Aircraft Energy Efficiency Technology

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During 1975 the National Aeronautics and Space Administration worked closely with the major air-frame and engine manufacturers, the airlines, and other government agencies to identify those technology advancements with the greatest potential for saving fuel in future air transportation. The result of that planning activity was the formulation of a 10-year, multiphased plan for the development of technology related to more energy-efficient transport aircraft. This paper reviews the technologies selected for emphasis in the National Aeronautics and Space Administration's Aircraft Energy Efficiency Program, describes some recent accomplishments, and summarizes the activities planned for 1978 and later.

On January 31, 1975, the U.S. Senate Committee on Aeronautical and Space Sciences requested the National Aeronautics and Space Administration (NASA) to establish a special program to develop technology for more energy-efficient transport aircraft. NASA spent the succeeding 7 months working closely with the major engine and air-frame manufacturers, airlines, other government agencies, and universities to develop a comprehensive technical program plan for improved aircraft energy efficiency. This plan, submitted to the U.S. Senate on September 10, 1975, called for the expenditure of additional resources of $670 million over 10 years for the aggressive development of aeronautical technology in the areas of propulsion, aerodynamics, and structures (1, 2). Figure 1 shows the schedule for the six elements of the Aircraft Energy Efficiency Program. This paper reviews recent progress and future plans in each of these areas.

ENGINE COMPONENT IMPROVEMENT

The objectives of the Engine Component Improvement (ECI) program are to develop components to reduce the fuel consumption of current engines and to identify methods to minimize the performance deterioration of current and future turbofan engines. The program consists of performance improvement and engine diagnostics, which are complemented by several smaller supporting technology efforts. The work is being carried out largely under contract with the two major commercial engine manufacturers, Pratt & Whitney (United Technologies) and General Electric Corporation, and is being supported by the transport aircraft manufacturers and the airlines.

The performance improvement work is directed toward improved components for existing and new production JT8D, JT9D, and CF6 engines. A number of candidate component improvements are being analyzed to select the most promising concepts on the basis of fuel savings potential, retention characteristics, and economic considerations. Among the performance improvement candidates that are undergoing the final stages of the screening process are new lower aspect ratio fan blades; redesigned front-mount and fan-exit guide vanes; improved aerodynamics in the high-pressure compressor and high-pressure turbine; improved turbine thermal barrier coatings, ceramic air seals, and active clearance control; supervisory or full-authority digital controls; and improved nacelle design.

The first two components selected for further development, a new fan blade and revised high-pressure turbine, are shown in Figure 2. For the General Electric CF6 fan blade, the benefit results from improved aerodynamics, optimization of the fan operating line, and a fan-case stiffener ring for reduced clearances. The Pratt & Whitney JT8D improvement includes revised turbine blade cooling and an added knife edge and honeycomb material for reduced leakage. Additional concepts to be investigated include a new front mount, improved turbine aerodynamics, and a shortened core nozzle for the CF6 engine, and a new fan and improved turbine clearance control for the JT9D engine.

The supporting technology work in seal flow effectiveness has recently been completed and has provided an improved understanding of advanced seal configurations.

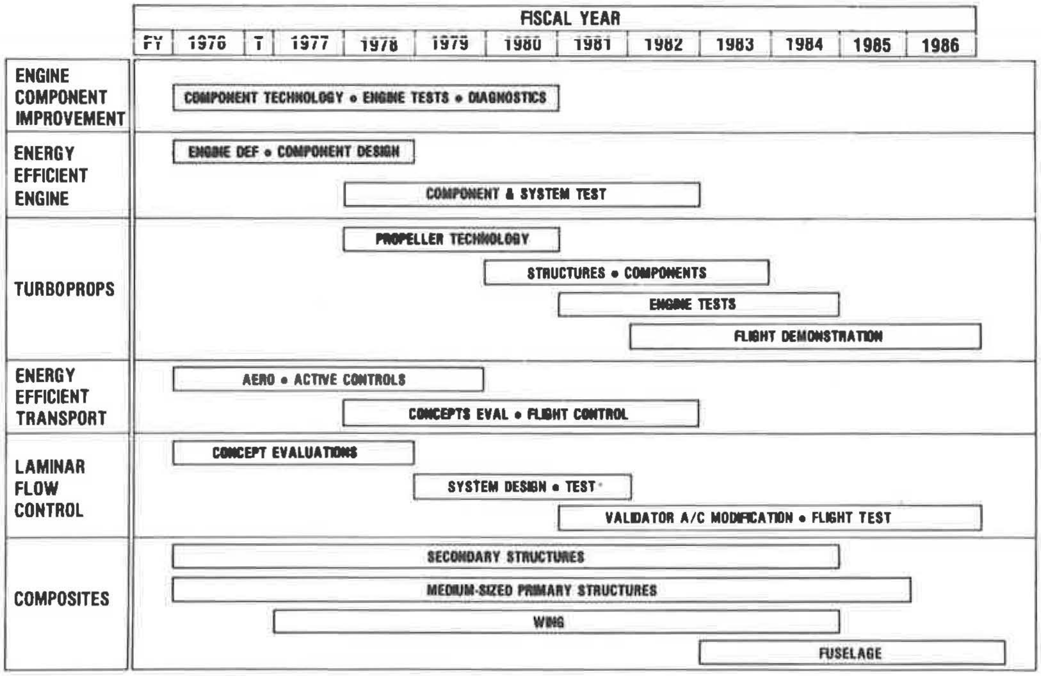
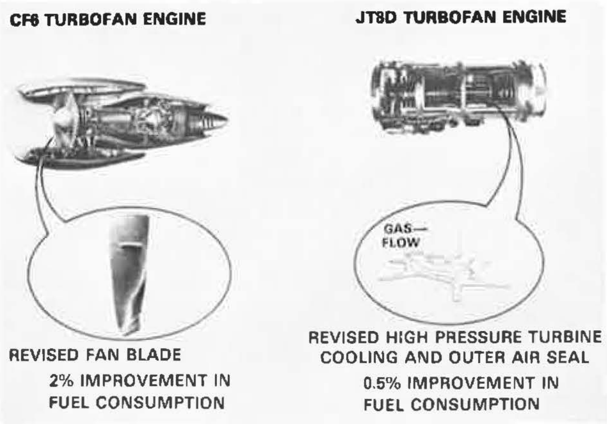


