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AIRFRAME TECHNOLOGY FOR AIRCRAFT ENERGY EFFICIENCY

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ABA: A.R.H.
ABS: The economic factors that resulted in the implementation of the aircraft energy efficiency program (ACEE) are reviewed and airframe technology elements including content, progress, applications, and future direction are discussed. The program includes the development of laminar flow systems, advanced aerodynamics, active controls, and composite structures.

ENTER:

SUMMARY

NASA's Aircraft Energy Efficiency program began in 1976, following a year of planning. This half-billion dollar program focused on the development and demonstration of advanced technologies applicable primarily to transport aircraft, with about half the effort devoted to engine technology and the other half to the airframe. This paper reviews the factors that resulted in the implementation of the ACEE program and discusses airframe technology elements including content, progress, applications, and future direction.

INTRODUCTION

Commercial jet aircraft energy consumption was the primary factor in ACEE program formulation[1,2]. The country had been shaken by the 1973 OPEC oil embargo with one result being widespread concern about the future availability and cost of fuel. Commercial aviation fuel consumption was increasing 5 percent annually, and fears about resource depletion were rampant. Also, airline fuel prices had just risen from 10 to 28 cents per gallon and additional increases were rapidly occurring. Presently, the supply of jet fuel seems more plentiful; however, fuel costs have continued to cause serious airline financial problems. Fuel is now the major factor in airline direct operating cost (DOC)--accounting for about 57 percent--versus only 35 percent in 1975 (fig. 1). Also, in recent years, other economic factors motivating aeronautical technology development have come into view. The world aircraft market now amounts to over ten billion dollars annually, and the American aircraft manufacturing industry is being challenged as never before. World market share captured by the European Airbus, for example, has grown from only 3 percent in 1975 to more than 20 percent, significantly affecting the economy and trade balance of the United States. Thus, an even stronger economic argument exists today for a technology program which improves transport aircraft fuel efficiency.

The ACEE airframe program[3] is developing technology for commercial transport application of laminar flow systems, advanced aerodynamics, flight controls, and composite structures (fig. 2). Objectives are met through ground and flight testing a variety of aerodynamic concepts, aircraft flight systems, and advanced structures. The Transport Aircraft Laminar Flow (TALF) program, for example, building on the solid technology base developed during the past eight years[4], is about to enter a new phase characterized by major flight testing. Likewise, the Energy Efficient Transport (EET) program has completed an extensive amount of flight and ground based aerodynamic and flight control testing which featured a strong interaction between industry and NASA research. The highly successful Advanced Composite Structure Technology (ACST) program began with composite use in secondary structures such as rudders, ailerons, and elevators (all now in service) and now has been applied to the horizontal stabilizer of the 737, the vertical stabilizer of the DC-10, and the vertical fin of the L-1011 (all ground tested). Future efforts focus on use of primary composite structure in the aircraft's wing and fuselage.

RESULTS AND DISCUSSION

Laminar Flow. - Major flight elements of the NASA Transport Aircraft Laminar Flow program consist of the JetStar leading edge flight test (LEFT); the recently completed F-111 natural laminar flow (NLF) transition tests; the upcoming F-14 variable sweep transition flight experiment (VSTFE); and and the Citation III fixed-sweep flight tests (fig. 3).

The LEFT objective is to demonstrate candidate leading-edge system effectiveness in maintaining laminar flow under simulated airline service conditions (fig. 4). Flight testing of the NASA LEFT aircraft began in late 1983. This program utilizes LFC leading edge test articles on an extensively modified JetStar aircraft[5]. Suction surfaces are integrated with a ducting system such that cleaning and repair are easily accomplished. Mounted on the left wing is the Lockheed-Georgia Company (GELAC) test article; slots on the upper and lower surfaces are used for boundary layer suction and dispensing washing and de-icing fluid[6]. The right wing leading edge test article has a perforated suction panel developed by the Douglas Aircraft Corporation (DAC)[7]; this system uses a Krueger-type flap as a high-lift device and insect shield. This device also houses a washing and a de-icing fluid spray system. The LEFT effort has resulted in the fabrication and development of practical leading edge LFC systems which offer solutions to concerns about the maintenance of laminar flow in the difficult leading edge region.

Recent NLF flight studies include limited tests using an F-111 fitted with a wing glove[8] (fig. 3). These tests showed that significant laminar flow occurs with moderate wing sweep. Results obtained on general aviation aircraft are also encouraging[9]. Measurements on existing wings of both aluminum and composites resulted in transition Reynolds number to 11 million, demonstrating that laminar flow can be obtained in flight on production-quality general aviation-type aircraft. Additional flights will obtain more detailed data; the fixed-wing Citation III was tested in late 1983, and the gloved wing F-14 variable-sweep tests will be accomplished during 1984 and 1985. The objective is to determine conditions under which NLF is possible. Transition Reynolds number and boundary layer data will be measured as a function of sweep angle for various flight conditions.

Industry system studies show that attractive gains may be achieved by combining LFC in the leading edge region with NLF over the wingbox[10].

This technique, referred to as "hybrid" LFC, avoids the structural complexity required when locating an LFC system in the wingbox. The previously described Citation III and F-14 tests will provide data needed to help evaluate the hybrid concept.

Flight tests are complimented by wind tunnel research (fig. 5) aimed at providing a data base useful for design efforts; ongoing research includes the laminar flow control (LFC) supercritical transonic airfoil test in the Langley 8-foot Transonic Pressure Tunnel[11,12], high-lift research on a similar advanced LFC airfoil in the Langley 4X7-meter tunnel, and swept wing boundary layer instability tests at the Virginia Polytechnic Institute and State University. These research activities are providing promising results. For example, laminar flow was achieved by suction on an advanced airfoil with extensive supercritical flow.

To evaluate the difficult problem of integrating LFC systems with aircraft wing structure, industry contract programs were initiated. GELAC and DAC have defined structural concepts for future LFC transports and demonstrated their feasibility through detailed wing designs, manufacturing studies, and structural testing. The GELAC concept (fig. 6) has the LFC ducting integrated into primary structure[13]; DAC uses a gloved-on suction panel approach[14]. These efforts have shown that advanced structural and material technology may be used to build laminar flow suction panels utilizing design and production techniques applicable to modern aircraft.

Aerodynamics. - A major factor contributing to the success of the Energy Efficient Transport (EET) aerodynamics program was the extensive use of NASA wind tunnels, computational facilities and personnel to complement industry application efforts. Three examples of aerodynamic research programs are shown in figure 7. NASA wind tunnels provided an extensive aerodynamic data base on advanced transport configurations employing high aspect ratio, supercritical wings. Both high- and low-speed tests were conducted on various wing configurations, empennage arrangements, propulsion/airframe integration concepts and high-lift and lateral-control systems. With the focused efforts of both NASA and industry researchers, application of supercritical-wing technology was highly accelerated[15-18].

Considerable effort was also devoted to the application of winglets to large transport aircraft. Wind-tunnel tests were conducted on jet aircraft ranging from first generation (KC-135) and second generation (DC-10, B-747, L-1011) transports to third generation configurations having high aspect-ratio, supercritical wings. Full scale winglet flight tests were performed on both a KC-135[19] and a DC-10[20] aircraft. This research helped pave the way for winglet application on the Grumman Gulfstream III, several Learjet models and the proposed MD-100[21] aircraft.

Another aerodynamic research example is the Boeing Commercial Airplane Company (BCAC) flight-test program to determine aerodynamic and inertial loads on the B-747 nacelle[22]. These results make it possible to design nacelles that prevent engine efficiency degradation caused by nacelle deformation. This data is also of value in evaluating analytical methods for assessing wing-nacelle-pylon interference.

Active Controls. - Active control technology activities pursued under the EET effort include maneuver load control (MLC) and pitch active control systems (PACS) (fig. 8).

