

Northrop's new experimental aircraft, the X-21, is exploring a revolutionary aerodynamic technique called Laminar Flow Control. The use of LFC can, in theory, double an aircraft's range and endurance. The implications for military or civil aircraft are extraordinary: nonstop, unrefueled flights around the world . . . forty-eight-hour defensive patrols 3,000 miles from base . . . commercial passenger fares reduced twenty-five percent . . . the same payload weight carried nonstop across the Pacific that is now the maximum for transatlantic flights. A giant step for the manned aircraft is . . .



USAF/Northrop X-21 Laminar Flow Control aircraft lands at Edwards AFB, Calif., after a flight test of its air-inhaling wings. Although it is still early in the flight-test program, the X-21 has demonstrated substantial reduction of friction drag.

# LAMINAR FLOW CONTROL

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**B**RUTE power, traditionally the aircraft designer's strongest ally in his endless quest for higher performance, is taking a back seat to aerodynamic finesse in a revolutionary aeronautical experiment.

The Northrop Corporation, with Air Force and Federal Aviation Agency support, is attempting a major aircraft performance improvement by controlling the airflow around an airplane in new ways, rather than depending upon raw power.

If the attempt is successful—and early flight test results from the X-21 test-bed are favorable—it will be the first time that aircraft range and endurance have been extended significantly without using a more powerful or less fuel-hungry engine.

The revolutionary aerodynamic technique utilized

on Northrop's new experimental aircraft, the X-21, is low-drag boundary-layer control, called Laminar Flow Control, or LFC. Theoretically, LFC can double the range and endurance of a large subsonic airplane by raising its aerodynamic efficiency by more than fifty percent. The lift/drag ratio of an aircraft such as the commercial DC-8 or the military B-52, for example, could be raised from about twenty to more than thirty. Put another way, LFC would allow a reduction in size of an airplane of more than forty percent—say from 400,000 pounds to 225,000 pounds for one B-52 model—without changing the aircraft's speed, range, endurance, or load-carrying ability.

The implications of Laminar Flow Control, for both  
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military and civil air operations, are as obvious as they are amazing.

Coupling the low drag of LFC with new, very-low-fuel-consumption turboprop and turbofan engines now under development conceivably could permit aircraft with useful military payloads eventually to fly nonstop around the world without refueling. A global air force based entirely on the continental US could become a reality.

Such a dramatic improvement in endurance and range could change the character of nearly all military aircraft missions. LFC and the new engines could have the same kind of impact on aircraft that the nuclear powerplant has had upon submarines.

Defensively, a large LFC airplane, loaded with two dozen or more high-performance air-to-air missiles and a large tracking radar, could stay on station for more than two full days 2,000 to 3,000 miles out from the continental limits of the United States.

Offensively, an LFC used as a carrier for air-launched missiles could greatly complicate Soviet air-defense problems. The aircraft's great range would allow the Eurasian land mass to be approached from any quadrant. It would dilute the defensive concentration now permitted along the few routes of strategic approach available to conventional bombers.

Transports using LFC would be able to carry the same payloads nonstop across the entire Pacific that current aircraft of comparable size can today lift only across the Atlantic.

Airborne command and control posts in LFC aircraft would have a vastly improved security and reconnaissance capability due to their longer time in the air.

In addition to performing specialized missions, it also appears possible that one large LFC airplane could be given the proper multipurpose capability to perform the defensive, offensive, transport, and command-and-control jobs plus the ASW mission. Such multipurpose studies, generally included under the name tag "Dromedary" a few months ago, now are identified by the name "Maple."

On the civil side, LFC aircraft could conceivably bring twenty-five percent reductions in fare and freight rates and still make greater profits for the airlines than possible with current equipment.