Figure 1. Aircraft energy efficiency program.

The goal of this effort is to reduce leakage by 25 percent, thereby providing up to 2.5 percent reduced engine fuel consumption. Figure 3 shows a typical improved seal configuration contrasted with a current design. The slant of the knife-edge seals and the lip on the flow passage create additional internal flow turbulence that reduces leakage. These types of seals could be incorporated in new production of current engines to provide significant performance improvements.

Figure 2. Initial concepts selected for performance improvement.



The engine diagnostics portion of the ECI program consists of the analysis and testing of JT9D and CF6 engines to quantify the sources of engine performance deterioration with time. Some of the more common contributors to performance degradation are fan nicks, duct leaks, warped combustors, eroded turbine blades, and wear in the turbine, seals, and compressor.

Existing data related to engine performance deterioration have been obtained with the cooperation of engine and aircraft manufacturers and airlines from in-flight measurements, ground tests, used parts condition reports, and parts replacement and repair records. The data represent over 1300 major parts records from approximately 300 engines and are currently being evaluated to establish deterioration trends. Several planned performance ground tests have been conducted on engines with accumulated service from approximately 1000 to 8000 hours. Preliminary results indicate that a significant portion of the increase in specific fuel consumption can be attributed to field checkout and early fleet operation, and that a part of the long-term engine deterioration associated with the low-pressure system can be recovered through minor refurbishment. Additional performance tests will be conducted during the next sev-

Figure 3. Improved seal effectiveness, engine component improvement program.

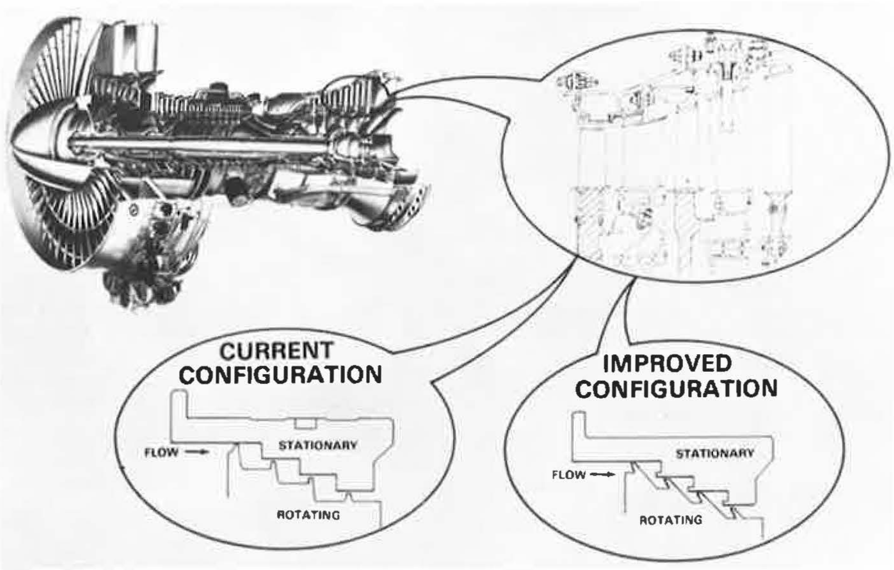
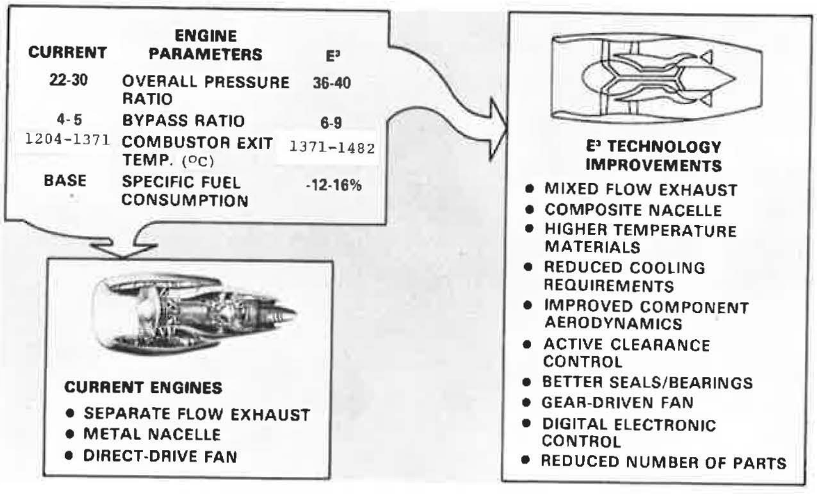