Maneuver load control is achieved by modifying the wing load distribution using the aircraft's control surfaces and fast-response actuators commanded in response to motion sensors. The MLC system uses symmetrical deflection of the outboard ailerons to modify spanwise lift distribution for reduced bending stress while maintaining overall wing lifting force.

Thus, higher aspect ratio, lower sweep wings are possible without a major penalty in wing structural weight. This technology was successfully applied to the Lockheed L-1011-500 aircraft introduced in 1979[23].

In addition to active wing load alleviation, future aircraft can be expected to employ an increasing degree of active stability augmentation. These aircraft will have less static stability and thus benefit from smaller tail surfaces and reduced trim drag. To explore PACS application, a flight test program employing the L-1011 aircraft was conducted by the Lockheed-California Company (CALAC)[24]. The aircraft, equipped with a PACS and a center-of-gravity (cg) management system, was flown with varying static stability levels. Flight tests with the PACS operating showed considerably improved handling qualities (Cooper-Harper Rating) with cg positions up to 3 per cent aft of the neutral point (fig. 8).

Hardware for the Boeing Integrated Application of Active Controls (IAAC) system is also shown in figure 8[25]. The IAAC system, now being laboratory tested, includes wing load alleviation, fly-by-wire, and pitch augmented stability. IAAC combines the computing capability of both analog and digital technology to achieve the necessary reliability. To evaluate system performance, extensive laboratory testing will be conducted including deliberate failure injections.

Composite Structures. - The ACEE composite structures program objective is to develop lighter, more efficient airframes. Graphite epoxy composite materials reduce structural weight by about 25 percent over current aluminum structures, leading to an improvement in fuel efficiency of about 15 percent. Also, as manufacturing experience is gained and more automation is employed, the cost of composite airframe structures may be less than aluminum counterparts[26-28]. Program thrust is to develop within the transport aircraft industry both the technology and the confidence required for a commitment to composite structures construction. This means not only developing the know-how for predictable designs and low-cost fabrication, but also having enough test and manufacturing experience to accurately predict durability for product warranty, costs for product pricing, maintainability for airline acceptance, and safety including FAA certification.

The composites program consists of two phases; the secondary and medium primary components phase, and the large primary component phase for wing and fuselage structures (fig. 2). In the first phase, the commercial transport manufacturers redesigned selected components of existing aircraft using composite materials. Included were rudders, ailerons, elevators, vertical stabilizers, vertical fins and horizontal stabilizers (fig. 9).

Secondary components work has been completed and several units are in flight service on domestic and foreign commercial airlines[29-31]. Weight savings on the order of 25 percent were realized. Service experience was routine with only minor maintenance required. These efforts provided the data base required for composites application to the latest transport aircraft. The Boeing 767/757 aircraft include more than 3000 pounds of composite structure (fig. 10) which reduce weight about 850 pounds and improve fuel efficiency about 2 percent. Clearly, aerospace industry use of graphite fiber will increase rapidly as this technology develops and composite material cost declines.

Medium primary or empennage components offered a significant challenge for composites application as compared to secondary structure. Physical size is much greater; design requirements, load interaction, manufacturing and tooling are far more complex. Components selected for development include the Douglas DC-10 vertical stabilizer, Lockheed L-1011 vertical fin, and the Boeing 737 horizontal stabilizer (fig. 9). Initial verification testing of all three components resulted in structural failure at less than design ultimate load; modifications were made and subsequently all empennage components successfully completed ground testing. Investigation and analysis of the failed components provided insight into the problems which must be addressed in applying composites to primary structures[32-35]. Foremost among these, the brittle nature of composites and their relative weakness in interlaminar tension and shear will be a major concern until composite material with improved interlaminar toughness becomes available. The 737 horizontal stabilizers have been certified by the FAA and five shipsets are expected to be in flight service during 1984. The DC-10 flight unit is being assembled; FAA certification is expected later this year, followed by flight service beginning in 1985. Development of the L-1011 vertical fin was completed after extensive ground testing.

Extension of composites technology to the larger wing and fuselage structures could produce benefits nearly an order of magnitude greater than with control surface and empennage structure applications. A major technology advance is required because transport wing and fuselage structure is characterized by unprecedented composite physical dimensions. NASA initiated contracts with the commerical airframe manufactuers in 1981 to address the most critical wing technology issues. Similar fuselage contracts will begin in 1984 (fig. 11). Great progress is being made in this second phase of the ACEE composites program. Development of wing and fuselage sections will challenge industry and government research teams for several years to come.

CONCLUDING REMARKS

NASA's ACEE airframe program, begun in 1976, helped focus government and industry research programs in laminar flow systems, advanced aerodynamics, flight controls, and composite structures. Fuel savings ranging from 10 to 40 percent are possible as new technologies mature to the point of application (fig. 12). The rapid fuel price increases which have occurred since program inception combined with increased competition by foreign transport manufacturers mean that ACEE airframe technology is even more economically important today.

Technical progress made in recent years has been impressive. Introduction of new technology into existing and planned aircraft was sharply accelerated. Prominent aircraft applications include the 767, 757, DC-10, L-1011, 727, 737, and numerous general aviation aircraft. More applications will be included in future aircraft as industry adopts this new technology and improves its product line. NASA in-house capabilities have benefited from the ACEE funding support and the cooperative research effort between industry and government.

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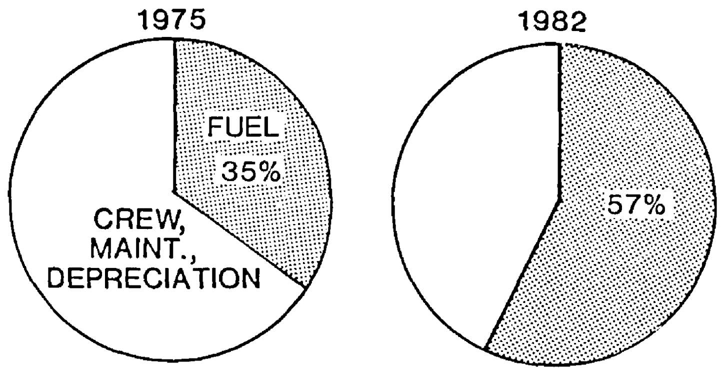
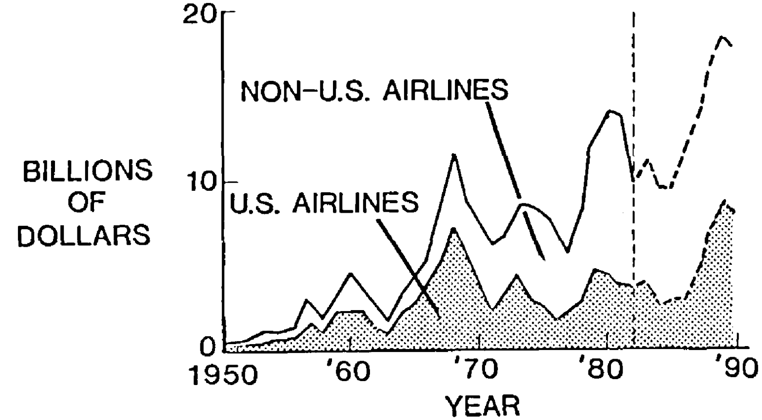
AIRLINE DIRECT OPERATING COST

