas Aircraft Company: Laminar Flow Control SPF/DB Feasibility Demonstration. NASA CR-165818, 1981.

[33]McNay, D.; and Allen, J.: Laminar Flow Control Leading Edge Glove Flight Test Article Development. (NAS1-16220, Douglas Aircraft Co.) Presented at NASA-Dryden Flight Research Center, September 1981.

[34]Nastrom, G. D.; Holdeman, J. D.; and Davis, R. E.: Cloud Encounter and Particle Number Density Variabilities from GASP Data. AIAA Paper No. 81-0308R, January 1981.

[35]Gross, L. W.; and Pfenninger, W.: Experimental and Theoretical Investigation of a Reichardt Body of Revolution With Low Drag Suction in the NASA Ames 12-Foot Pressure Wind Tunnel. Northrop Report NOR 63-46, BLC-148, 1963.

[36]Gross, L. W.: Investigation of a Reichardt Body of Revolution With Low Drag Suction in the Norair 7 x 10 Foot Wind Tunnel. Northrop Report BLC-143, NOR 62-126, 1962.

[37]Gross, L. W.: Investigation of a Laminar Suction Reichardt Body of Revolution in the Ordnance Research Laboratory 4-Foot Water Tunnel. Northrop Report BLC-167, NOR 65-311, 1965.

[38]Boeing Commercial Airplane Company: Hybrid Laminar Flow Control Study Final Technical Report. NASA CR-165930, 1982.

[39]Hefner, J. N.; Weinstein, L. M.; and Bushnell, D. M.: Large-Eddy Breakup Scheme for Turbulent Viscous Drag Reduction. Viscous Flow Drag Reduction, Vol. 72, Progress in Astronautics and Aeronautics, 1980.

[40]Walsh, M. J.: Drag Characteristics of V-Groove and Transverse Curvature Riblets. Viscous Flow Drag Reduction, Vol. 72, Progress in Astronautics and Aeronautics, 1980.

[41]Corke, T. C.; Nagib, H. M.; and Guezennec, Y. G.: A New View on Origin, Role and Manipulation of Large Scales in Turbulent Boundary Layers. NASA CR-165861, February 1982.

[42]Jobe, C. E.; Kulfan, R. M.; and Vachal, J. D.: Application of Laminar Flow Control to Large Subsonic Military Transport Airplanes. AIAA Paper No. 78-95, January 1978.

TABLE 1 - AIRCRAFT CHARACTERISTICS SUMMARY

	Takeoff Gross Weight, lbs.	Operating Empty Weight, lbs.	Lift/Drag at Mid-Cruise	Seat Miles / Gallon at Mid-Cruise
1970 Technology	839,000	399,000	17.2	60
Advanced Technology*	603,000	298,000	20.1	112
Hybrid LFC*	580,000	292,000	22.0	125
LFC Wing/Tail*	557,000	285,000	24.4	140
LFC Wing/Tail + Reduced Turbulent Skin Friction*	547,000	282,000	25.9	149
LFC Wing/Tail/Fuselage*	511,000	272,000	31.7	189
All-Laminar Aircraft*	490,000	266,000	36.7	225

Payload = 490 passengers and 43000 pounds cargo

Design Range = 4800 n.mi.

Engines = 4

*1990 Technology (AR = 12)