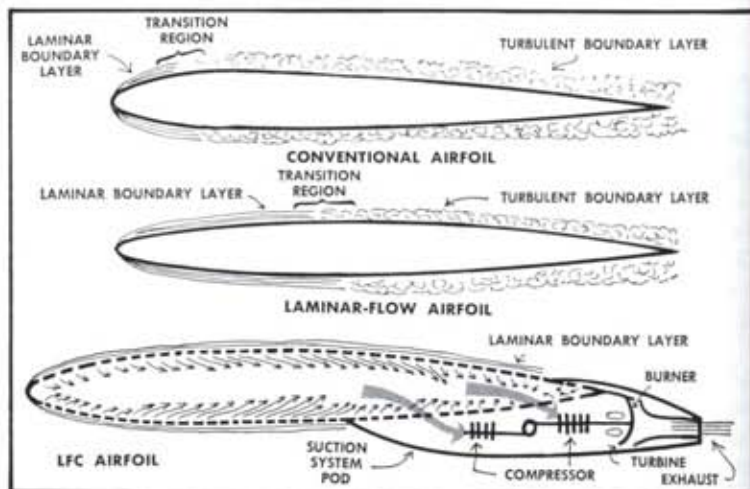
Sketch shows boundary-layer conditions on major airfoils with boundary layer thickened out of proportion to make it visible. Conventional, high-lift airfoil (top) has laminar boundary layer on only a small area, with relatively high friction drag. Maximum thickness of laminar-flow airfoil (middle sketch) is at a point midway between leading and trailing edges, keeping the boundary layer laminar over a larger area. On LFC airfoil (lower sketch), pumping system draws boundary layer into wing and prevents it from becoming thick and turbulent. LFC system reduces thickness of the turbulent boundary layer at the trailing edge from the normal ten inches or so to only about a half an inch of laminar.

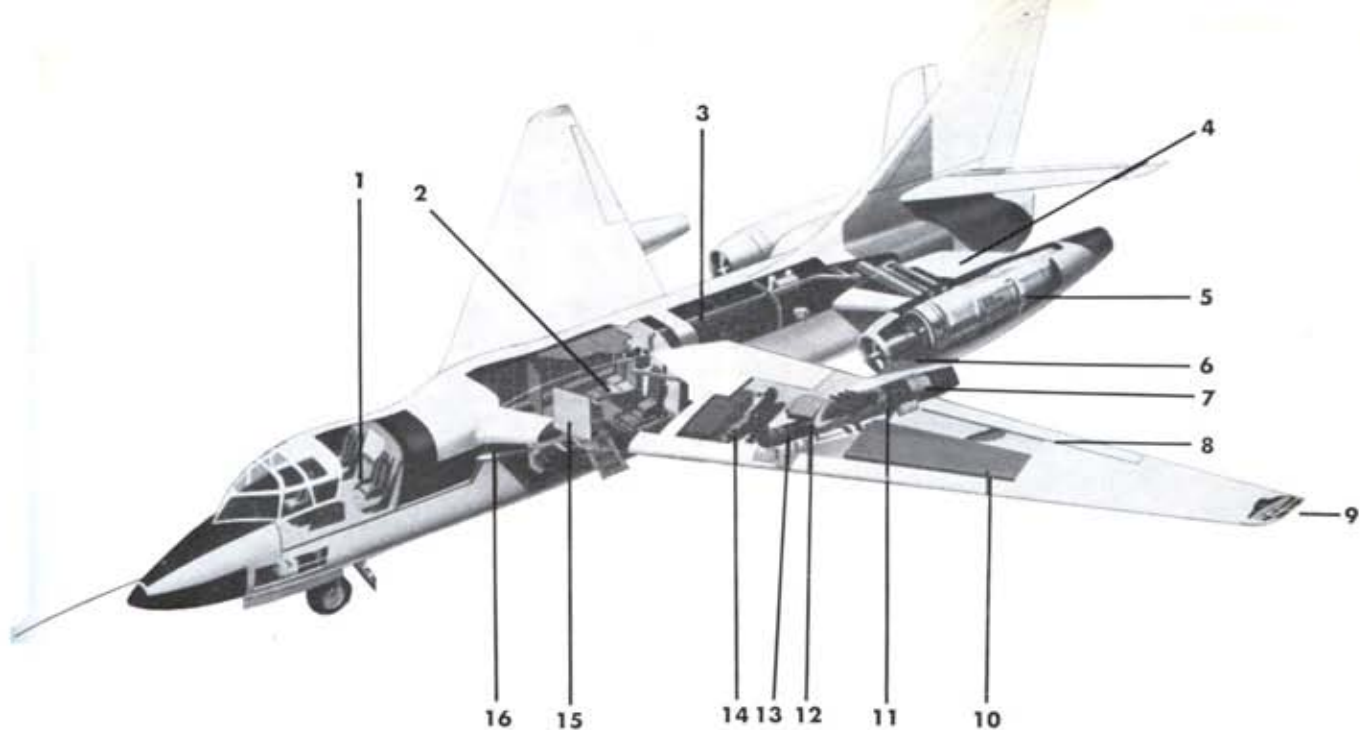
The idea of deriving a significant performance improvement by "controlling" the thin boundary layer of air, which covers all surfaces of an aircraft in flight, is not new. The pioneer German aerodynamicist, Ludwig Prandtl, published in 1904 the first accurate theoretical description of the boundary layer of a fluid in motion. (One of Prandtl's prize pupils at the University of Göttingen was Theodore von Kármán.) Prandtl's theory, applied to the movement of air over an airfoil, points out that the molecules of air immediately adjacent to an airplane in flight do not "slip," but "stick" to its surfaces. The molecules in the layers above the "stuck" layer move at progressively higher speeds until at some distance from the surface the air is moving at full free-stream velocity—the airplane's velocity. All of the layers of air moving at less than free-stream velocity comprise the so-called boundary layer. Boundary-layer thickness can vary from a fraction of an inch to more than twelve inches. On the fuselage nose or a wing leading edge this boundary layer is hair-thin. On the aft sections of very large aircraft it may be as thick as a foot or more.