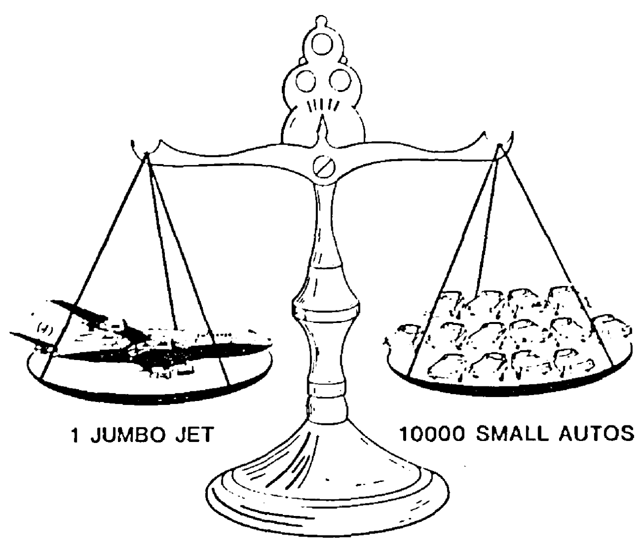


WORLD COMMERCIAL AIRPLANE DELIVERIES

(1983 DOLLARS)



TRADE BALANCE



FOREIGN COMPETITION

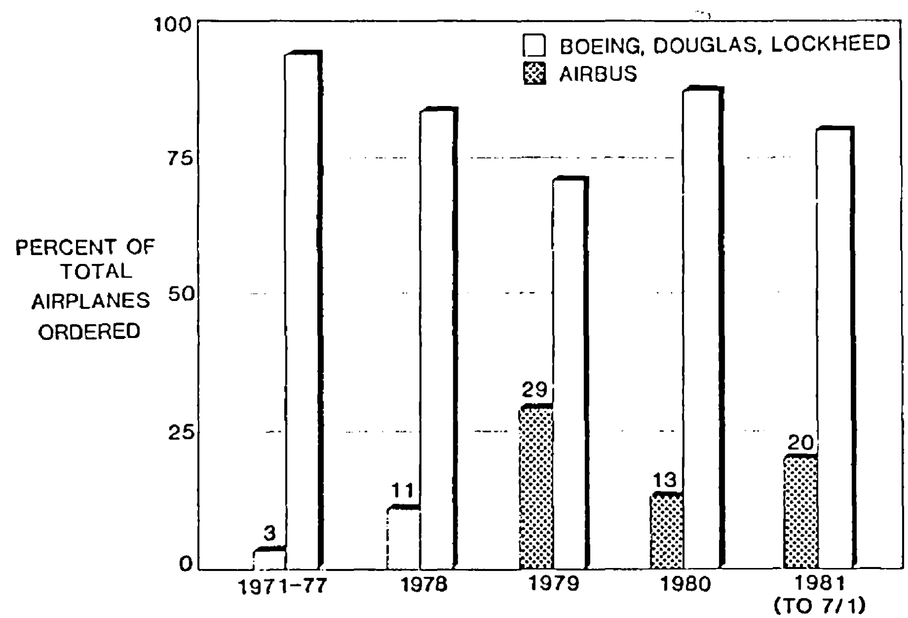


FIGURE 1 - ECONOMIC CONSIDERATIONS

DEVELOP TECHNOLOGY IN LAMINAR FLOW SYSTEMS, AERODYNAMICS, FLIGHT CONTROLS, AND COMPOSITE STRUCTURES FOR APPLICATION TO FUTURE TRANSPORT AIRCRAFT

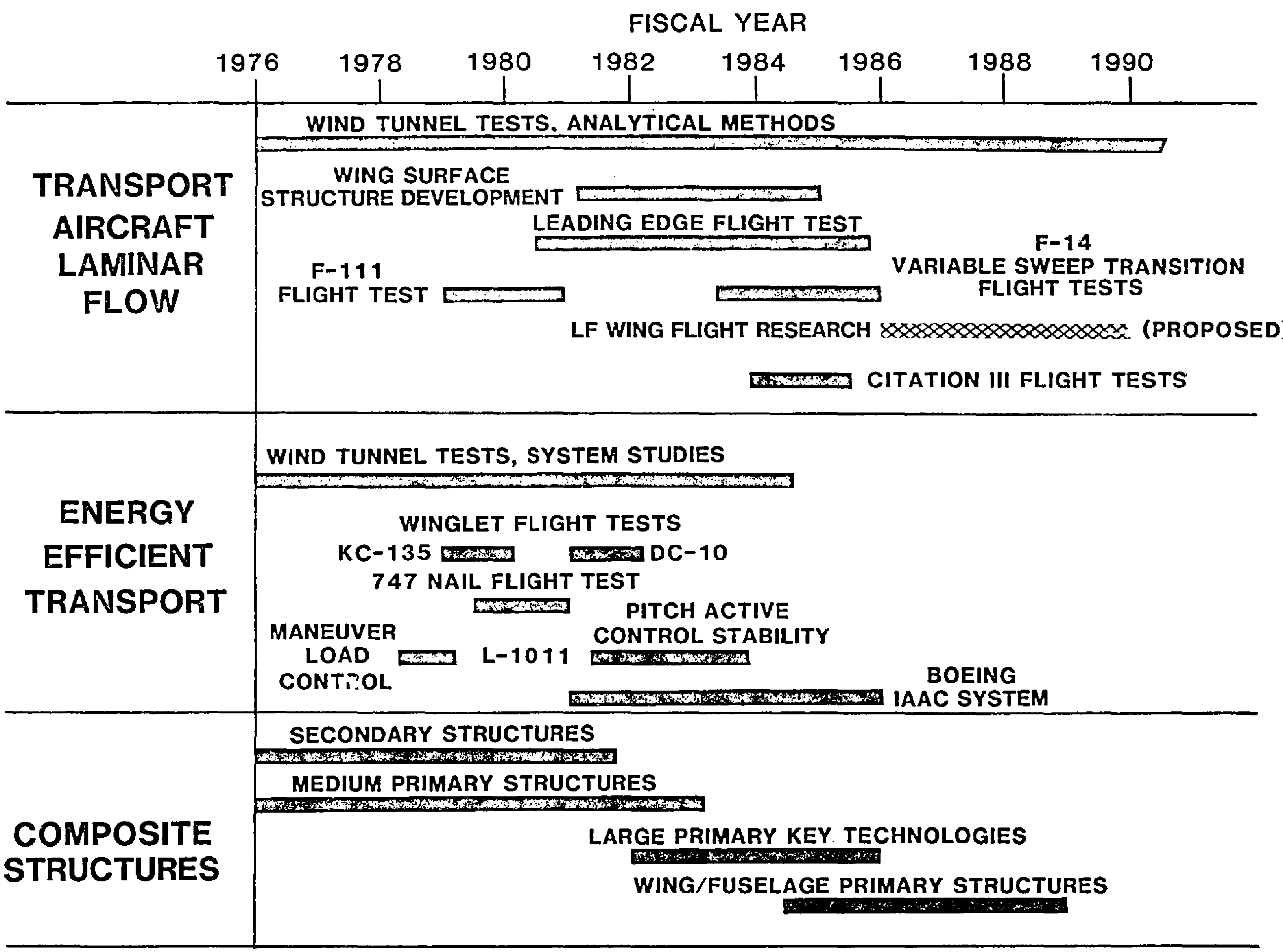
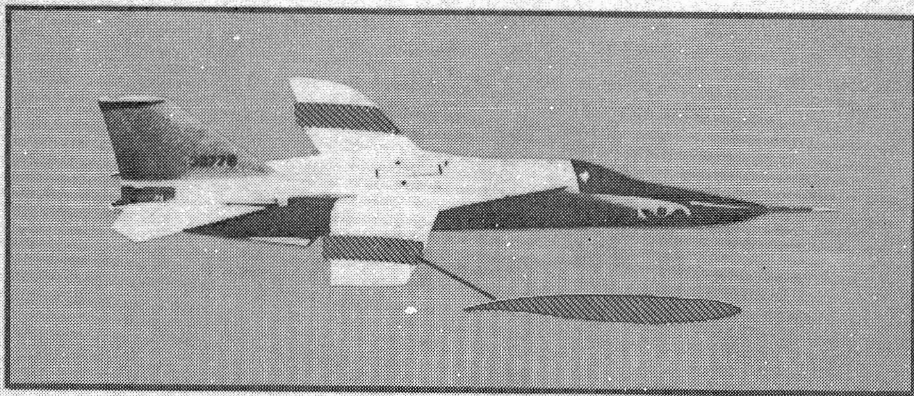
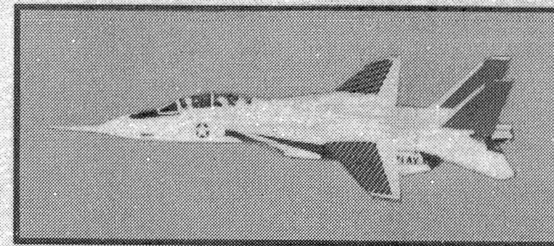