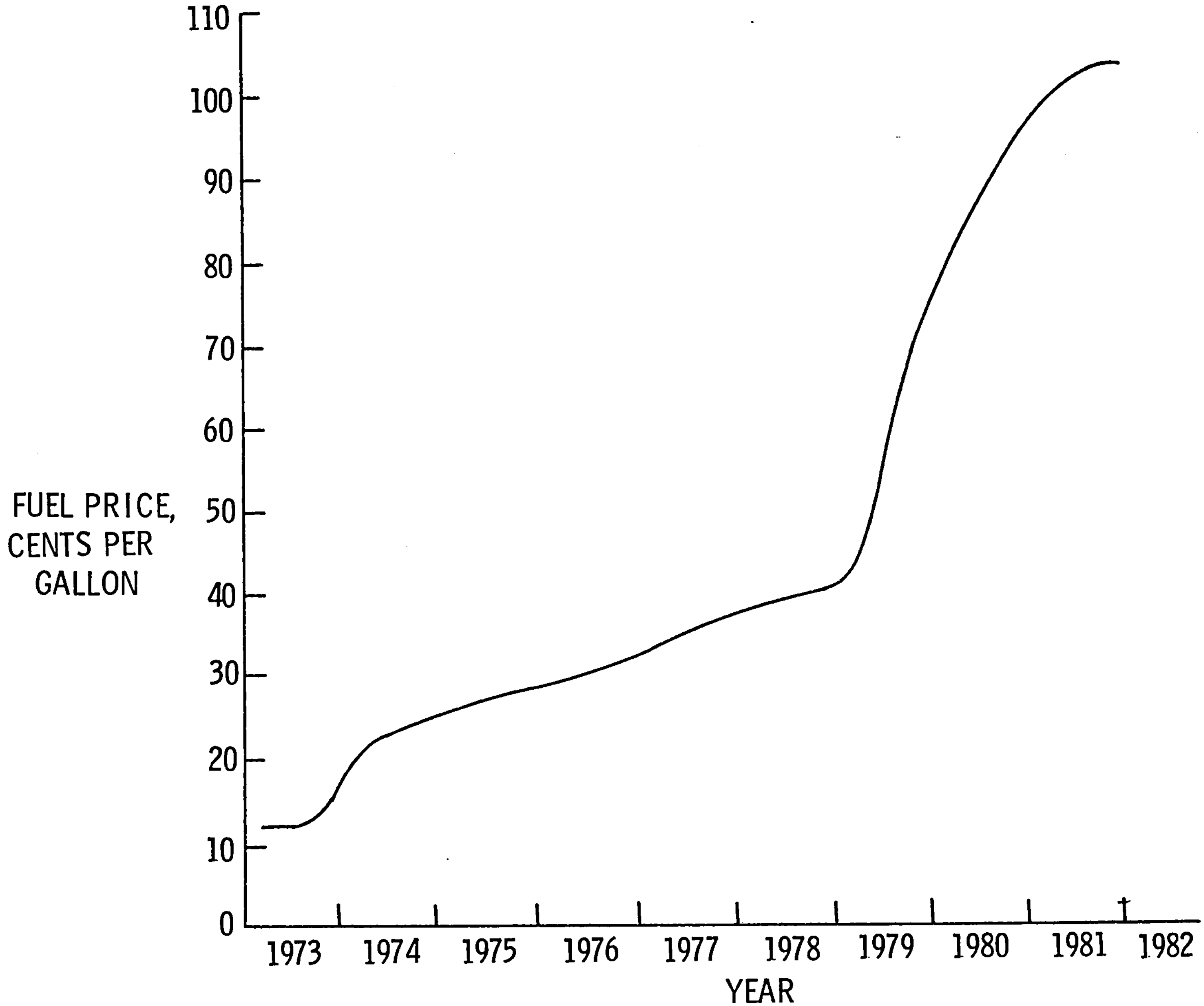


FIGURE 1 - DOMESTIC U. S. AIRLINE JET FUEL PRICE HISTORY

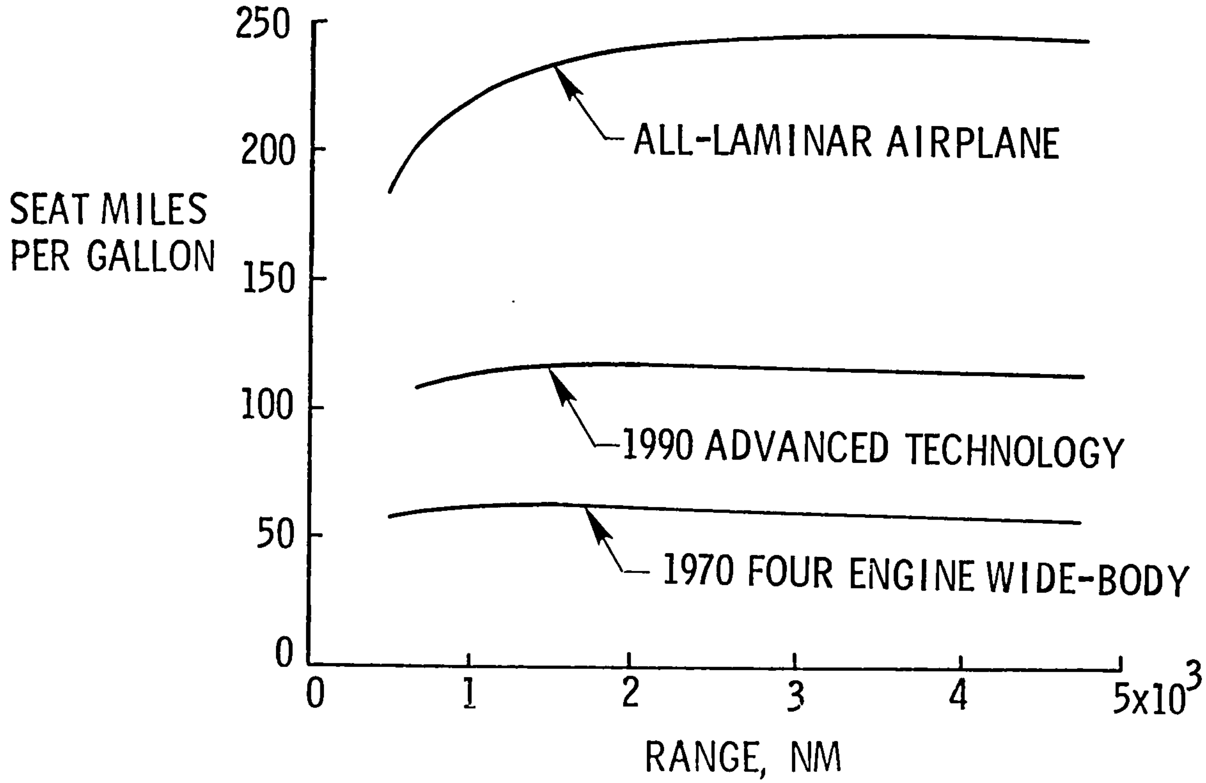


FIGURE 2 - ADVANCED TECHNOLOGY FUEL CONSERVATION POTENTIAL

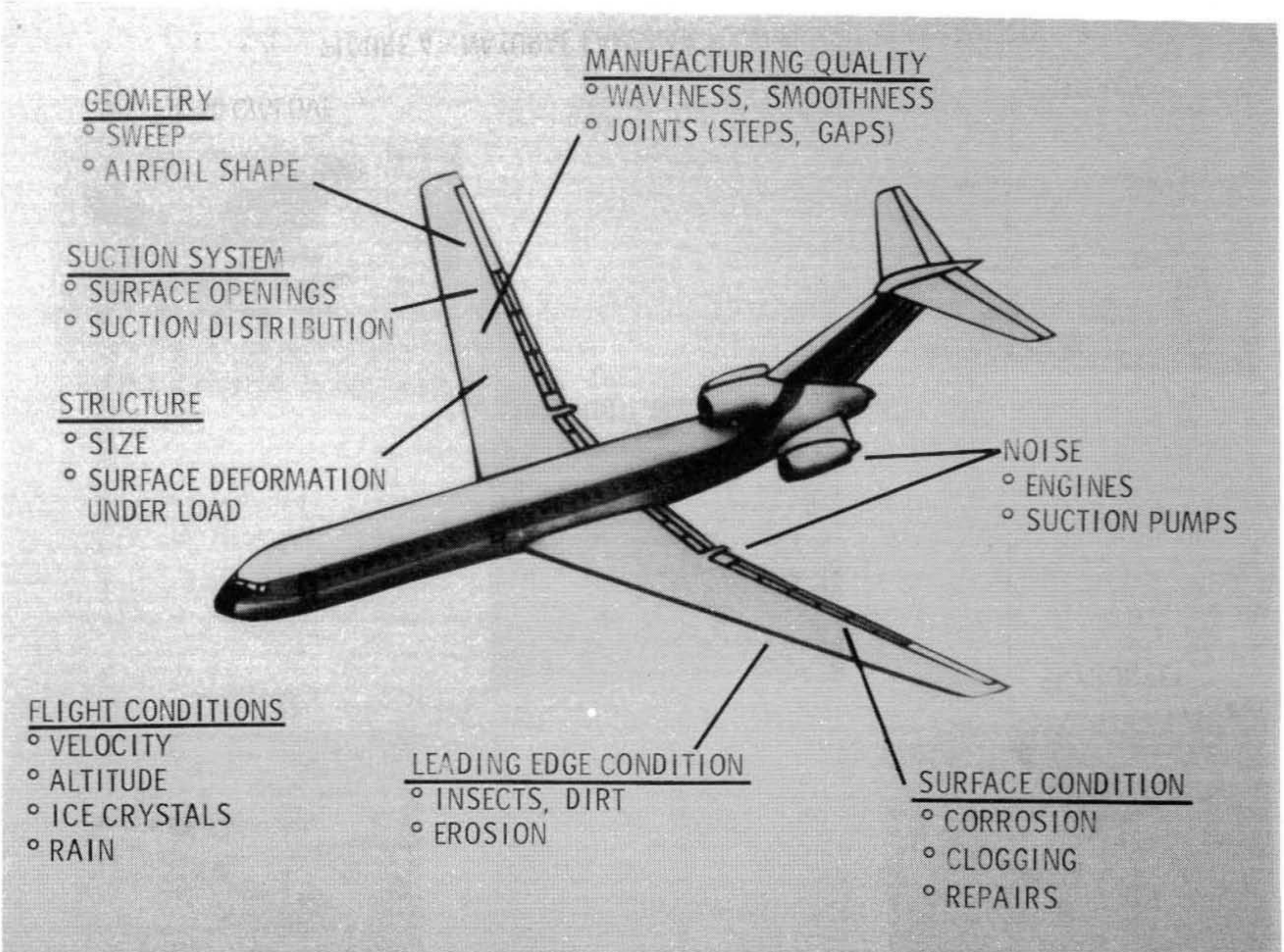
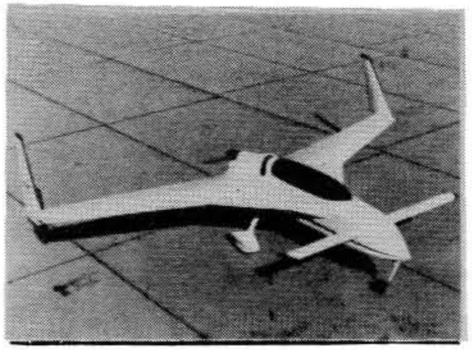
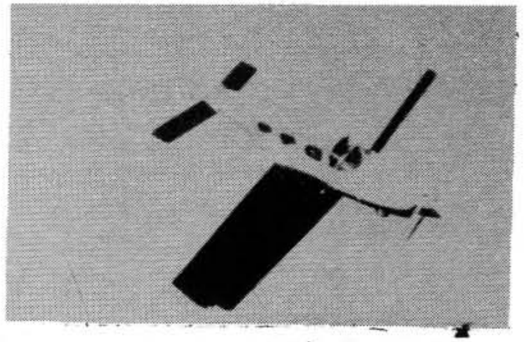


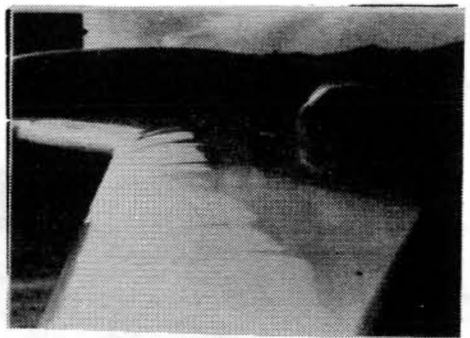
FIGURE 3 - FACTORS AFFECTING LAMINAR FLOW



