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Aerodynamics/ACEE

Aircraft Energy Efficiency

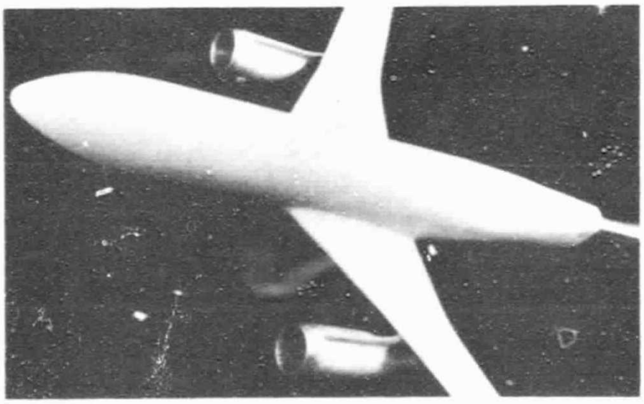
Aerodynamic concepts that point toward a new generation of energy-efficient air transports are part of the Aircraft Energy Efficiency (ACEE) program managed by the National Aeronautics and Space Administration.

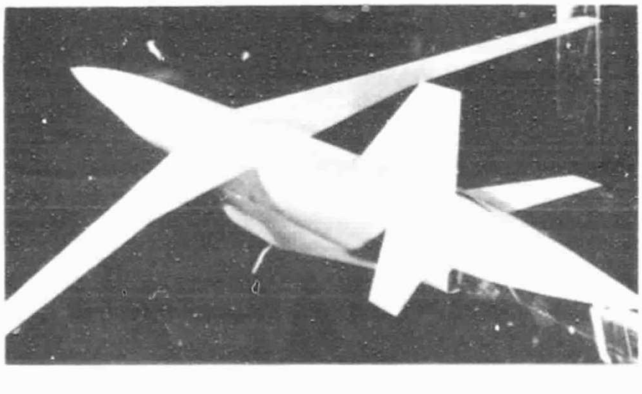
The basic goal of the program is to make possible the most efficient use of energy for aircraft propulsion and lift. That, in turn, will reduce energy costs in air transport operations.

ACEE is a ten-year planned program, developed in response to a request from the United States Senate Committee on Aeronautical and Space Sciences. It looks simultaneously at near-term and far-term problems. It attempts to develop expedient solutions that can be applied to today's generation of transport aircraft and engines, to their derivatives expected in a few years, and to wholly new classes of transports designed specifically to be fuel-efficient.

Several NASA research centers divide the workload of the ACEE program. Langley Research Center, Hampton, Virginia, is responsible for technology programs in aerodynamics, and in materials and structures. Wind-tunnel testing is shared by Langley and the Ames Research Center, Moffett Field, California. In-flight research is conducted by the Dryden Flight Research Center, Edwards, California. Propulsion research is at the traditional home for such work, Lewis Research Center, Cleveland, Ohio.

Overall, the broad purpose of the ACEE program is to provide an inventory of technology that can be used by the major manufacturers of transports and engines in the United States. It will help them to develop near-term derivative airliners that extend their current product lines, to develop families of new designs for the near





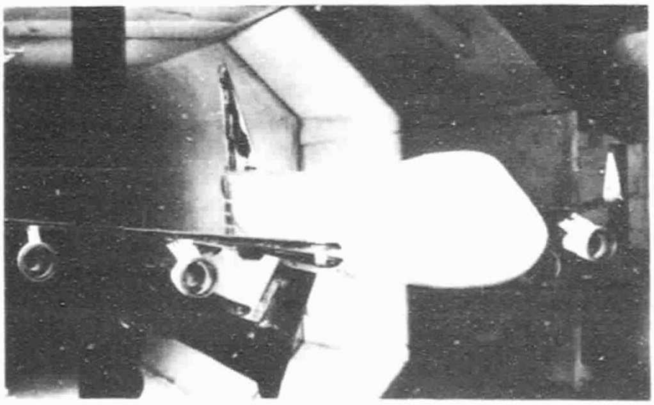


Figure 1: Three basic wind-tunnel test programs characterized the Energy-Efficient Transport (EET) portion of NASA's ACEE project. Integration of the propulsion system into the airframe for optimum efficiency was one of these, and typical tests included determining the interference effects of the long-duct nacelle on the wing. From that series of tests came another, to develop and test an optimum pylon mounting for the nacelle. Advanced aerodynamic testing included evaluating winglets and wingtips on a model of the Boeing 747, and the use of active control systems for wing load alleviation. Active controls also were tested first in model form on high-aspect-ratio wings, and later, in free flight on a drone aircraft launched from a NASA-operated Boeing B-52D bomber loaned by the USAF.