Inside the shallow boundary layer, as the air is slowed from several hundred miles per hour to zero, high friction forces and shearing stresses occur. These shearing stresses manifest themselves as a kinetic energy loss in the airstream, which becomes a drag force on the airplane. In simple terms, the boundary layer of air is essentially a part of the airframe itself, speaking aerodynamically. The smoother it is, the lower the drag force it induces. Thus, control of the boundary layer in such a way as to make it smoother will reduce drag and hence reduce power requirements.

In subsonic flight, the boundary layer is especially important because more than fifty percent of an airplane's total drag is due to the frictional drag forces of the laminar and turbulent boundary layers.

Over the forward portions of an airfoil, the layers of air moving at different velocities within the boundary layer slide smoothly over each other, without an exchange of particles. This is called a *laminar boundary layer*, and Prandtl first presented the means for calculating the rate at which it will thicken and "grow" as it passes over a flat surface. After the laminar layer grows to a certain thickness, depending upon pressure





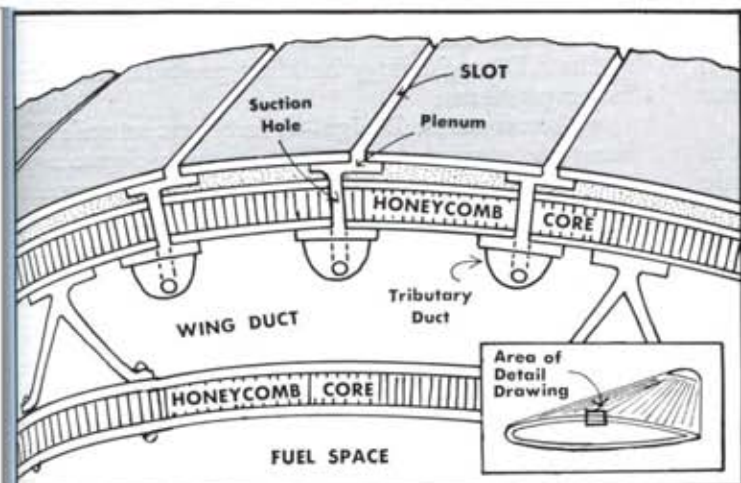
Cutaway drawing of USAF/Northrop X-21 shows the following major components: (1) crew compartment; (2) flight-test engineer's compartment; (3) bleed air line; (4) left-hand engine pylon; (5) left-hand YJ79-GE-13 engine; (6) plug for variable-area engine inlet; (7) high-pressure compressor; (8) aileron; (9) fuel tank vent; (10) outboard fuel tank; (11) low- and high-pressure mixing chamber; (12) low-pressure compressor; (13) low-pressure collector duct; (14) LFC system modulating valves for regulating pressure on wing slots; (15) flight-test instrumentation panel; and (16) fuselage side fairing. The early flight test results have substantiated estimates that LFC airframe maintenance costs would be about ten percent higher than those for conventional aircraft. Probably it will not be necessary to clean the wing surfaces after every flight, and steam cleaning once a month would keep it adequately free of dirt and grease.