FIGURE 2 - ACEE AIRFRAME PROGRAM OBJECTIVES

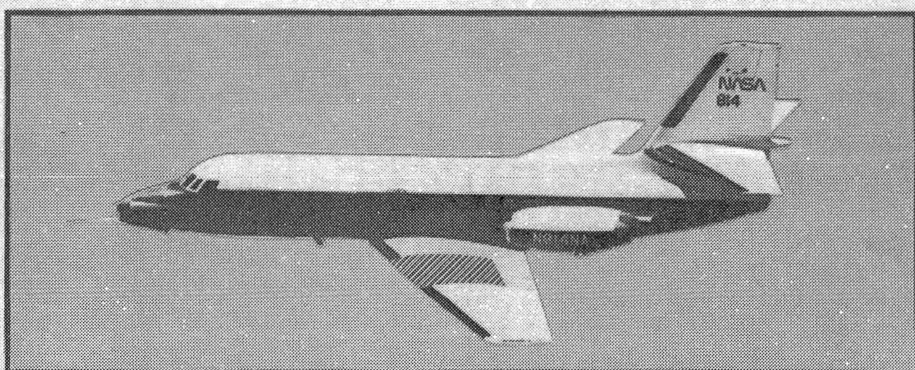
F-111 VARIABLE SWEEP



F-14 VARIABLE SWEEP



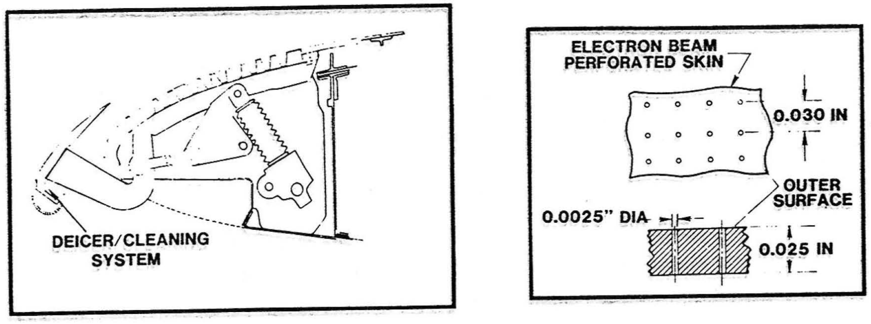
JETSTAR LEADING EDGE FLIGHT TEST

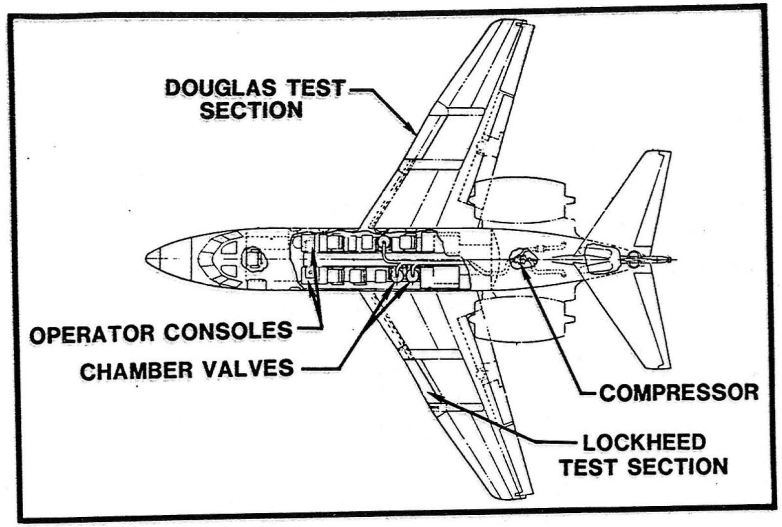


CITATION III FIXED SWEEP

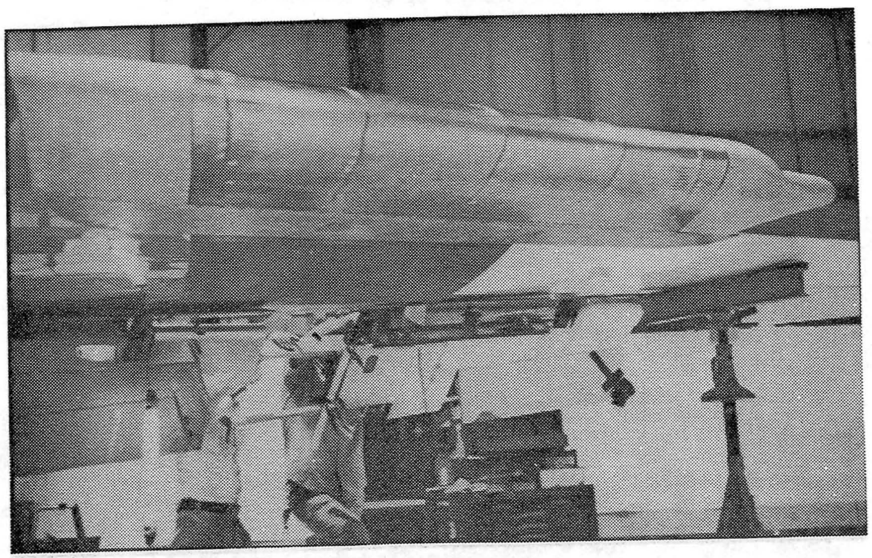
FIGURE 3 - LAMINAR FLOW FLIGHT EXPERIMENTS

DOUGLAS AIRCRAFT LEADING EDGE





LOCKHEED LEADING EDGE



SIMULATED AIRLINE SERVICE

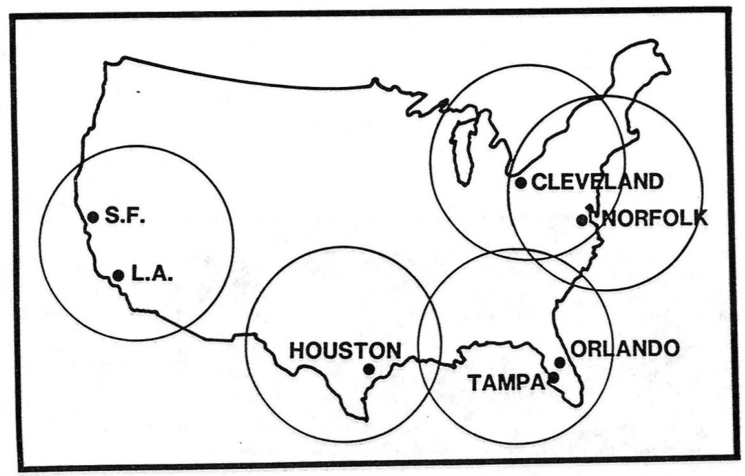
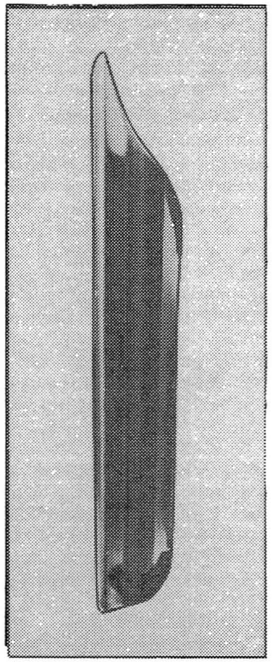