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Figure 2: Under contract in the ACEE program, the Lockheed TriStar prototype was modified with an active control system for maneuver load control, gust load alleviation, and suppression of the elastic mode of wing response to accelerations. This in-flight photograph shows the TriStar as modified with outboard ailerons, a flying stabilizer, and a boom with gust sensors. The outboard ailerons later were incorporated into an improved model of the Lockheed transport now in airline service.

term, and perhaps to develop radically different aircraft for the far term.

It is significant that NASA had been studying the problem of energy-efficient aircraft some years before the fuel crisis focused particular and concentrated attention on it. The Advanced Transport Technology program, initiated during the early 1970s, had as one goal the determination of the effect of a number of different new technologies on fuel consumption. It also is interesting to note that some of the same technologies under study then—supercritical aerodynamics, composite structural materials, active control systems, and quiet propulsion—are foundation stones for the current ACEE program.

A major portion of the ACEE program consists of funded studies placed with the major constructors of U.S. air transports and engines. They have the facilities and the test aircraft to do the work most efficiently. Additionally, studies have been done by commercial airlines, to provide their valuable input from the real world of day-to-day operations with jet transports of contemporary design.

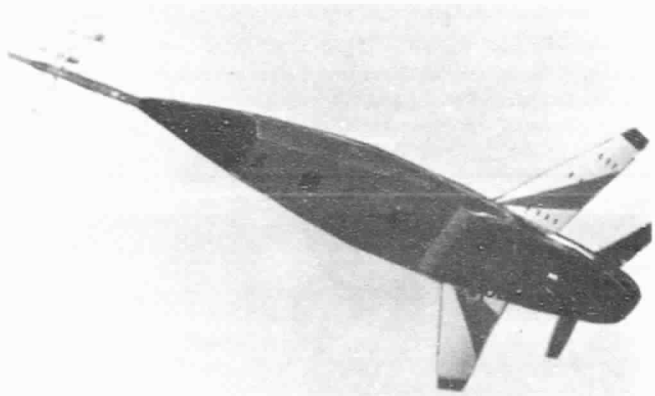

Figure 3: NASA's DAST program—Drones for Aerodynamic and Structural Testing—utilizes a modified Teledyne Ryan Firebee drone as a research vehicle for free-flight evaluation of advanced technology. Typical of the tests conducted in the DAST program were these three: The in-flight verification of an advanced control system using new technology; the first flight of a research wing, with a supercritical airfoil and other advanced aerodynamic features; and the development of a second research wing, using active controls to alleviate flutter and other aerodynamic phenomena.

Energy-Efficient Transport

One of six major technology programs that comprise ACEE, the Energy-Efficient Transport (EET) is a planned sequence of analysis, experiment and flight research leading to advanced concepts for derivative and new air transport aircraft. It focuses on new technology in aerodynamics, propulsion, control systems, and materials and structures.

The efficient use of energy translates into three factors of design and performance that are important to commercial operators of air transports: Direct operating cost (DOC), range, and aircraft gross weight. Since fuel costs currently make up more than half of the total direct operating cost, the efficient use of energy can have a major impact on the level of airline DOC. By drag reduction, and by improvements in the ratio of lift to drag, gains in range are achieved. Finally, through new materials and structural concepts, coupled with active control technology, airframe size and weight can be