conditions on the surface, it undergoes a "transition" and becomes turbulent. In the turbulent boundary layer the laminar layers disappear and the air particles tumble violently. The energy losses, or drag, of a turbulent boundary layer are about three times higher than for a laminar layer.

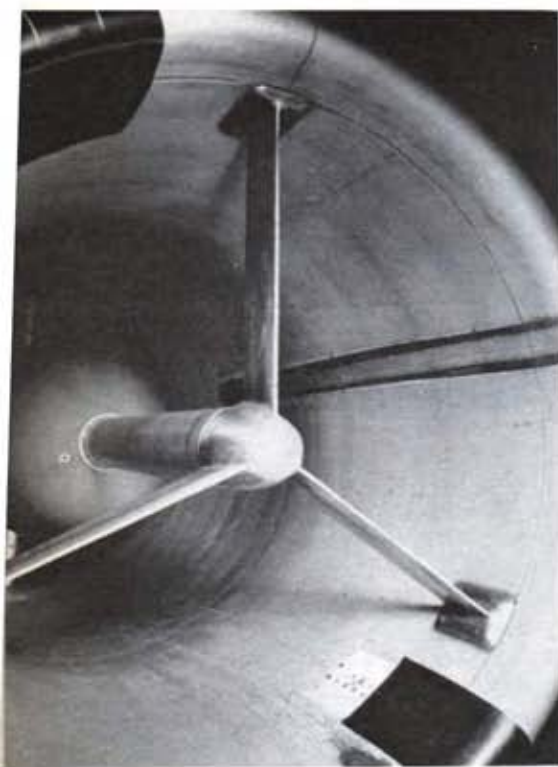
The first successful step in controlling the boundary layer came with the development of the so-called laminar flow airfoils in the late 1930s and early 1940s. They were studied independently in Japan, Russia, England, and the United States. The first successful operational application of one of these airfoils was on the North American P-51. This work was instrumental in increasing the Mustang's operational radius well beyond its contemporaries; in response to the desperate need for long-range fighter escort for the US Air Force's daylight bombing of Germany.

The Mustang airfoil worked because the stability of the laminar boundary layer can be preserved, and drag-inducing transition to turbulence prevented, as long as the flow on a surface is accelerating. The designers of the Mustang airfoil made its thickest part at the point halfway between the leading and trailing edges—the fifty percent chord point. In other airfoils of the day, the maximum thickness was much nearer the leading edge, at about the twenty-five percent chord point (see page 32). As a result, the airflow over the Mustang wing ran uphill, accelerated and remained laminar over most of the forward half of the wing. Laminar flow, with its consequent drag reduction, existed over a much greater area than on conventional fighter wings.

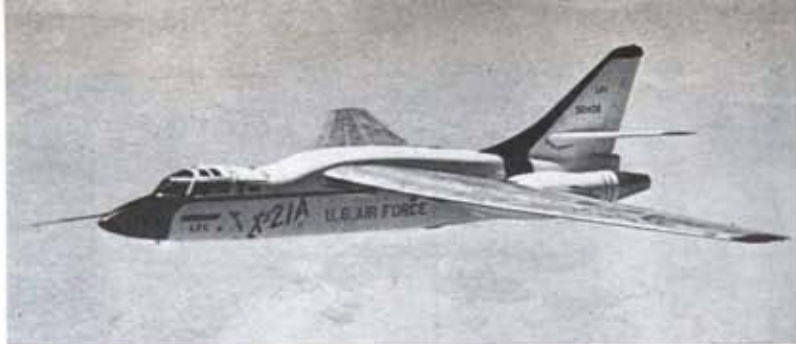
The Mustang-type wing represented about the best  
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Schematic drawing shows razor-thin slots and duct system built into X-21 wing. Boundary-layer air is drawn through slot cut in outer skin into a plenum, or settling chamber, milled in the second skin layer. It then passes through long holes drilled in the honeycomb reinforcing panel and into small plastic tributary ducts bonded to the honeycomb. From the tributary ducts the air enters the main wing ducts and is drawn into the pumping system. The outer-skin layers are bonded together, eliminating all riveting and leakage and maintaining a smooth surface for the X-21 wing important to the technique.