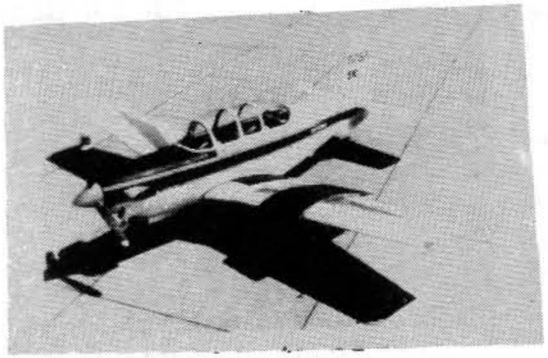
LONG-EZE



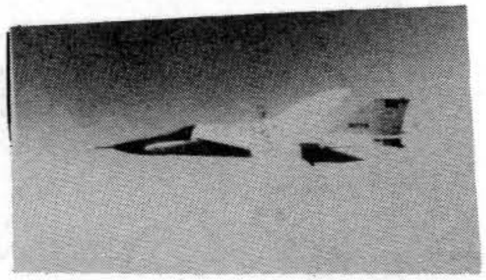
SKYROCKET



IN-FLIGHT TRANSITION



T-34 C/GLOVE



F111/TACT

FIGURE 4 - NATURAL LAMINAR FLOW FLIGHT EXPERIMENTS

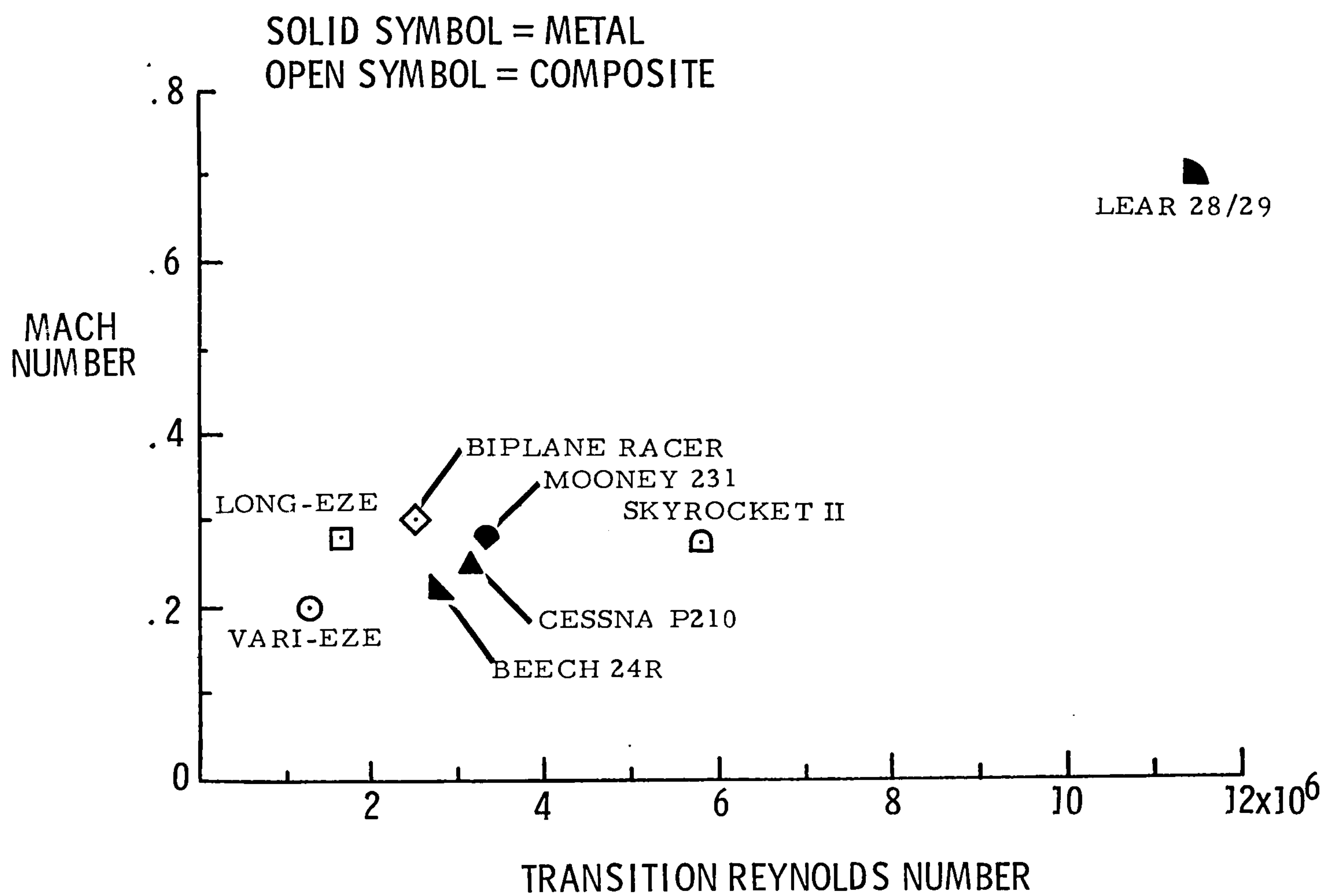