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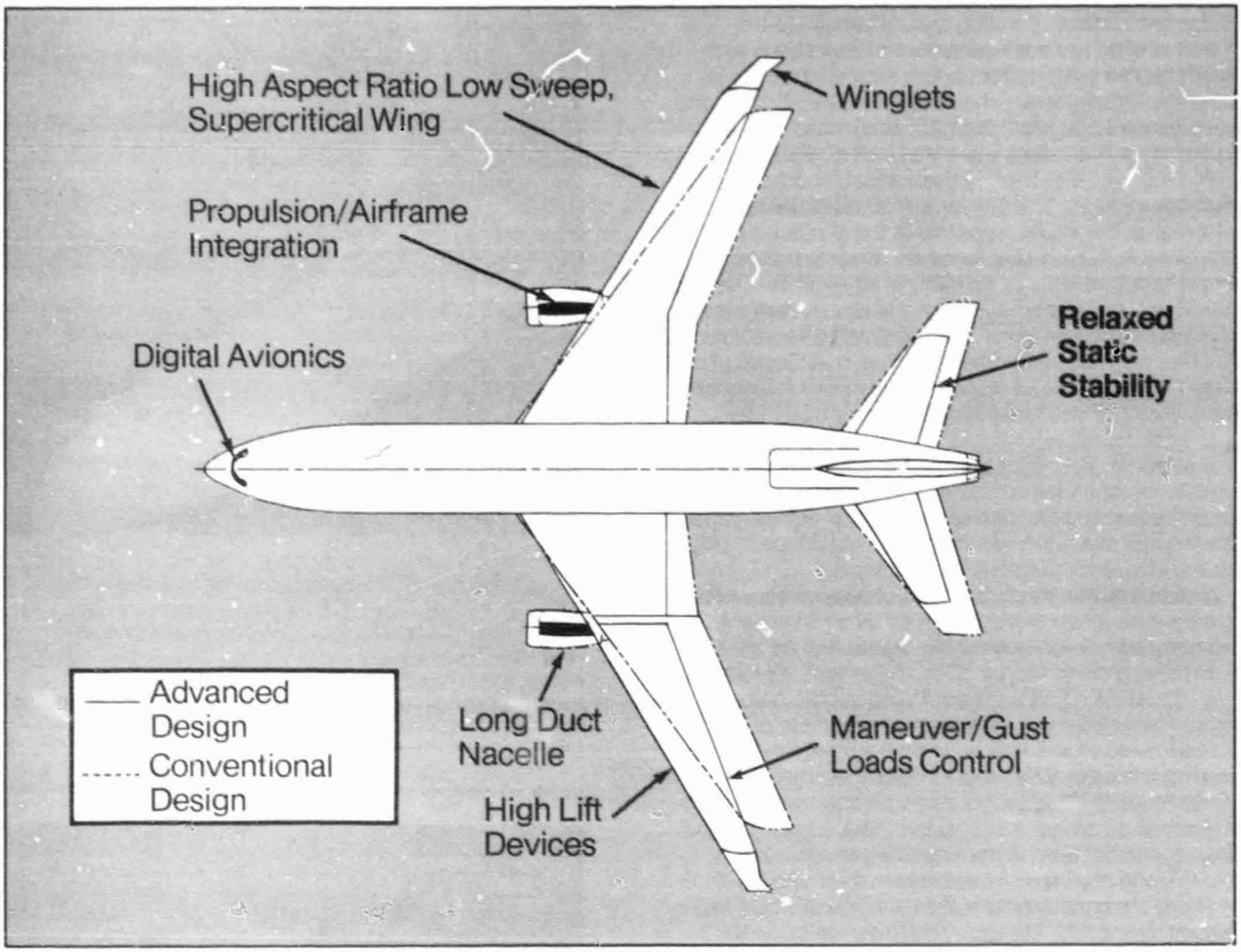

Figure 4: This plan view compares the layout geometries of a contemporary transport and one using advanced technolog[illegible] ing investigated under NASA's ACEE program, in the studies of Energy-Efficient Transports (EET). Aerodynamics, structures, propulsion and control systems are integrated into a single airframe of advanced layout. It features a supercritical wing with a high aspect ratio and low sweep, with high-lift devices, winglets and maneuver/gust load control. The propulsion system is integrated into the airframe with great care, and uses the long-duct nacelle concept. Relaxed static stability and digital avionics systems are part of the active controls designed for the EET. The structure of such an aircraft would include a number of components made from composite materials.

reduced. That makes for a lower initial purchase cost, and for a greater fraction of the gross weight available for payload.

A hypothetical energy-efficient transport would combine a number of technological advances in several aeronautical disciplines. It would feature a supercritical wing of high aspect ratio, with winglets at its tips and high-life devices on its leading and trailing edges; a system of active controls to handle relaxed stability requirements; other active controls to moderate maneuver and gust loadings; and a meticulous integration of the airframe and the propulsion system.

Its overall technology would be interdisciplinary. Integration of propulsion system and airframe, for example, would involve applying advances in aerodynamics, propulsion, and materials and structures. (Other publications in this "NASA Facts" series describe the work of the agency in propulsion, guidance and control, and NASA in propulsion, guidance and control, and materials and structures in the context of the overall ACEE program and of the EET. This publication is concerned only with the technology of aerodynamics.)

There are two broad aerodynamic studies under EET. The first addresses the eternal problem of drag reduction, a traditional task at NASA and at the National Advisory Committee for Aeronautics, NASA's pre-1958 predecessor. The second considers one specific means for drag reduction, laminar flow control (LFC), as a long-range project looking toward a future transport design of wholly new configuration.

New Aerodynamic Technology

The supercritical wing, a NASA development dating back to the mid-1960s, uses an unconventional airfoil shape to control the flow to avoid a sudden increase in drag. At very high flight speeds, flows that are curved

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above the surface of a wing can accelerate to a critical speed at which a shock wave forms. That shock wave, which can be seen under certain atmospheric conditions as a small ghostly shape seeming to dance on the wing, causes a sudden, dramatic drag increase. In an earlier time, that shock wave was part of what was called the "sonic barrier", a theoretical hindrance to high-speed flight. The barrier turned out to be as ethereal as the visual presence of the shock wave. It was conquered by brute force, by howling rocket motors at first, and later by screaming jet engines. The trick now is to subdue it quietly. That's where supercritical aerodynamics comes in. "Supercritical" refers to the fact that outstanding airfoil efficiency is achieved at a speed higher than the critical speed at which a shock wave would form, destroying efficiency on a more conventional airfoil.