Engine noise can cause boundary-layer transition. A movable plug on a rod in X-21 inlet (above) creates a standing shock wave and stops engine noise from reaching wing.



Flights of the X-21 at Edwards AFB, Calif., have to date covered an altitude range from 8,000 to 45,000 feet and speeds up to Mach 0.8. Bugs sticking to wing have not bothered the LFC system so far.

Space problems on X-21 experimental aircraft are emphasized in photo at right, showing aft end of wing-mounted LFC pumping system (on right side) and J79 inlet (left side). Operational LFC aircraft would have a more simplified arrangement.



## LAMINAR FLOW CONTROL

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one could do in reducing boundary-layer turbulence through airfoil design. Further progress depended on development of mechanical means to eliminate turbulence over the entire wing by progressively removing the boundary layer to keep it from growing thick enough to cause transition to turbulence. This has been the object of all low-drag boundary-layer control measures. There have been studies in many places, notably by Dr. Gustav Lachmann at Handley Page in England, and Professor Jakob Ackeret at the Swiss Federal Institute of Technology in Zurich, Switzerland. The Northrop program has been under the guidance of Dr. Werner Pfenninger, one of Ackeret's students. Dr. Pfenninger came to this country after World War II.

In the Northrop LFC system the boundary layer on both the upper and lower surfaces is sucked into the wing through a vast series of razor-thin slots that run spanwise from wing root to tip. These slots are from .0025 to .008 inches wide (the cutting edge of a razor blade is about .004 inch).

The suction is created by compressors positioned in nacelles under the wings, where room has been made for them by moving the X-21's two jet engines back beside the tail. Air drawn through the slots is gathered in small chambers and channeled through pin-size holes (more than 800,000 of them in the X-21) into larger ducts. The air then is drawn through these ducts downward into the compressors themselves (there are two small, lightweight gas turbines in each nacelle under each wing—one turbine to draw air from the front part of the wing and the other from the trailing edge), and then the air is expelled.

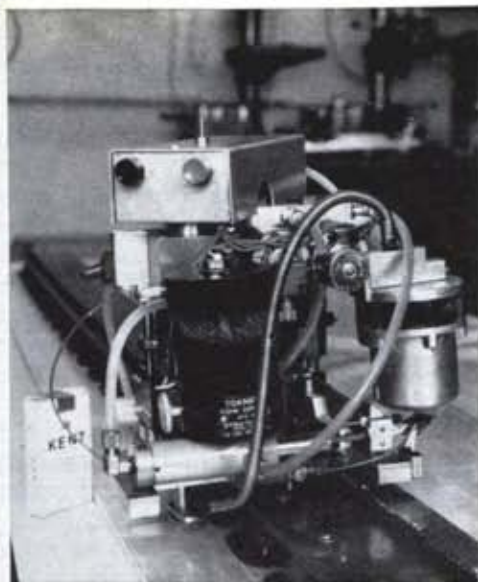
The first flight tests of this system took place during the middle 1950s on a Lockheed F-94 fighter with an LFC section built into one wing. The Starfire's flights proved that laminar flow could be attained over the entire LFC section.

After several years of discussion in the Air Force and Department of Defense, Northrop was given the go-ahead in 1960 to build two X-21s by extensively modifying two WB-66 weather reconnaissance aircraft. The objective of this program, in which the Air Force has invested \$35 million and the FAA \$2 million, was to build a complete LFC technology. Solid answers were to be found for all questions which would arise if LFC aircraft were compared on a cost-effectiveness basis with other systems in such mission areas as air defense, early warning, strategic bombardment, command and control, air transport, etc.