FIGURE 5 - NATURAL LAMINAR FLOW TRANSITION REYNOLDS NUMBER IN FLIGHT FOR EIGHT GENERAL AVIATION AIRCRAFT

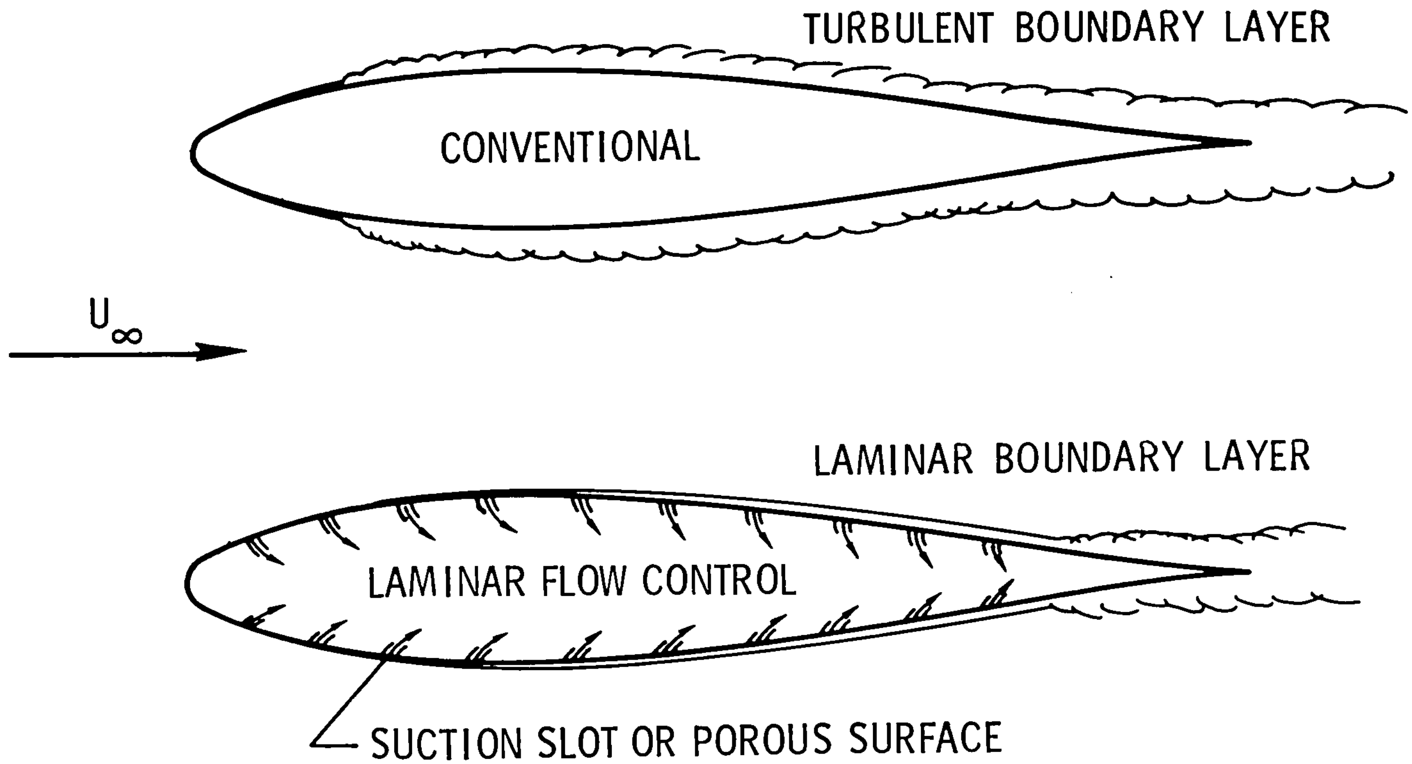


FIGURE 6 - LAMINAR FLOW CONTROL CONCEPT USING SUCTION

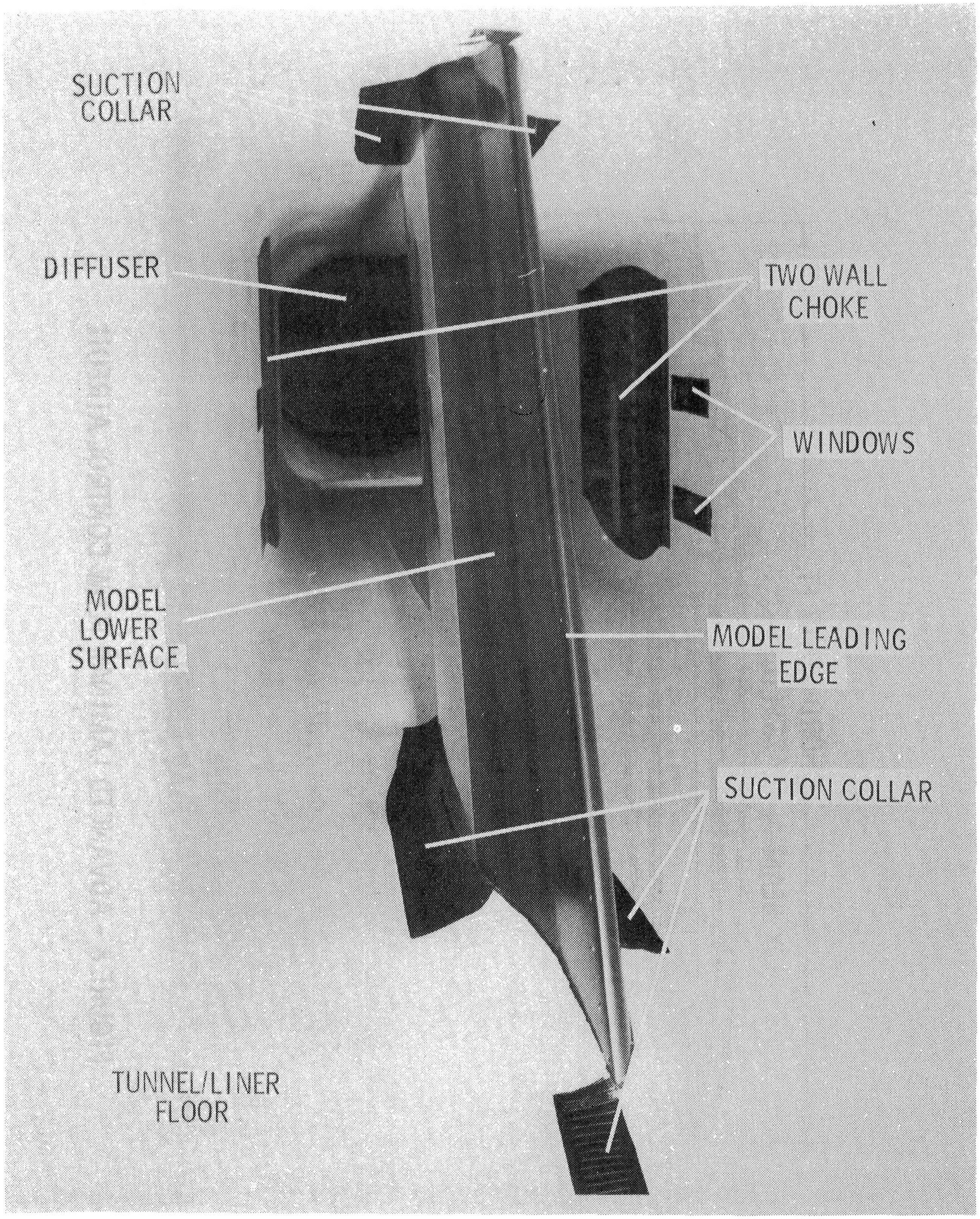
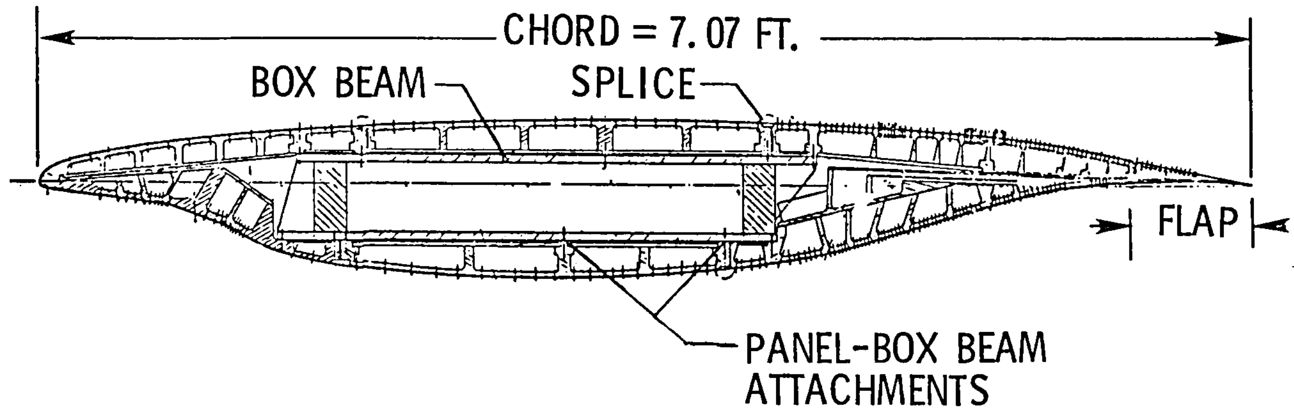