Supercritical aerodynamic technology has been applied to several recent aircraft, including a new business aircraft. The backlog of experience with this and other types of aircraft has validated NASA's early claims for the efficiency of the new airfoil family.

It indicates that the application of supercritical aerodynamics to a new wing design for aircraft similar to contemporary wide-bodied jets would reduce the fuel burned for a given trip by 10 to 15 percent. It would do this by permitting an increased wing aspect ratio, a factor that relates the wing span to a multiple of the aerodynamic chord, or fore-and-aft average measurement of the wing. Wing aspect ratio is an important term in the classical Breguet equation for determining theoretical still-air range. It affects the induced drag, or the drag due to lift, term in the equation; an increase in aspect ratio produces a decrease in drag due to lift.

There are collateral benefits from supercritical technology. Generally, the use of the new NASA airfoil permits a thicker wing without incurring an additional drag penalty. In fact, compared to a conventional wing, the supercritical wing may not only have less drag, but also be thicker. That extra thickness provides more useful internal volume for the storage of fuel. It also provides a greater depth for wing structure, which results in a lighter and more efficient structural design.

In sum, then, a supercritical wing design can pay off in increased aircraft efficiency in three ways: By reducing the drag of the wing; by increasing the internal volume for fuel storage; and by increasing the structural efficiency of the wing, thereby permitting a lighter overall structure.

Vortex Drag Reduction

Winglets, which look like small jib sails mounted at and above the wingtips, came from some of the same considerations of drag reduction that sparked development of the NASA supercritical wing. One source of drag on a wing is the trailing vortex, a twisting, small-scale whirlwind that trails from the tip and contains enough energy to upset an airplane flown by an unwary pilot through the invisible twister.

That tiny tornado starts because a lifting wing has different pressures above and below its surface: Positive pressure on the underside, negative pressure on

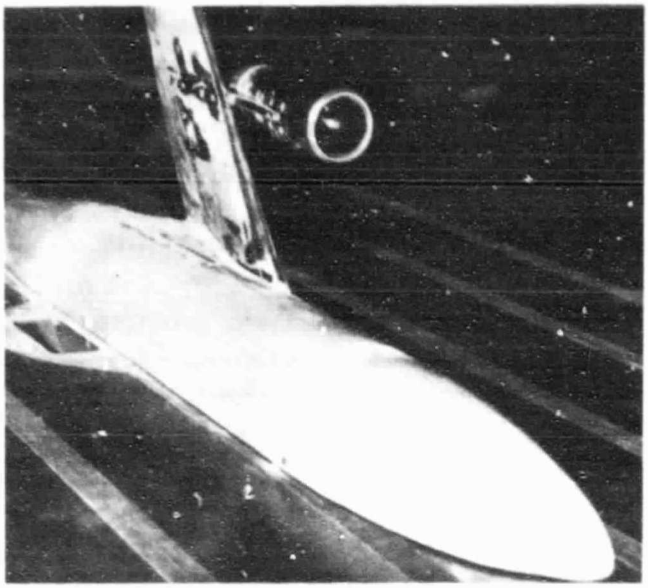

Figure 5: This semispan wind-tunnel model shown under test during the NASA EET program was used to evaluate the long-duct nacelle concept. This nacelle design provides greater mixing length for the air which bypasses the jet engine via the outer annulus of the flow pattern, and that which goes through the hot core of the engine and is exhausted at high speed and high temperature. Better mixing due to the longer dimension available produces greater efficiency and a lowered noise level.

Figure 6: This artist's concept shows a McDonnell Douglas DC-10 modified with two of the features developed under NASA's EET program: Winglets and long-duct nacelles.

the upper. Nature being what it is, the flow fields try to adjust to reduce that pressure differential to zero. They do this by moving air from the bottom of the wing to the top, from the high pressure area to the low. That motion, combined with the normal slipstream, produces the tip vortex flow.

A winglet, carefully designed as a lifting surface, reduces the cross-flow on the wing, and modulates the tip flow field to a weaker state. The trailing vortex is reduced in strength; this reduced strength subtracts drag from the lifting wing, improving its ratio of lift to drag.

An aerodynamicist would say that the induced drag term has been reduced. Induced drag is the reference to the component of drag due to the generation of lift; it is that generation of lift that creates the vortex flow in the first place.