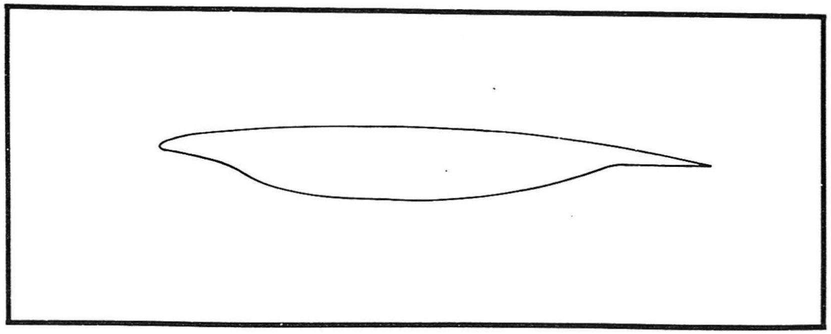
FIGURE 4 - LEADING EDGE FLIGHT TEST

TRANSONIC AIRFOIL

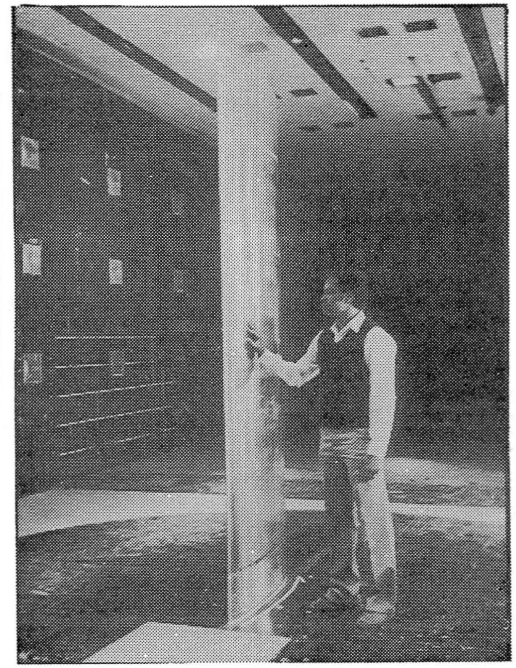
- SLOTTED SUCTION SURFACE
- PERFORATED SUCTION SURFACE



LAMINAR FLOW CONTROL ADVANCED AIRFOIL



HIGH - LIFT



STABILITY THEORY/EXPERIMENT

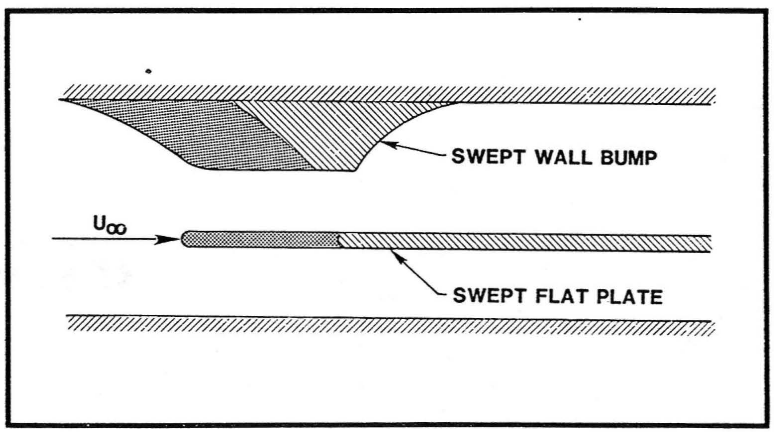


FIGURE 5 - LAMINAR FLOW WIND TUNNEL EXPERIMENTS

PERFORATED **SLOTTED**

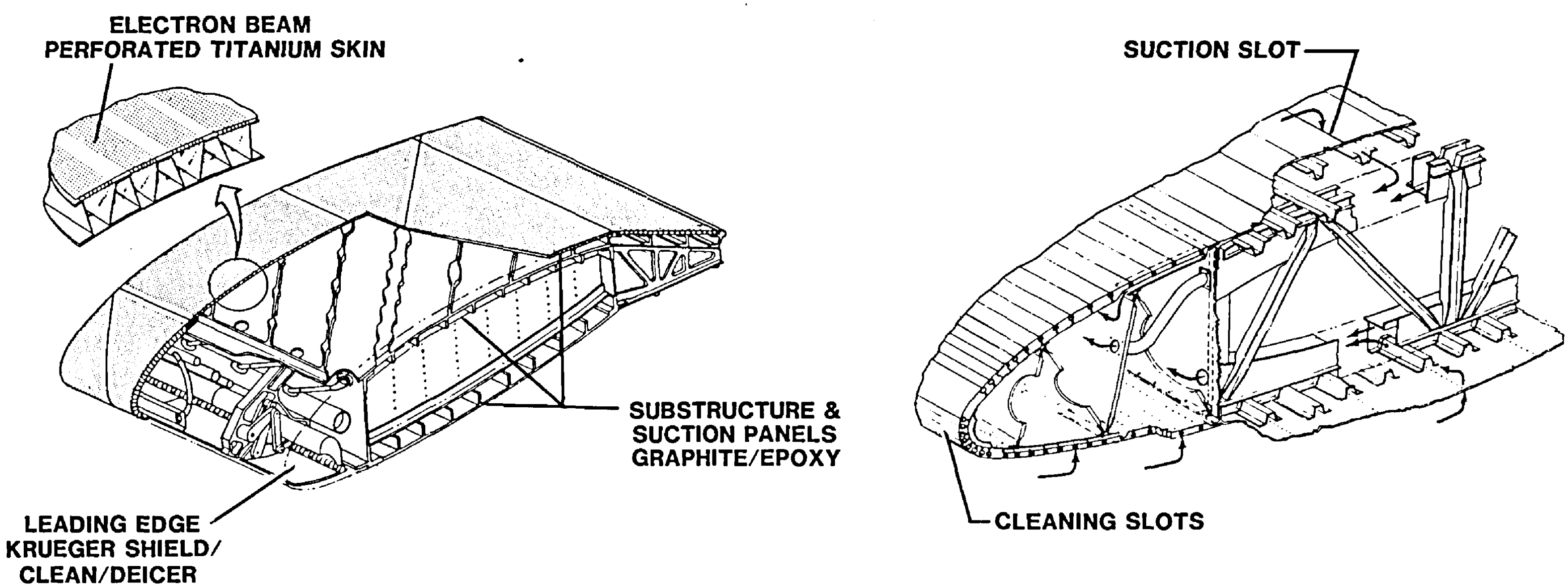
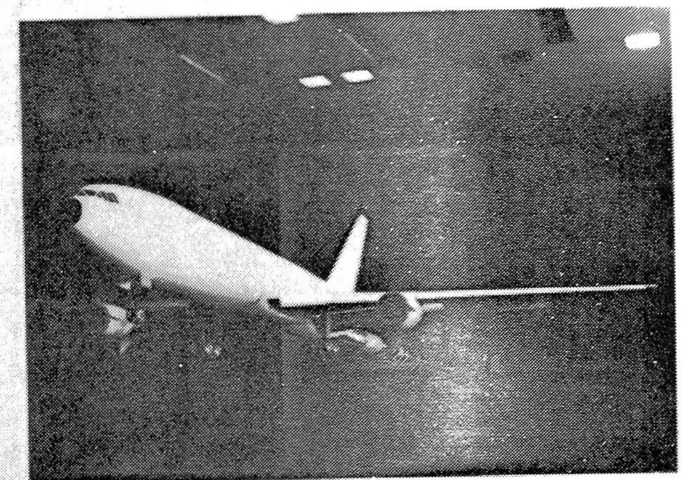