FIGURE 7 - ADVANCED LAMINAR FLOW
CONTROL AIRFOIL IN LANGLEY 8 FOOT TUNNEL



MODEL DESIGN POINT

$M = 0.82, M_{\perp} = 0.755$

$R_C = 20 \times 10^6$

$c = 7.07', \Lambda = 23°$

$(t/c)_{\perp} = 13.0\%$

$(C_L)_{\perp} = 0.55$

FLAP CHORD = 10.9%

FIGURE 8 - ADVANCED LAMINAR FLOW CONTROL AIRFOIL

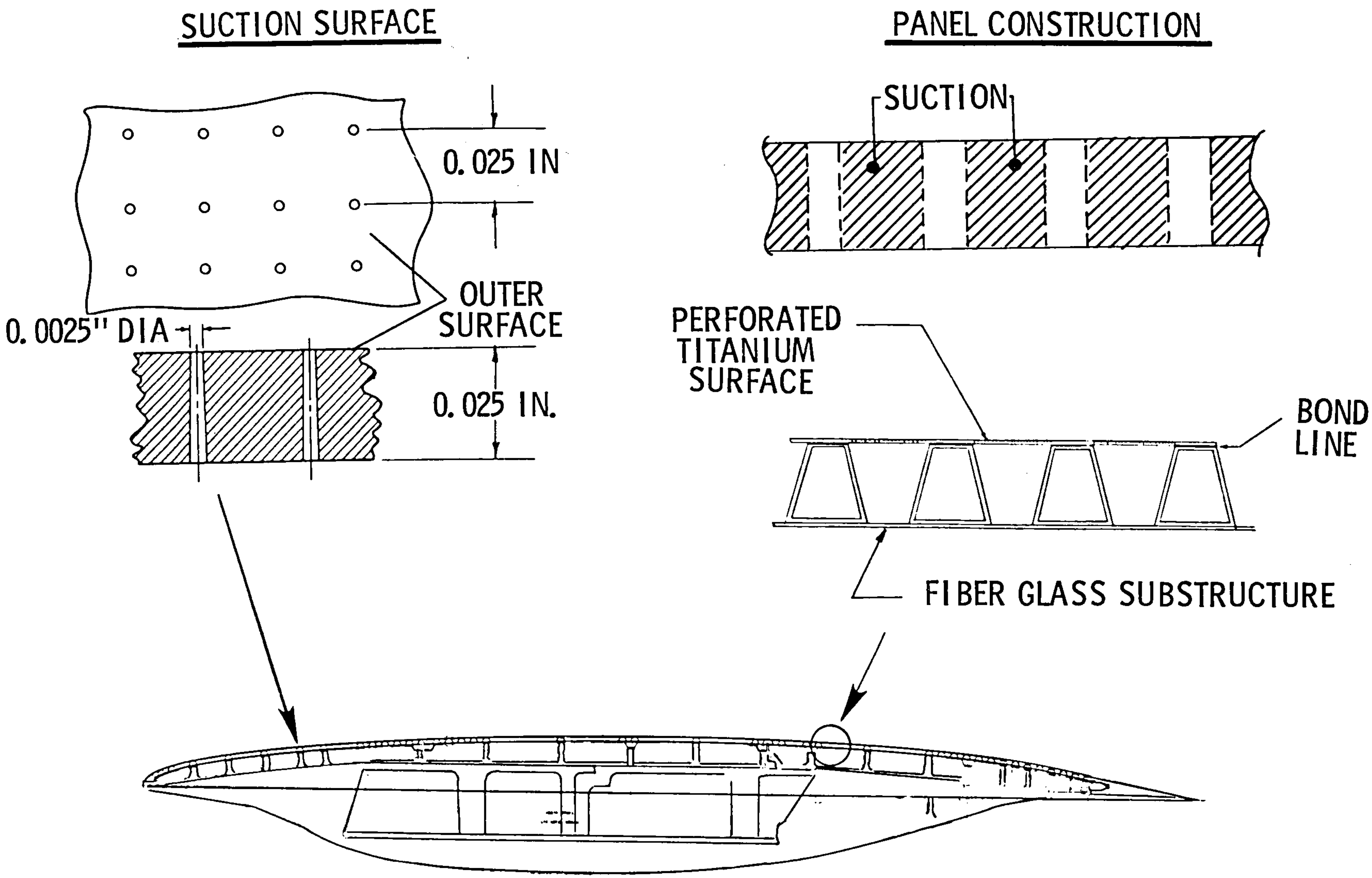


FIGURE 9 - ELECTRON BEAM PERFORATED TITANIUM WIND TUNNEL MODEL PANELS

MODIFIED JETSTAR

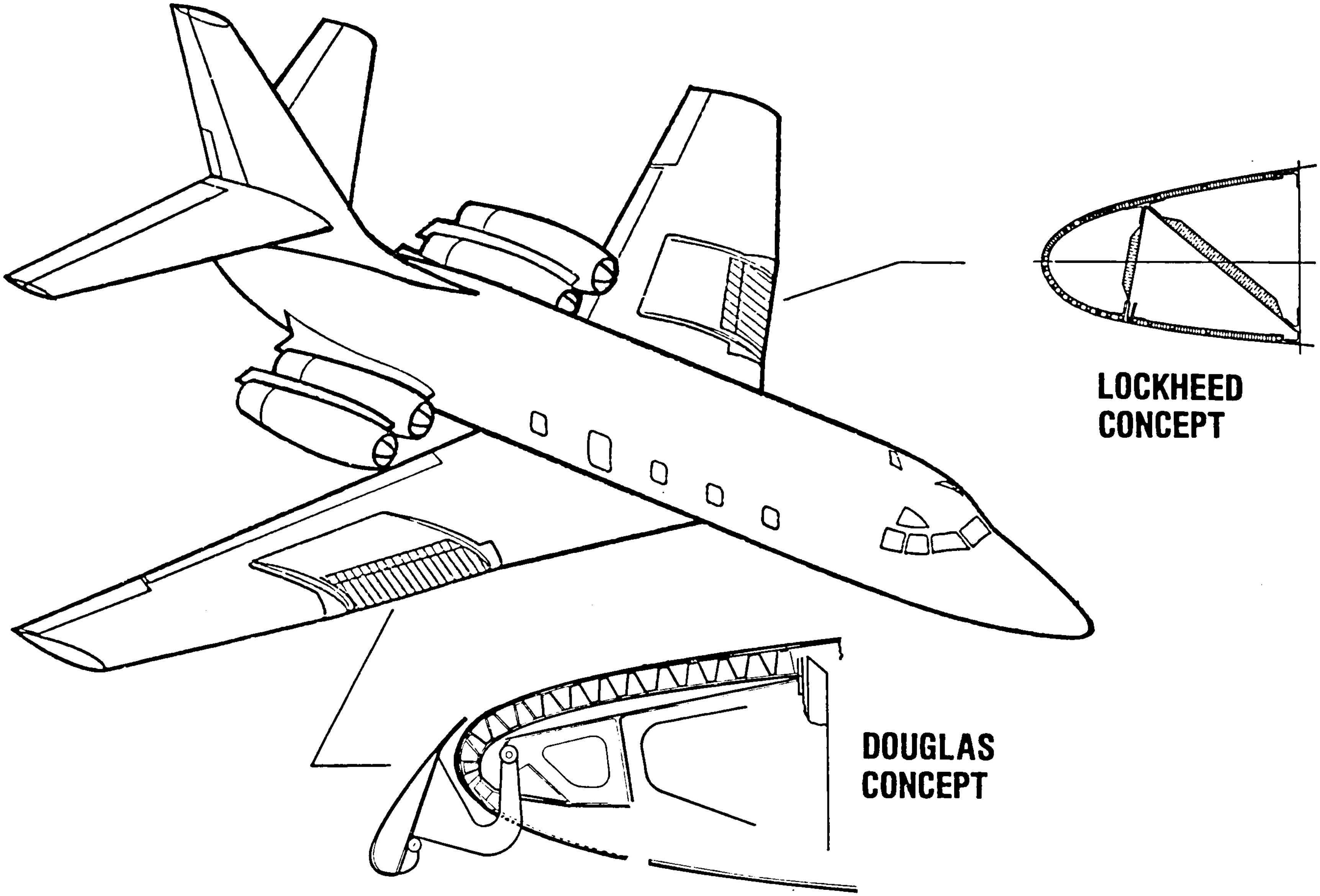
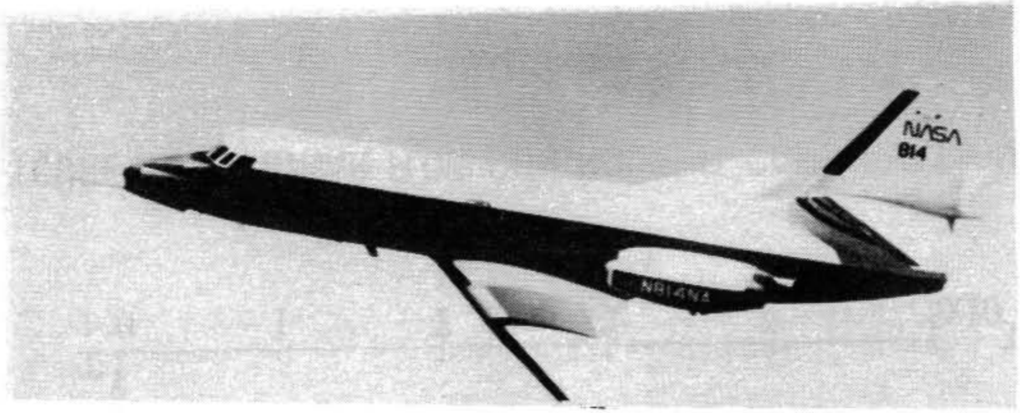
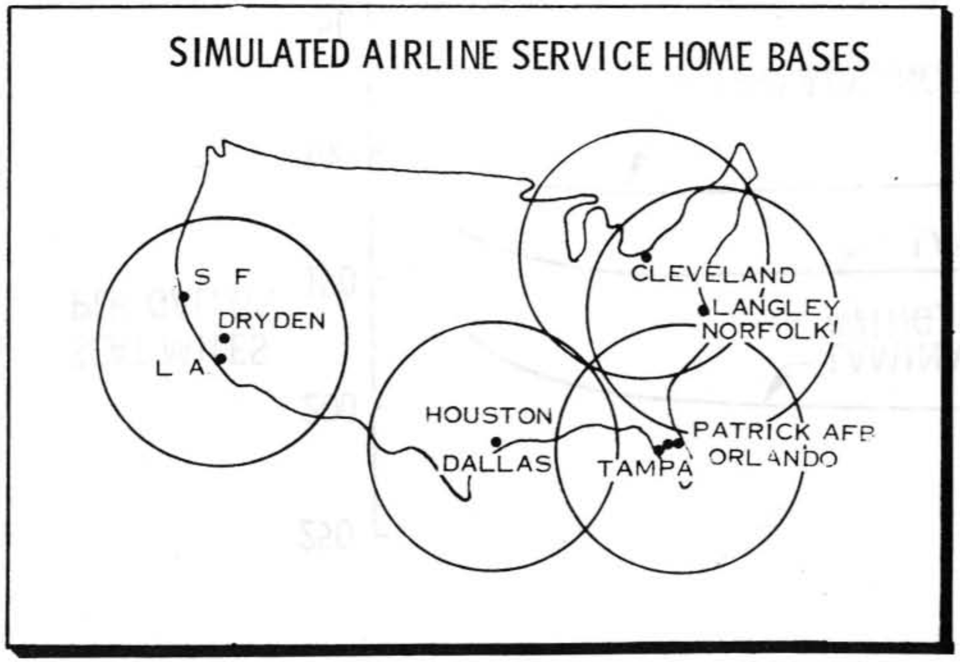


FIGURE 10 - LFC LEADING EDGE FLIGHT TEST





- GROUND AND FLIGHT ACCEPTANCE
- SYSTEMS EVALUATION AND PERFORMANCE
- SIMULATED AIRLINE SERVICE (200 HOURS)