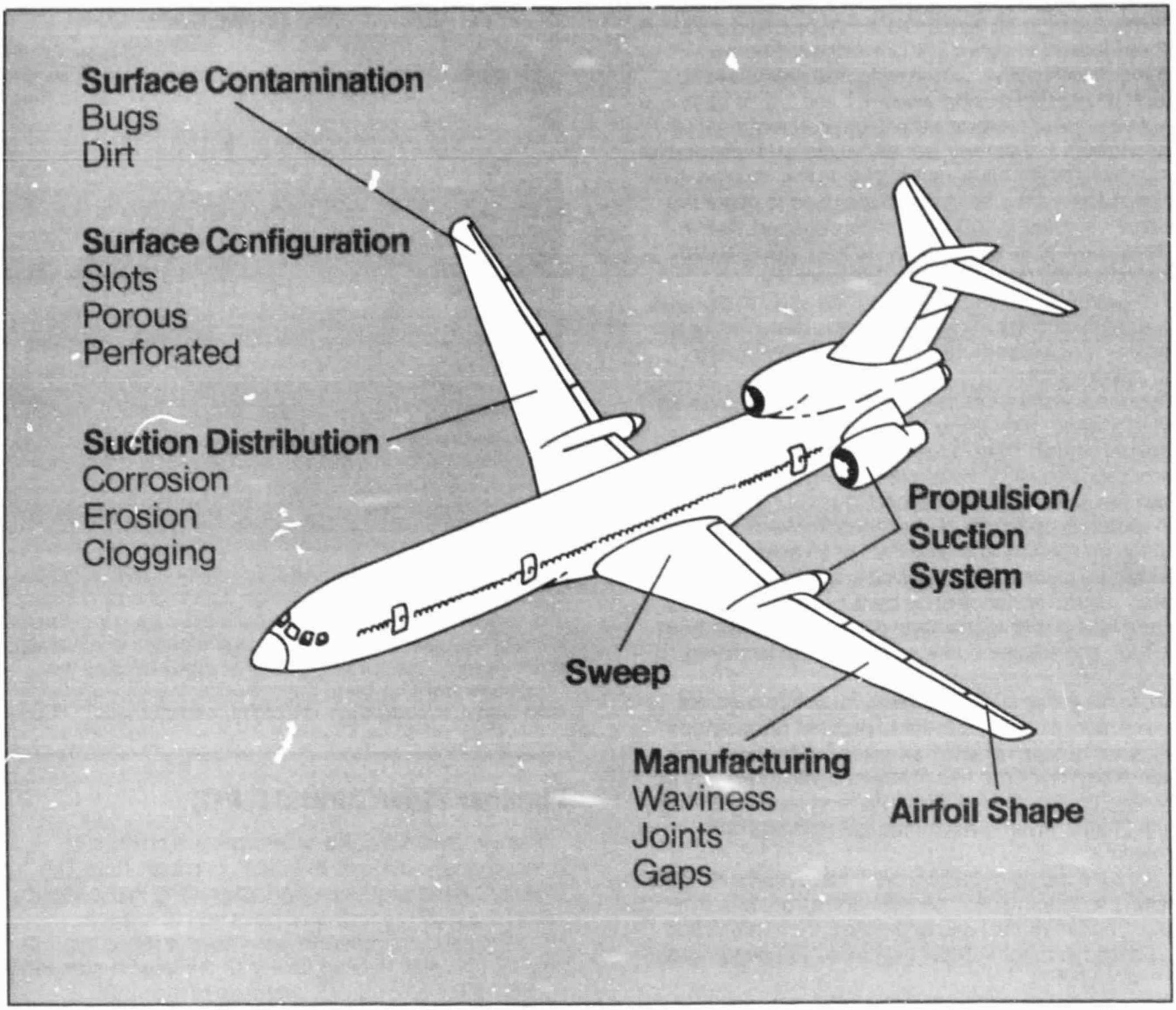

Figure 7: This sketch of an installation of laminar-flow control (LFC) on a typical three-engined transport illustrates some of the problems of the system. Bugs and dirt can contaminate the surface; corrosion, erosion and clogging can affect the air flow through the tiny slots. Manufacturing irregularities can reduce the effectiveness of the system. The general concept shown here calls for a supercritical wing with either slots, perforations, or a porous surface through which boundary layer air is sucked.

During the latter half of 1979, flight tests began on a Boeing KC-135A tanker operated by the U.S. Air Force Strategic Air Command. It was modified by the addition of winglets, and the purpose of the flight research was to evaluate the contribution of the winglets to reduced fuel consumption. Some NASA estimates anticipate a fuel saving of about five percent.

High Lift and Active Controls

High-lift devices offer yet another way of saving incremental fuel during two phases of flight: Takeoff/climb and approach/descent. Contemporary transports use wing flaps, sometimes coupled with leading-edge lift systems, to increase the available lift coefficient for takeoff and landing. The extension of flaps or other high-lift devices also causes an increase in drag.