FIGURE 6 – LFC STRUCTURAL DEVELOPMENT

AERODYNAMIC DATA BASE



DC-10 WINGLET

NACELLE AERODYNAMICS AND INERTIAL LOADS

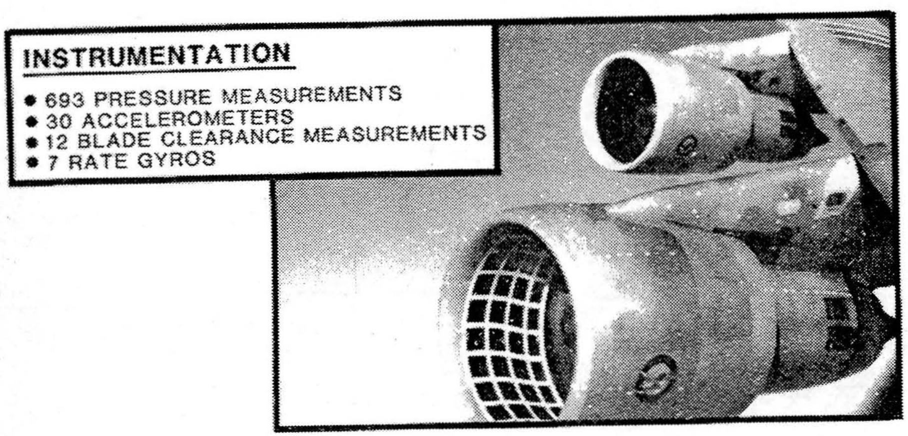
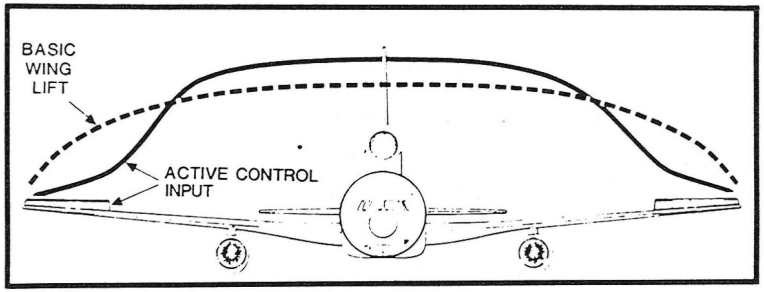
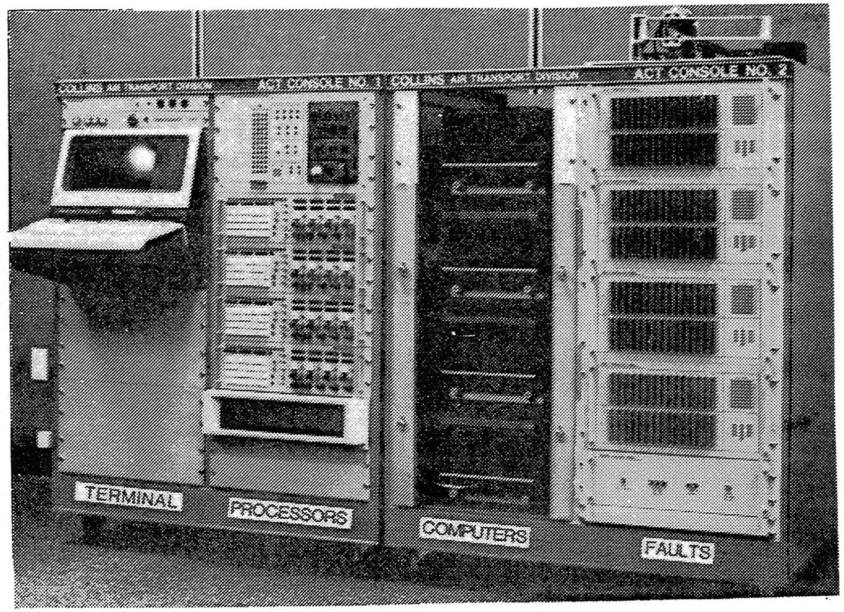


FIGURE 7 - EET AERODYNAMICS

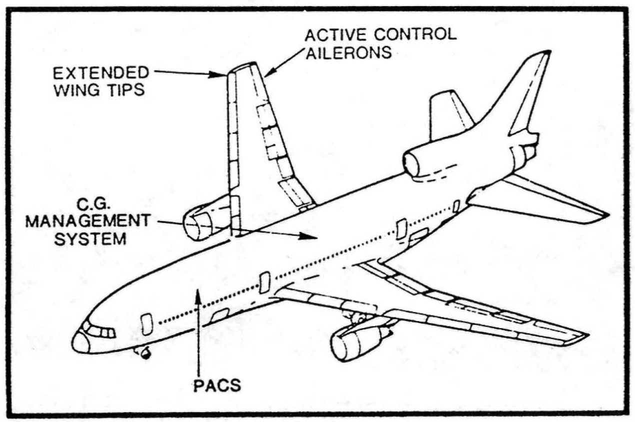
L-1011 MANEUVER LOAD CONTROL



BOEING
INTEGRATED APPLICATION OF ACTIVE CONTROLS



L-1011 PITCH ACTIVE CONTROL FOR RELAXED STATIC STABILITY



L-1011 RELAXED STATIC STABILITY

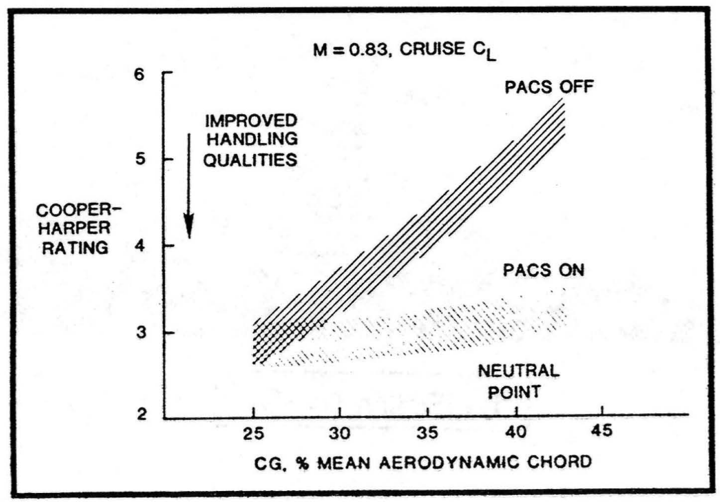
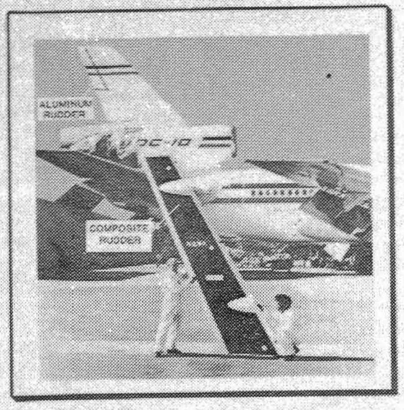