FIGURE 11 - LEADING EDGE FLIGHT TEST PROGRAM

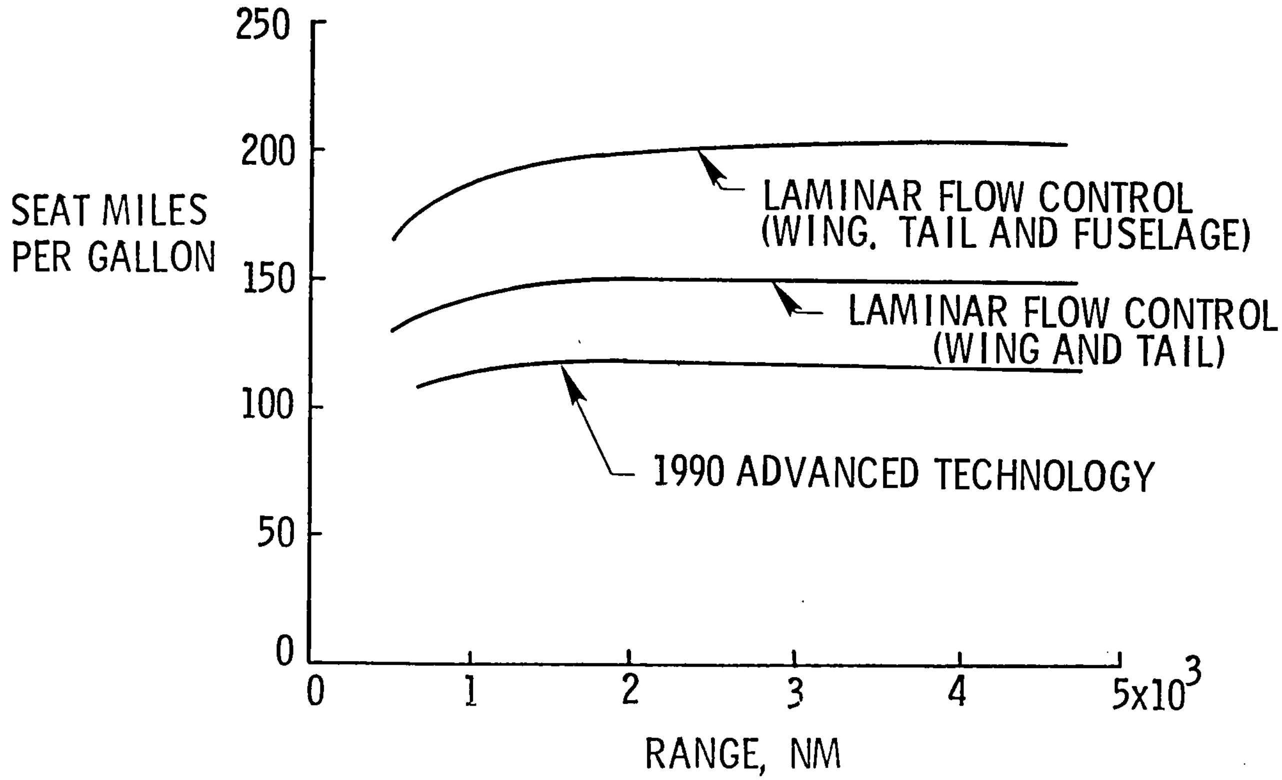


FIGURE 12 - LAMINAR FLOW CONTROL FUEL CONSERVATION POTENTIAL

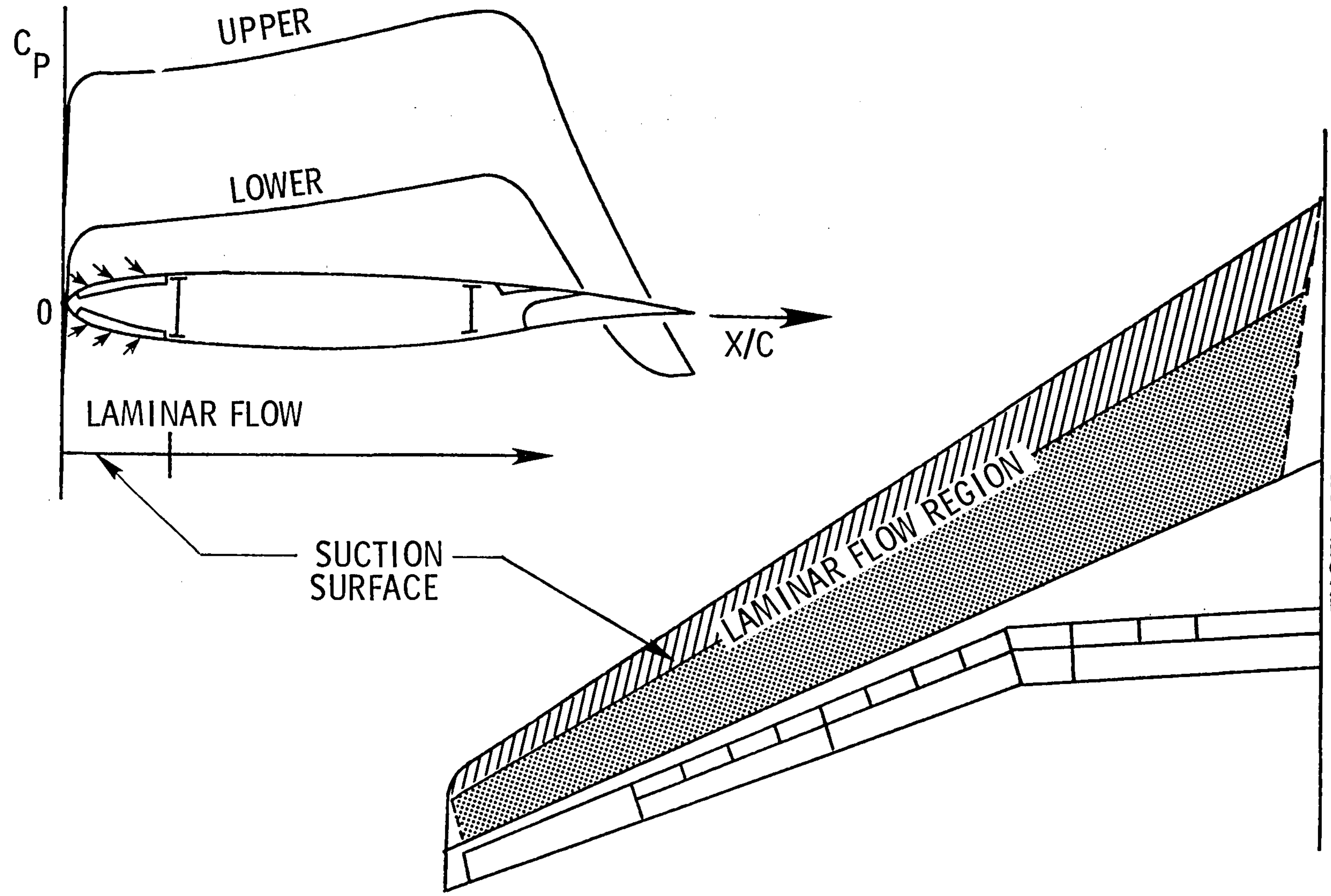


FIGURE 13 - HYBRID LAMINAR FLOW CONTROL WING CONCEPT