Typically, an airplane making a descent for a landing will extend flaps partially at first, then once or perhaps twice again before finally touching down. Each of those flap increments is matched by an increase in power, to balance the added drag of the lifting surface. That power is used at low altitudes, where jet engines burn the most fuel. Consequently, any way to reduce thrust at the lower altitudes seems worth consideration.

NASA traditionally has studied the widest variety of high-lift systems, both passive and active. That work continues, but with a different emphasis: The application of high-lift devices to the leading and trailing edges of a supercritical wing.

One such experiment combined leading-edge slats with a partial-span, two-segment slotted flap. For takeoff, a hypothetical jet transport built around a supercritical wing and high-lift systems of this type could generate a lift coefficient of about 2.3. Current wide-bodied transports with conventional wing designs generate takeoff lift coefficients between 1.7 and 2.2, at best.

Active control systems differ from conventional aircraft controls in that they are automatic, and respond to some external stimulus, rather than to the command of the pilot. Conventional controls are used to make the airplane do something: Climb, turn, descend. Active controls work to keep the airplane from doing something, generally detrimental to its efficiency.

For example, active controls can be used to dampen the response of an aircraft to violent turbulence, or to keep the wings from fluttering dangerously in very high-speed flight.

Such moderations of the aircraft's usual behavior can lead to a longer life for the aircraft structure, and a lighter structure. That, in turn, reduces the amount of power required to fly the airplane, and therefore reduces the amount of fuel burned.

In their first concepts, active controls were planned to be used on rudders and elevators of an aircraft. The use of an active system would permit smaller, and therefore lighter, control surfaces to be built. Lighter aircraft require less power to maintain performance, and burn less fuel. The smaller surfaces also create less drag; less drag equals less fuel.

More recent applications ideas for active controls have centered on using them to prevent phenomena that cause unusual or peak stresses on the wing. Examples include the use of active control systems to suppress flutter, or to redistribute wing loading during turning flight, where unsymmetrical loadings are created.

(Because the use of active controls involves interdisciplinary technologies in aerodynamics, guidance and control, and materials and structures, they have been considered in greater detail in NF-95, "Guidance and Control/ACEE".)

In the first generation of jet transport designs, the engines were slung underneath the wing on pylon mounts, whose shapes were chosen using the best available information. As alternate engines were selected by different airline customers, engine pylons and mounts were modified slightly to accommodate the new powerplants.

When the second generation of jet transports came along, the pylon mount system was well-established and was used for the newer aircraft as well. But it wasn't necessarily the most efficient way of mounting an engine to a wing in an aerodynamic sense.

So as part of its ACEE program, and as part of the ATT program before that, NASA has been systematically investigating nacelle design, position and mounting techniques on a number of wind-tunnel models tested at speeds corresponding to cruise conditions for the full-scale planes. The tests have pointed out the interference effects that exist in the airstream around the juncture of the nacelle and the wing.

NASA studies are deriving ways of reducing the interference drag caused by the wing-nacelle intersection. Wind-tunnel tests have been made, and evaluated both by NASA and by the aircraft manufacturers for possible future use.

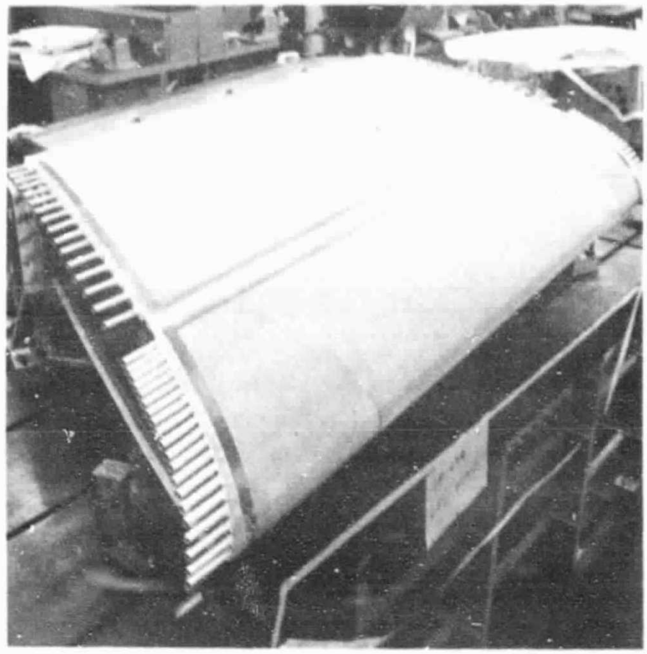

Figure 8: Part of NASA laminar-flow control studies under the ACEE program called for the design, construction and testing of typical wing sections that were candidates for incorporation in any LFC system. This unit is a small portion of a leading-edge structure with a porous surface. Designed and built by the Douglas Aircraft Company, this component was scheduled for wind-tunnel evaluation in a test of the characteristics of LFC.