The LFC technology building program faced three major problems:

- **Aerodynamic Design**—A forty percent scale DC-8 wing was chosen for the X-21. Its thirty-degree sweep and general characteristics were considered representative of the kind of wings used to delay the beginning of shock-wave drag on large high-subsonic-speed LFC aircraft.

On sweptwings there are obstacles to achieving laminar flow that are not present in the straight wing. One is that the boundary-layer flow has a strong tendency to turn outward toward the wingtip, and this "cross-flow" causes transition to turbulence almost immediately. Even with the latest sweptwing with laminar-flow airfoil, turbulence in the boundary layer



Simple tooling used in manufacture of LFC wing is illustrated by automatic drilling machine at left. The tool drills up to ninety holes per minute, traveling on a track that can be quickly placed in position.



Shown in the mockup at right is the elaborate system of ducts that connects the X-21's pumping system to long ducts built into the wings. Valves control the suction system's pressures. The operational system would be more simple.



X-21 wing in production jig shows rows of tributary ducts bonded in place. Tributary ducts are needed to maintain nearly constant pressures in wing ducts, thus preventing high flow losses.

begins no more than a couple of inches back from the leading edge. To complicate matters, strong centrifugal forces created in the flow of air around the curved leading edge further tend to thicken the boundary layer on a sweptwing.

An extensive computer program was required to tailor and twist the X-21 wing to minimize these cross-flow and leading-edge centrifugal forces and to keep a favorable pressure distribution around the wing-fuselage juncture. The most visible evidence of the tailoring work is the large fuselage hump in the forward wing-root area.

Problems still are expected around the wing roots, and the program guarantee calls for attaining complete laminar flow only on seventy percent of the X-21 wing area. If this goal is attained on the X-21 it is considered certain that full laminar flow can be achieved on an aircraft designed from the start for LFC.

• **Structural and Manufacturing Problems**—The wing of an LFC aircraft, first of all, must be extremely smooth, much smoother than that of a conventional subsonic transport or else the boundary-layer-control system may not work. Surface roughness tends to cause transition turbulence that no amount of suction will prevent. Second, a relatively economical method had to be found for manufacturing the very smooth LFC wing that contains hundreds and hundreds of little ducts and an elaborate pumping system. If production costs were several times those for a conventional wing, the LFC idea would likely die aborning.

The development of relatively simple structural design and manufacturing techniques is one of the key

achievements of the LFC program. Data indicates that an LFC wing will cost only about twenty percent more to produce than a conventional wing of the same size and weight.

The X-21 wing has two main spars, with an acceptably large fuel tank volume in between. The outer-skin assembly is built up of several layers bonded together to form the first portion of the duct system through which the boundary layer is removed. As shown on page 33, the outer aluminum skin with the slots is bonded to an under skin of thermal adhesive, in which a plenum chamber is milled to align with the slots. Below this is a layer of aluminum sandwich bonded to the V-shaped stringers, which in turn are riveted to another layer of sandwich. Holes are drilled from the plenum chamber in the under skin down through the top sandwich into the deep duct formed by the two layers of sandwich. As the LFC system operates, the air in these deep ducts reaches speeds up to 200 mph. If the ducts were not relatively large there would be a boundary-layer problem in the duct itself, with high drag and pumping system losses.

Northrop and its subcontractors have developed some relatively simple tools which do an extremely rapid and accurate job of cutting the skin slots, milling the plenum chambers, and drilling the thousands of tiny holes from the chambers into the ducts.

The proper wing smoothness, with very small tolerances in the match of the skin panels, is achieved by building the wing from the outside in. That is, the wing-skin panels, usually measuring about five by twenty

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feet, are fixed into the proper position in the final assembly jig and then the spars and the other understructure components are added. In conventional manufacturing the understructure goes in first with the skin following its contours.

● **Operational Problems**—The X-21 flight-test program is designed to get firm answers to a number of key questions about LFC operations. A major one is the allowable surface roughness. The X-21 wing today is polished and smoothed until it resembles a giant wind-tunnel model. From this ideal and operationally impractical beginning the wing will be roughened to see how much structural distortion, dirt, bugs, etc., can be tolerated without disrupting the laminar flow. A de-icing system which electrically heats sections of the wing at intervals will be tested to see if it can keep the LFC functioning during icing conditions at lower altitudes. All types of maintenance problems are being probed.