Figure 4. Energy-efficient engine definition studies.



CURRENT	ENGINE PARAMETERS	E^3
22-30	OVERALL PRESSURE RATIO	36-40
4-5	BYPASS RATIO	6-9
1204-1371	COMBUSTOR EXIT TEMP. (°C)	1371-1482
BASE	SPECIFIC FUEL CONSUMPTION	-12-16%

CURRENT ENGINES
- SEPARATE FLOW EXHAUST
- METAL NACELLE
- DIRECT-DRIVE FAN

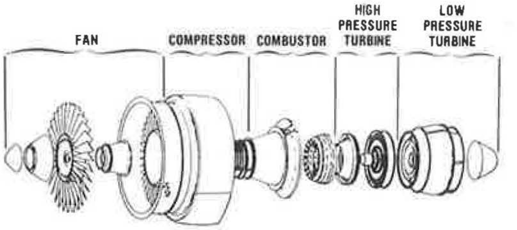
E^3 TECHNOLOGY IMPROVEMENTS
- MIXED FLOW EXHAUST
- COMPOSITE NACELLE
- HIGHER TEMPERATURE MATERIALS
- REDUCED COOLING REQUIREMENTS
- IMPROVED COMPONENT AERODYNAMICS
- ACTIVE CLEARANCE CONTROL
- BETTER SEALS/BEARINGS
- GEAR-DRIVEN FAN
- DIGITAL ELECTRONIC CONTROL
- REDUCED NUMBER OF PARTS

eral years to identify the specific sources of performance deterioration throughout the life of an engine.

ENERGY-EFFICIENT ENGINE

The objective of the Energy-Efficient Engine (E^3) program is to develop and demonstrate the technology base for achieving higher thermodynamic and propulsive efficiencies in future turbofan engines. The goal is to reduce specific fuel consumption by 10 to 15 percent over current high-bypass engines, while simultaneously improving direct operating costs, emissions, and noise levels.

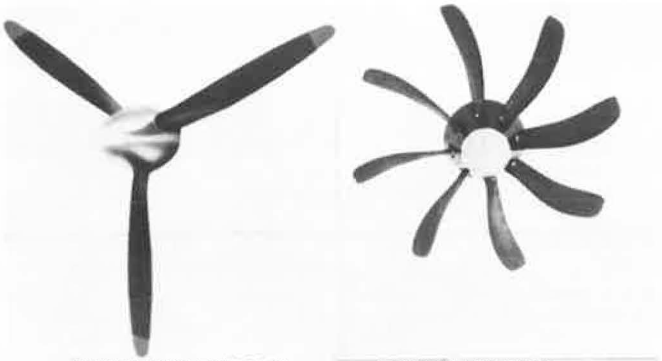
Figure 5. Energy efficient engine program, full-scale component test.



CORE AND LOW SPOOL COMPONENT PERFORMANCE EVALUATION

- AERODYNAMICS
- HEAT TRANSFER
- NOISE/EMISSIONS
- MECHANICAL INTEGRITY
- DURABILITY
- SEALS/CLEARANCE CONTROL

Figure 6. Advanced turboprop program.