Laminar Flow Control (LFC)

The air stream around an airplane is a mixture of laminar, or smooth, and turbulent, or rough, flow. The turbulent areas produce skin-friction drag that is about half of the total drag. One obvious way to reduce airplane drag—and therefore to improve fuel consumption—is to create laminar flow over the largest possible portion of the air-immersed surface of the craft.

Flow becomes turbulent when some triggering action occurs in the boundary layer, a thin, slow-moving lamina of air lying close to the wing or fuselage or tail surface. If the boundary layer can be removed, there is no triggering, and therefore no turbulence.

Simple aerodynamic tricks can create some areas of laminar flow where they would not normally exist. The use of compressed air, bled from a jet engine and ducted over wing trailing-edge flaps, produces a local boundary-layer control. But to create large areas of laminar flow requires the removal of the boundary layer over most of an aircraft's wing and tail surfaces.

LFC concepts generally have focussed on removing the boundary layer by suction. Internal pumping systems suck the boundary layer through slots or other porous surfaces in the wings and tail.

Laminar-flow control systems traditionally have been considered as wing installations; there is a major advantage to be gained by maintaining boundary layer laminar flow there. But in the drive to reduce drag, no aircraft component can be ignored, and the drag con-

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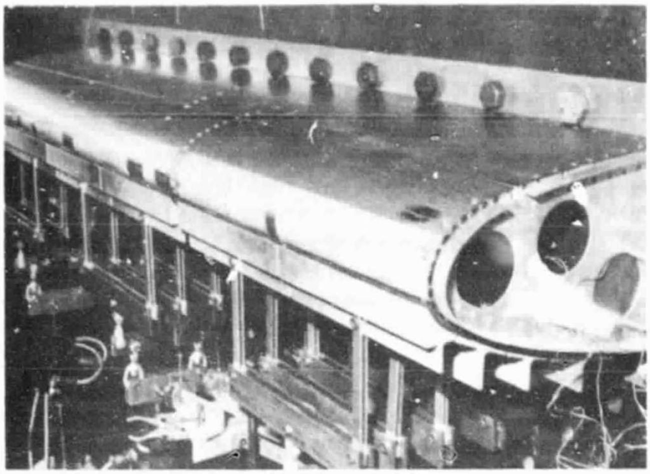

Figure 9: As part of the subsystems development in NASA's laminar-flow control project (LFC), typical components were built and evaluated for possible future incorporation in a complete research LFC aircraft. One such component is this specimen of a leading edge structure developed by Lockheed, shown here undergoing a structural proof-load test.

Figure 10: The tail insignia, showing a soaring eagle with outstretched wings, identifies—if identification is needed—a winglet installation on an Air Force KC-135A. The winglets are about 12 feet high, with a 6-foot root chord and a 2-foot tip chord. They are expected to improve the cruise efficiency of the modified tanker aircraft by about seven percent. Since defense requirements keep a large tanker fleet airborne around the clock, substantial fuel savings could be achieved by retrofitting the winglets to the entire fleet of KC-135As operated by the Strategic Air Command. One early estimate, based on 1975 utilization rates, indicates that 68,000 gallons of fuel could be saved per year per aircraft.

tributed by turbulent flow over the fuselage is also under study.

Laminar flow is maintained over only a very short portion of the fuselage now, and is triggered into turbulence in its rush over a curved canopy or a windshield. In some current transports, it is possible to walk from the most forward part of the cabin toward the tail and to be aware, from the sudden change in interior noise level, of the point where laminar flow has changed to turbulent.

NASA scientists have been investigating ways to maintain the laminar flow over greater distances. They include a suction system, pulling boundary-layer air in through longitudinal slots on the fuselage in a manner much like suction systems for maintaining wing laminar flow. The converse, blowing air out through slots tangential to the fuselage surface, appears also to offer some promise. Both these types—and in fact any LFC system—must be considered in light of the power they consume to maintain the lower drag. It does little good to save drag, and therefore power, if an equivalent amount of energy is expended sucking or blowing air through slots.

The availability of lightweight, powerful energy sources such as the gas turbine sparked another round of interest in LFC about 20 years ago. It culminated in flight research on the X-21A aircraft, a pair of Douglas WB-66Ds modified by the Northrop Corporation to test their LFC system under an Air Force contract. The limited flight program proved the feasibility of the basic system, but was terminated before the program had been exploited fully.

The potential for fuel savings from LFC is enormous by comparison to the few percentage points picked up here and there from other aerodynamic or propulsion system developments. For a typical long-range commercial transport, LFC could reduce the fuel burned by 20 to 40 percent.