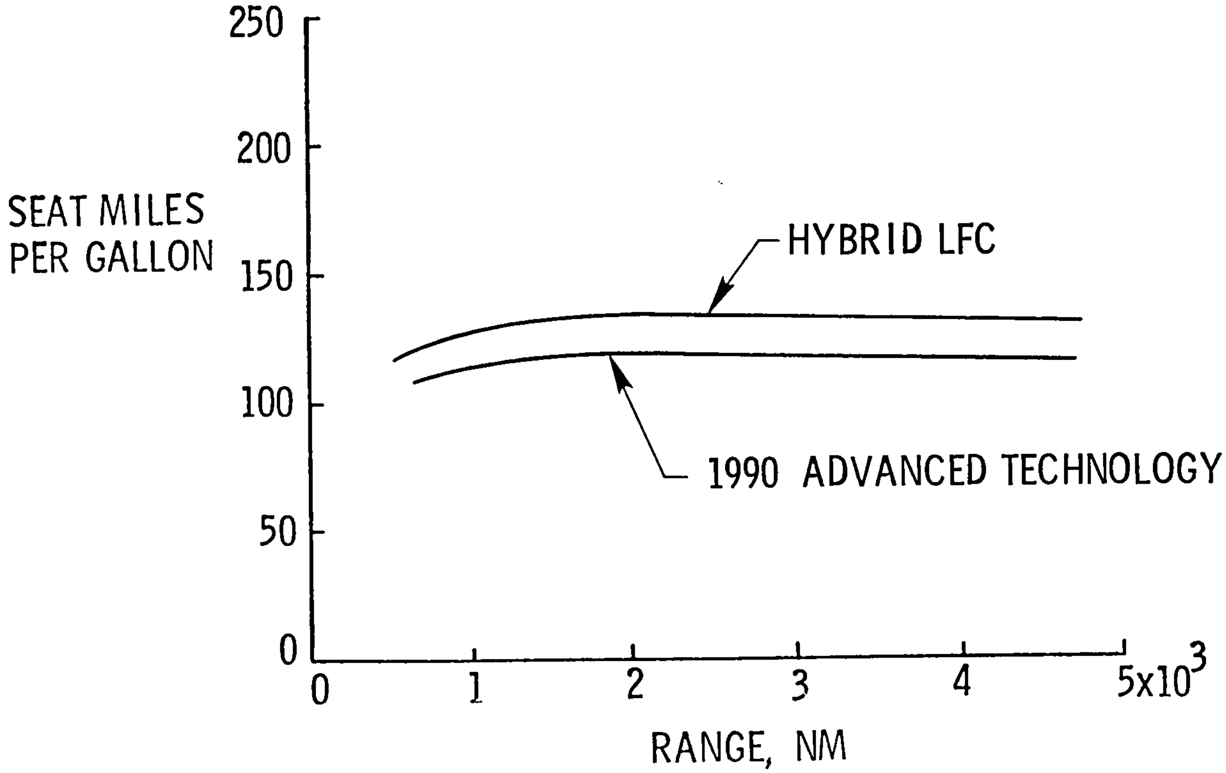


FIGURE 14 - HYBRID LAMINAR FLOW CONTROL FUEL CONSERVATION POTENTIAL

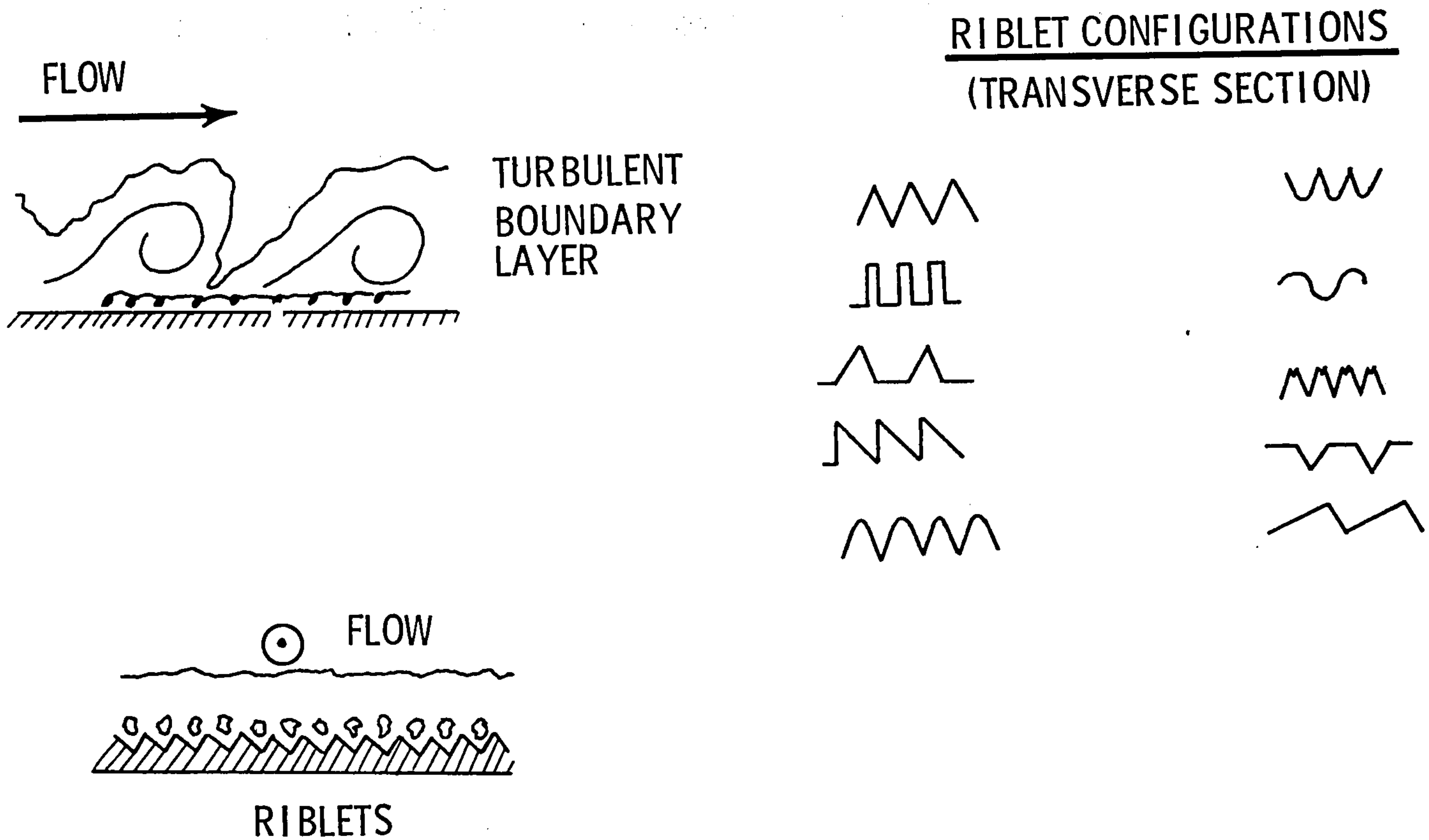
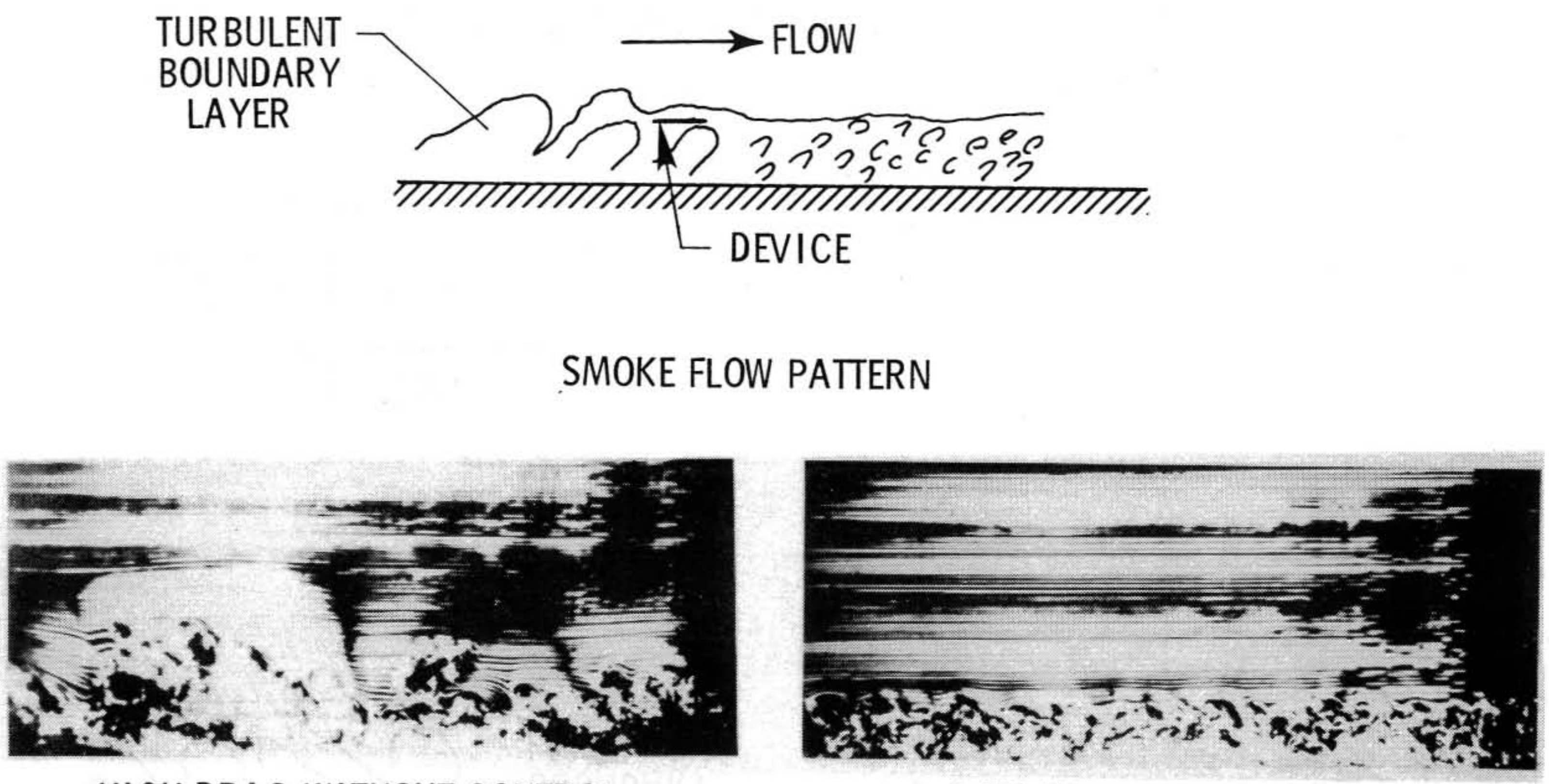