FIGURE 8 - EET ACTIVE CONTROL SYSTEMS

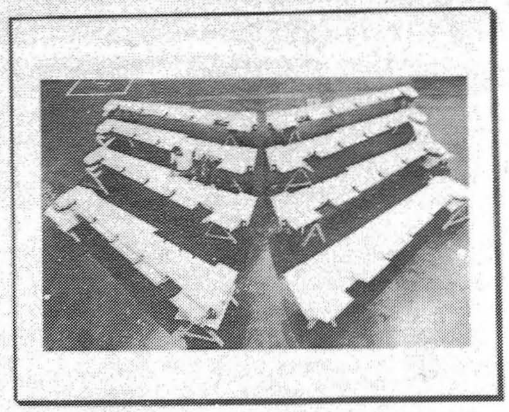
SECONDARY

DC-10 RUDDERS
12 FLIGHT UNITS



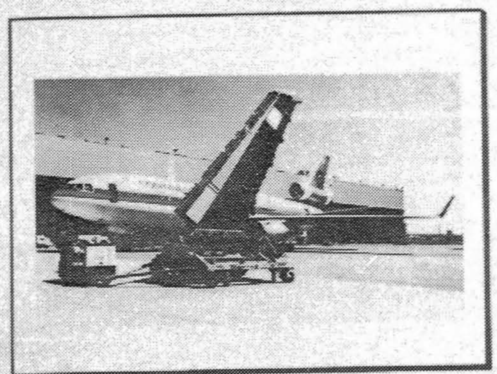
L-1011 AILERON
8 FLIGHT UNITS

727 ELEVATORS
10 FLIGHT UNITS

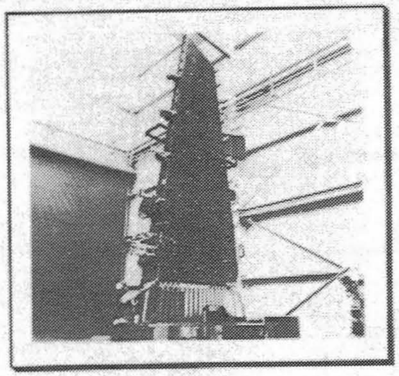


MEDIUM PRIMARY

DC-10 VERTICAL STABILIZER



L-1011 VERTICAL FIN



737 HORIZONTAL STABILIZER

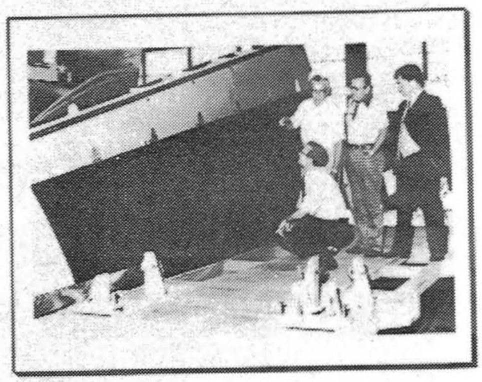
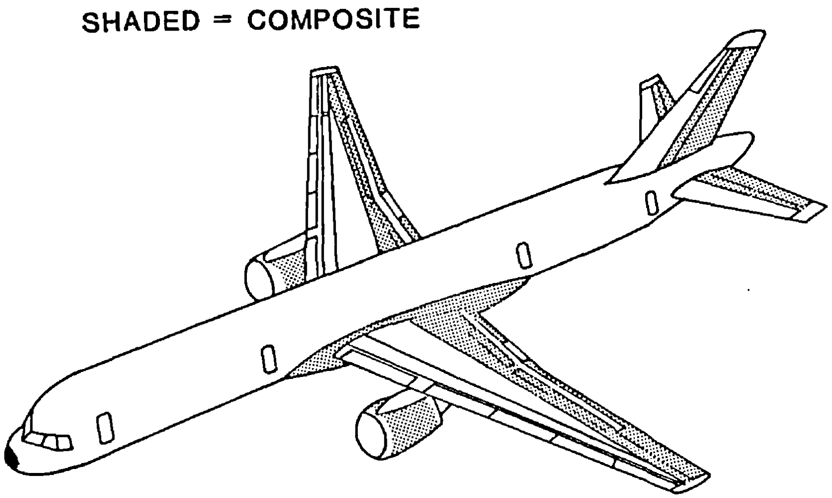
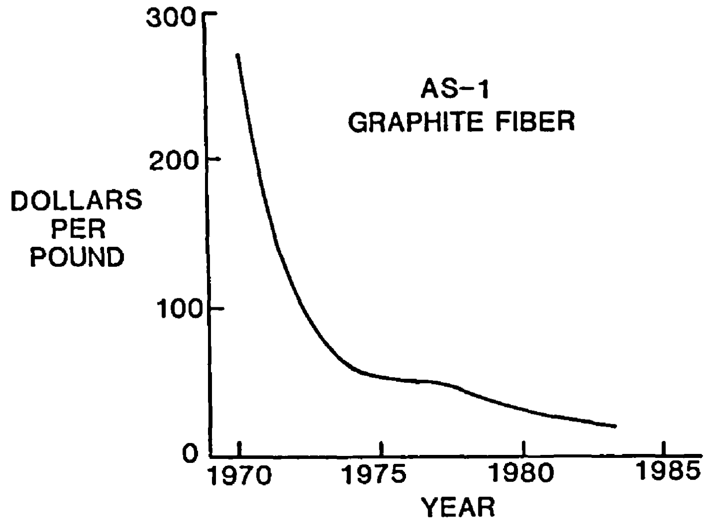