Previous LFC systems, using similar concepts, have often foundered on something as simple as a dirty wing surface. Dust, mud, even smashed insects can negate the suction system over an area large enough to be a drawback. Other problems have been encountered with suction distribution, and with the manufacturing irregularities that triggered drag even in the absence of the boundary layer. Finally, the shape of the aircraft itself, and the type and location of its engines, can affect the performance of the ideal LFC system.

LFC involves an interdisciplinary approach in two primary fields: Aerodynamics, and materials and structures. The aerodynamic concept of LFC has been known for many years; but only recently have lightweight, strong and rigid materials been developed that could make practical LFC systems a reality. (Some of the approaches in the materials and structures field are described in NF-117, "Materials and Structures/ACEE".)

The NASA LFC program is three-phased. The first, now completed, provided systems definition and concept selection. The second, now underway, involves subsystem development and evaluation. In the third, a research aircraft could be modified to integrate the selected LFC subsystems, and could be flown in a reasearch program in a simulated airline operational environment.

Aerodynamics by Computer

Much of the LFC aerodynamic study was done by computerized analysis, one of NASA's most powerful investigatory tools. Three complete computer codes were developed during Phase I of the program. The first two—an existing transonic wing code and a modified boundary-layer code—provided the analysis capability to define wing surface pressure distributions and bound-

Figure 11: A major objective of the NASA ACEE program was to get advanced technology into the hands of the manufacturers of transport aircraft as rapidly as possible. In turn, the manufacturers would incorporate that technology in their existing or near-term derivative aircraft, and plan for its use in future new designs. One manufacturer who did just that is Lockheed Georgia Company, whose Advanced TriStar prototype is shown in flight. It features extended wingtips, visible because they are a lighter shade of gray, and outboard ailerons, also a different color from the rest of the wing. Both these features improved the aerodynamic efficiency of the TriStar, and both have been incorporated in its near-term derivative, the L-1011-500 TriStar series now in airline service.

ary-layer characteristics in the presence of an LFC system. The third, a code that described boundary-layer stability, led to knowledge of the wing suction flow that would be required to maintain laminar flow over a desired wing design.

Parallel to these analyses of flow fields was the careful evaluation of advanced supercritical shockless airfoil sections. The chosen section has a most unusual shape, for those eyes accustomed to more conventional airfoils. The upper surface is a smooth, large-radius arc, rounding into a leading edge. The lower surface is concave near both leading and trailing edges, and convex between.

One of these airfoils was selected for thorough analysis and a wind-tunnel program to verify the theoretical calculations. The test wing section is being built as if it were a section of a typical advanced transport wing with an LFC system. It has a seven-foot chord, a 35-degree sweep, and a 13.5 percent thickness ratio. It is being equipped with full-span suction slots on both upper and lower surfaces, to maintain laminar flow over the wing. It spans the test section of the transonic pressure tunnel at the Langley Research Center, and will be tested at nearly full-scale Reynolds' number and at Mach numbers between 0.8 and 0.9, the high subsonic range where any future transport using LFC may be expected to cruise.

NASA set up parallel investigations to consider the best way to design and build a wing for the real world of airline service, where maintenance and repair are among the design criteria. The first steps toward that goal are being taken in the investigation of several different wing surface system concepts, using both slotted surfaces and suction areas made of porous materials. Sample wing surface panels and related suction systems are being designed and will be tested in Phase II of the LFC program.

Surface contamination problems were investigated in flight research, using a modified Lockheed JetStar light transport. The basic problem was to keep the leading edge of the wing as clean as possible. The tests used sample wing skin panels of very highly polished aluminum and of Teflon, with and without in-flight washing from a system of water spray nozzles mounted underneath the leading edge of the wing. The tests showed that washed Teflon tape was an effective way of keeping the surface contamination low enough to negate its effect on the LFC slots. These tests are continuing as new concepts evolve.

In Phase II, two promising leading edge systems consisting of suction surface and ducting, insect removal/protection, and de-icing, will be developed and tested in flight on the JetStar aircraft.

In the first phase work, the tests and development were done on small pieces, components of possible systems. In the second phase, components and subsystems are being designed and constructed for evaluation in both full-scale and sub-scale tests.

From this work could come a final selection of one LFC system to be designed, fabricated and qualified by flight research on a suitable aircraft, such as a modification of a commercial transport. It could first fly a series of experiments to prove the concept, and then could begin tests in a simulated airline environment.

As one major source of guidance for the program, NASA awarded study contracts to each of the three major air transport manufacturers in the United States. Their job was to select a design mission, and then to define a baseline configuration for an LFC transport that could become operational with commercial airlines in the future. These contracts also provide valuable inputs leading to consideration of alternatives in aerodynamics, propulsion systems, materials and structures, and all the rest of the facets of a commercially viable transport.

The goal of the LFC program is to develop a technically practical and economically attractive system. NASA will generate a technology base in this area of laminar flow control systems that will be available to industry for the design of a new generation of transports.