FIGURE 15 - TURBULENT DRAG REDUCTION - RIBLETS



SMOKE FLOW PATTERN

HIGH DRAG-WITHOUT CONTROL

LOW DRAG-WITH CONTROL

FIGURE 16 - TURBULENT DRAG REDUCTION LARGE-EDDY BREAK-UP DEVICE

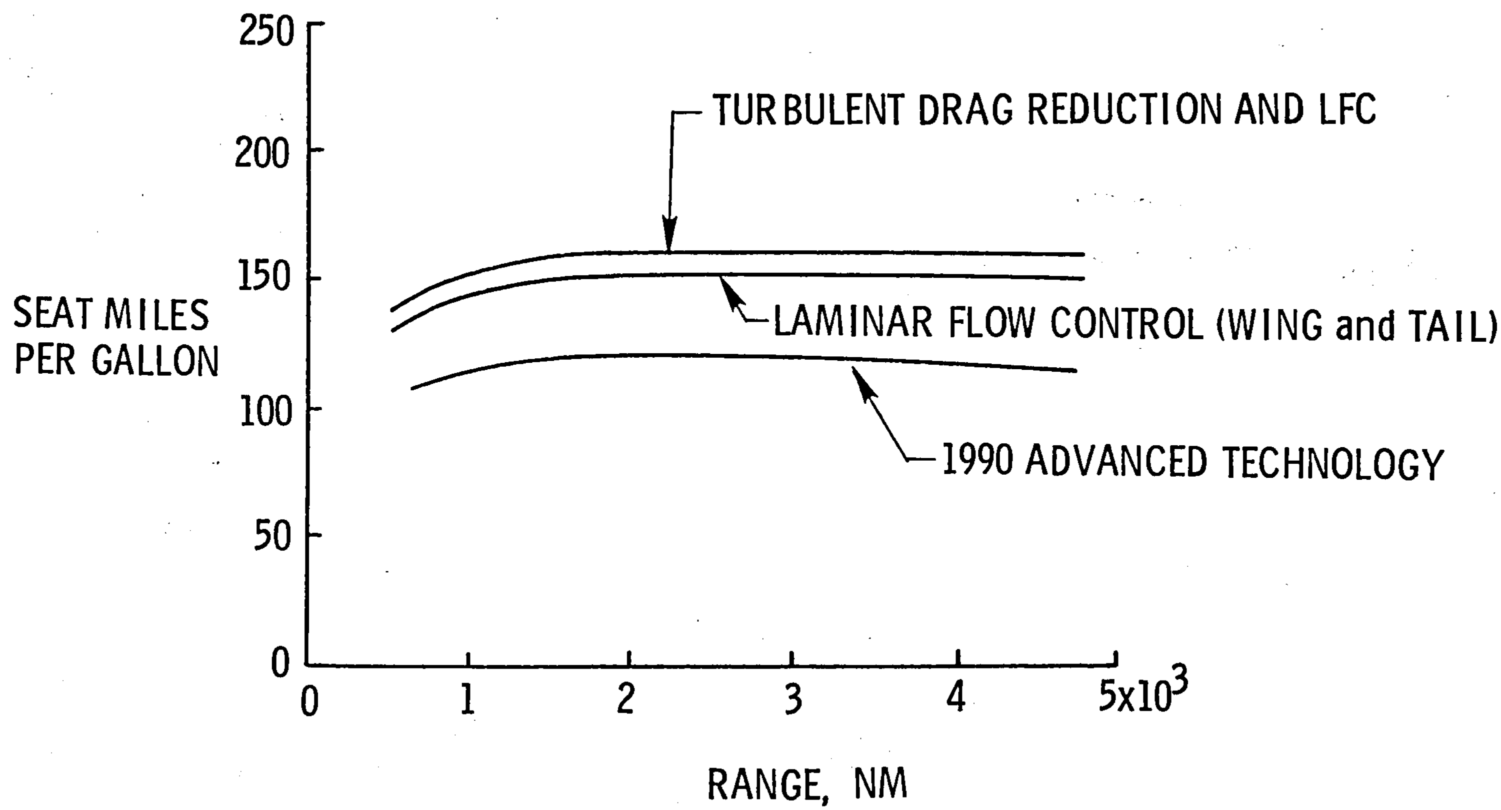


FIGURE 17 - TURBULENT SKIN FRICTION AND LFC FUEL CONSERVATION POTENTIAL

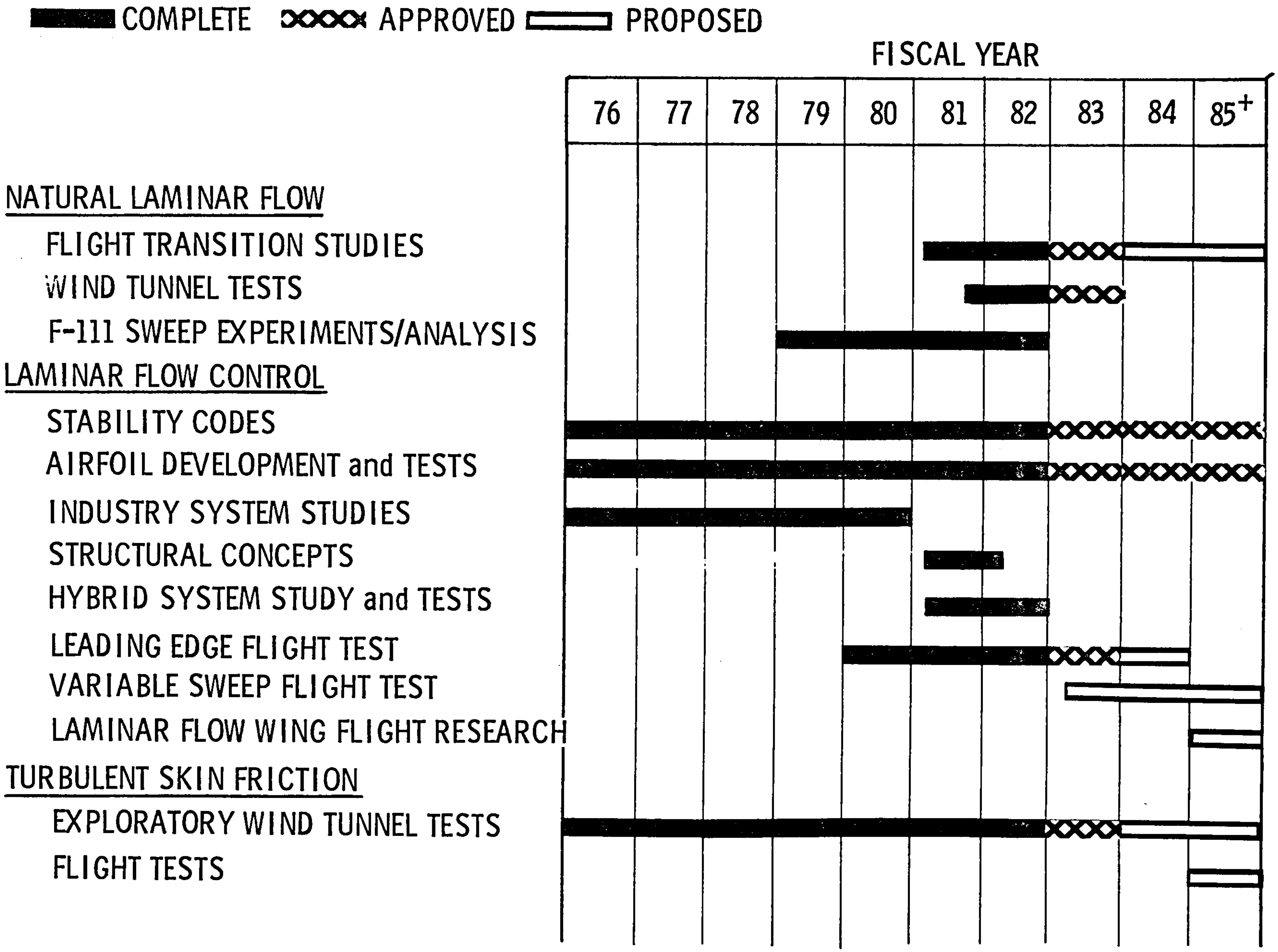


FIGURE 18 - NASA VISCOUS DRAG REDUCTION PROGRAM

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM- 84518		

4. Title and Subtitle NASA Research on Viscous Drag Reduction	5. Report Date August 1982
	6. Performing Organization Code 534-01-13-06
7. Author(s) Richard H. Petersen and Dal V. Maddalon	8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes
This paper was presented at the 13th Congress of the International Council of the Aeronautical Sciences (ICAS)/AIAA Aircraft Systems and Technology Meeting at Seattle, Washington on August 22 to August 27, 1982.

16. Abstract
Current NASA research points toward exciting opportunities for large reductions in viscous drag. Research is underway on natural laminar flow, laminar flow control by suction, and turbulent drag reduction. Preliminary results suggest that a significant amount of natural laminar flow can be achieved on small, straight-wing airplanes. On larger, swept-wing aircraft, laminar flow control by distributed suction is expected to result in significant fuel savings. The area over which laminar flow control is applied depends on tradeoffs involving structural complexity, maintenance, and cost. Several methods of reducing turbulent skin friction by altering the turbulence structure itself have shown promise in exploratory testing. This paper reviews the status of these technologies and indicates the benefits of applying them to future aircraft.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Viscous Drag Reduction Natural Laminar Flow Laminar Flow Control Turbulent Drag Reduction Perforated Materials	UNCLASSIFIED - UNLIMITED Subject Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	27	A03

For sale by the National Technical Information Service, Springfield, Virginia 22161