FIGURE 9 - SECONDARY AND MEDIUM PRIMARY COMPOSITE STRUCTURES PROGRAM

767/757 COMPOSITE APPLICATIONS



COMPOSITE MATERIAL COST



U.S. AEROSPACE INDUSTRY GRAPHITE FIBER USE

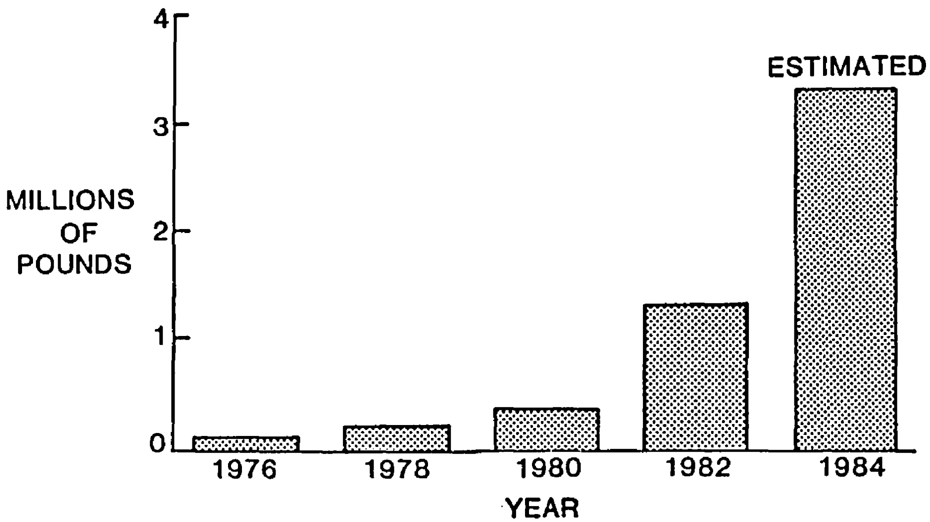


FIGURE 10 - USE OF COMPOSITES IN AEROSPACE

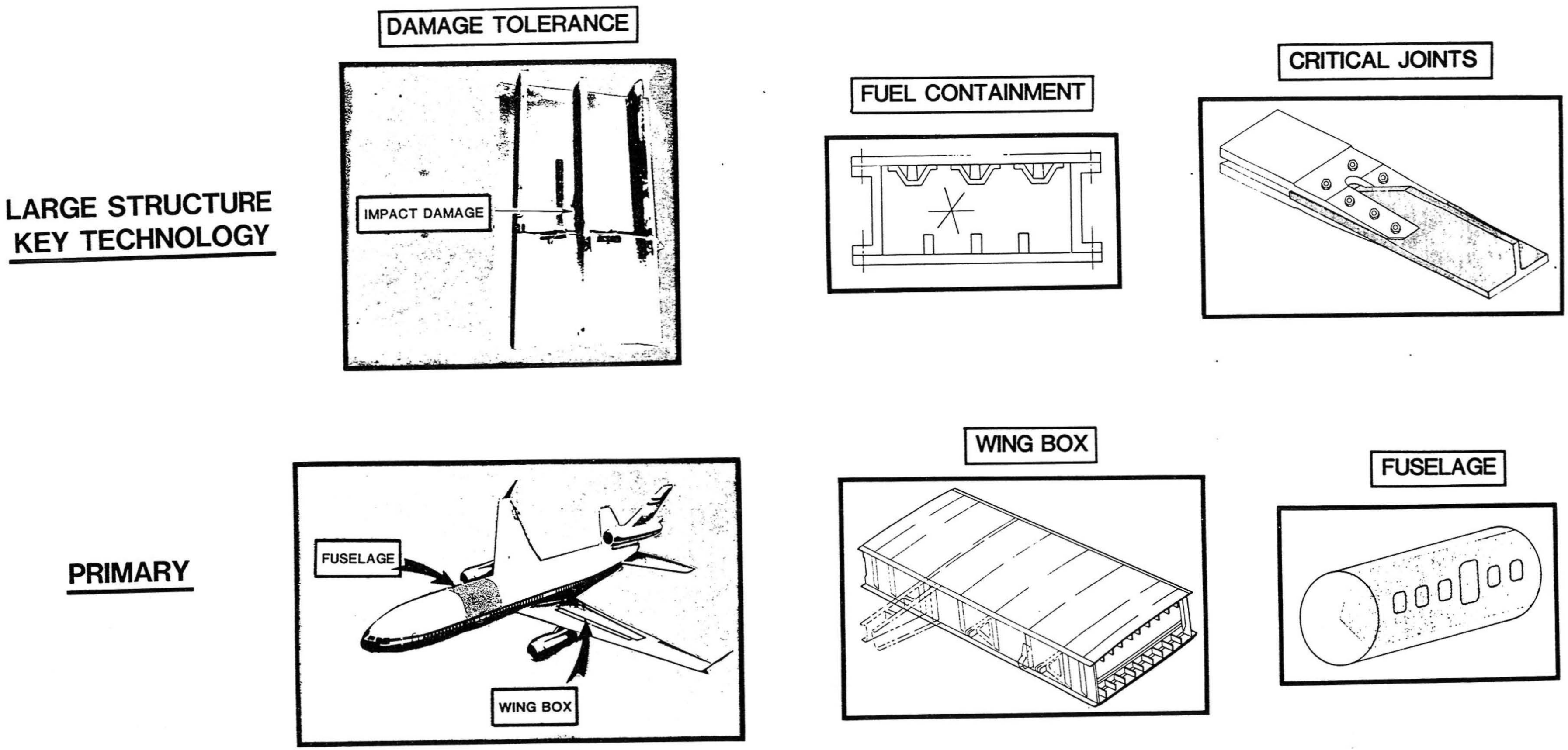


FIGURE 11 - LARGE PRIMARY COMPOSITE STRUCTURES PROGRAM

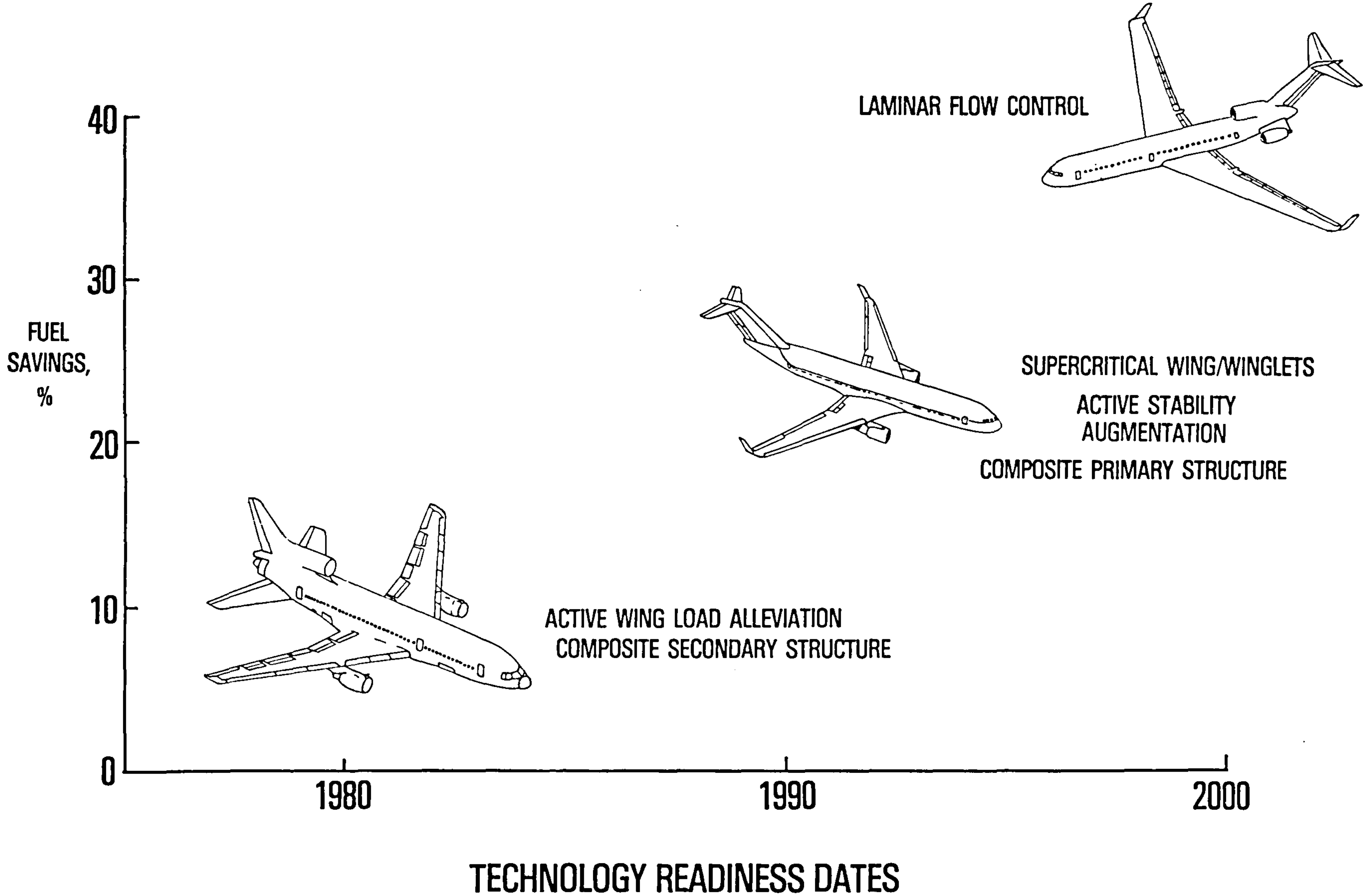


FIGURE 12 - ACEE AIRFRAME TECHNOLOGY BENEFITS

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16. Abstract

NASA's Aircraft Energy Efficiency (ACEE) program began in 1976, following a year of planning. This half-billion dollar program focused on the development and demonstration of advanced technologies applicable primarily to transport aircraft, with about half the effort devoted to engine technology and the other half to the airframe. This paper reviews the economic factors that resulted in the implementation of the ACEE program and discusses airframe technology elements including content, progress, applications, and future direction. The program includes the development of laminar flow systems, advanced aerodynamics, active controls, and composite structures.

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