When the X-21's LFC system was turned on initially during flight test, only about the outer twelve percent of the wing went laminar. At this writing laminar flow has been achieved over the outer fifty percent or so through a series of adjustments in the pumping pressures and flow rates on the leading-edge slots. If such adjustments do not continue to extend the laminar area inboard, external modifications will be tried. The experimental flights to date have pretty well convinced project managers that closer slot spacing probably will be necessary on the inboard leading edges to achieve 100 percent laminar flow on the wings of operational aircraft.

Even though the flight-test program has not been completed, enough data is available to indicate that the LFC system will work on large aircraft and that the proper technology has been created to turn the laboratory curiosity of low-drag boundary-layer control into an operational tool.

LFC aircraft will have several distinctive features, all of which will not be immediately apparent. However, a familiarity with the following basic characteristics will aid in evaluating various LFC aircraft proposals.

● **Wing**—LFC aircraft will need at least fifty percent more wing area than conventional aircraft of the same gross weight. Normally the wing on subsonic aircraft is sized to minimize wing weight, friction drag, and drag due to lift. When the friction drag is removed from consideration it is possible to reduce drag due to lift substantially by increasing the wing span, without paying an undue penalty in increased structural weight.

● **Landing and Takeoff Performance**—Even though an LFC airplane will have smaller engines than a conventional aircraft of the same weight, its takeoff-and-landing performance will be comparable. The large-wing and low-wing loading of the LFC airplane will make it exceptionally docile and easy to handle at low speeds.

● **Fuselage**—Current LFC aircraft designs under consideration by the military do not have boundary-layer control on the fuselage—only on the wings and tail surfaces. It might prove practical to apply LFC

to the fuselage as well with even further improvement in performance.

● **High- and Low-Altitude Performance**—The slot arrangement and pumping system on an LFC airplane are designed for a particular combination of flight speed and air density (altitude). However, an LFC airplane designed for maximum performance at high speed and high altitude (low air density) will perform well at low altitudes if the speed of the aircraft is kept commensurately low.

The X-21 was designed for high altitudes and high subsonic speeds. If it had been optimized for a lower altitude, its wing would have been bigger and its wing slots placed closer together.

● **Supersonic LFC**—LFC can be used to reduce friction drag at supersonic speeds. At relatively high supersonic speeds, Mach 3 or above, LFC also would reduce the rate at which a fuselage or wing would heat and would keep its maximum temperature down. It might well be possible to design a Mach 3 airplane with a heat range no greater than that currently conceived for a Mach 2 aircraft.

At relatively low supersonic speeds, when the shock wave from the fuselage nose stands out ahead of the wing so that the flow on the leading edge is subsonic, current theory can be used in the design of an LFC system. However, when the fuselage shock strikes the wing and there is supersonic flow on the forward portions, the design problem is complicated considerably. A solution is being sought at Northrop and elsewhere in industry and government.

The first major flight success for low-drag boundary-layer control has been achieved in the X-21 LFC program. Progressive program management has provided for the concurrent development of a sound basic technology to support this success, making it less likely that LFC will be regarded as an exciting but impractical curiosity.

There is little doubt that LFC aircraft have a heavy impact on Air Force planning for missions involving the long-range delivery of weapons, personnel, or equipment. By virtually eliminating range and "time in the air" as restraints on aerial operations, LFC technology has greatly expanded the potential usefulness of the airplane. Together with the new engines, LFC has brought almost all of the "infinite" range benefits of the nuclear airplane, without its formidable operational problems.

Unfortunately, the great promise of LFC has come at a time when Department of Defense spokesmen have voiced substantial doubts about the continued usefulness of manned aircraft for most long-range Air Force missions.

Many more months of study and justification will be necessary at the highest levels in DoD before new fleets of manned aircraft will be authorized to supplement or replace the missile and aircraft forces, either existing or on order.

Without LFC and the new engines, it is clear that the DoD discussions would be a formality and that the chances for development of new long-range manned aircraft would be small.—END