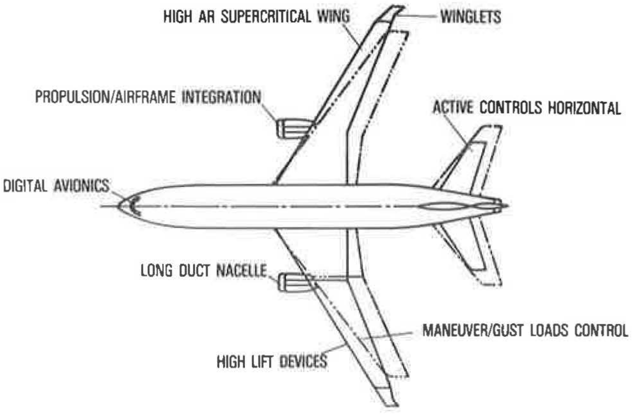
CONVENTIONAL TURBOPROP

- APPROXIMATELY 6.71 m DIA.
- EFFICIENCY : 80% AT 0.65M
- LOW LOADING
- CONVENTIONAL AIRFOILS

ADVANCED TURBOPROP

- APPROXIMATELY 3.96 m DIA
- EFFICIENCY : 80% AT 0.80M
- HIGH LOADING (3X CONVENTIONAL)
- SUPERCRITICAL AIRFOILS, SWEPT TIPS

Figure 7. Energy-efficient transport—near-term applications.



Design definition studies based on earlier NASA-supported efforts (3,4) are now being completed by the manufacturers of large commercial engines with the support of the transport manufacturers and airlines. The current study phase includes engine cycle selection, air-frame integration analysis, preliminary engine design, and the evaluation of risks and technology trade-offs required to meet program goals.

Progress to date has resulted in the selection of the thermodynamic cycle, basic configuration, and reference thrust size of an advanced fuel-conservative engine. Numerous technology advances that contribute to improved fuel efficiency were examined, as indicated in Figure 4. Among the general features of the new-generation engine is a substantial increase in the overall pressure ratio from the 22-30 range to 36-40. The increased compression ratio requires a substantial increase in work output but is accomplished with fewer compressor stages, providing an engine with improved efficiency, fewer parts, and lower maintenance costs.

Another feature contributing to the improved efficiency is an increase in turbine inlet temperature to approximately 1370°C (2500°F). The increased gas temperature creates a more severe environment for turbine operation, but the use of advanced materials, cooling techniques, and manufacturing processes allows operation of the hot section with even less cooling than current engines, resulting in a further improvement in efficiency. The engine designs will be modified periodically as the program proceeds and experimental results are obtained for the advanced engine components.

The major phase of the E^3 program, full-scale component development and tests, began in 1978. As illustrated in Figure 5, during 1978 the design of each engine component will be initiated, followed by fabrication, assembly and rig tests. The components will then be refined and integrated into an engine system for ground test and evaluation in later years of the program. The current E^3 schedule calls for initiation of the first core test by mid-1982, with tests of the integration core and low spool system by the first quarter of 1983. These tests are not intended to achieve the level of performance expected in a fully developed engine system but will demonstrate the integration of advanced-technology engine components and will provide a firm base for subsequent developments by the aircraft engine manufacturers.

ADVANCED TURBOPROP

The remaining propulsion element of the Aircraft Energy Efficiency Program is the Advanced Turboprop program. The objective of this program is to develop the technology to demonstrate that future aircraft powered by advanced turboprops will be efficient, reliable, and economical to operate at speeds and altitudes comparable to today's turbofan aircraft. The goal is a minimum of 15 percent fuel savings compared to turbofan engines with an equivalent level of core technology.

Figure 6 illustrates the type of advanced propeller, or prop-fan, that is being investigated. The desire for high Mach number and cruise altitude capability requires propellers with low compressibility losses (e.g., supercritical airfoils and swept tips) and a propeller power loading several times higher than usual to keep the overall diameter at a reasonable value. This can best be achieved by increasing the number of blades from three or four to eight or ten, as shown in Figure 6.

Recent wind-tunnel tests of a highly loaded, eight-bladed advanced propeller model indicate that the goal of 80 percent efficiency at Mach 0.8 can be attained (5). Continued tests are planned during the next several years to establish propeller efficiency and noise levels, determine blade structural feasibility, and evaluate the aerodynamic, acoustic, and structural trades required for optimized propeller design. Successful technology development will form the basis for subsequent work on full-scale propellers, advanced engine components, and special aircraft systems in a later phase of the program (6).

ENERGY-EFFICIENT TRANSPORT

In addition to the three propulsion programs described above, the Aircraft Energy Efficiency Program includes three programs aimed at improved aircraft configurations (7). The first, the Energy-Efficient Transport (EET) program, is directed at the development and evaluation of advanced aerodynamic and active controls technology for application to both derivative and new aircraft. The goal is the achievement of up to 20 percent improvement in aerodynamic efficiency for new transport designs.

The near-term application of these technologies is illustrated in Figure 7: higher aspect ratio supercritical wings with and without winglets; improved propulsion system integration, including the possibility of long-duct nacelles and forced mixers; optimized high-lift devices; digital cockpit avionics; and active controls for maneuver and gust load alleviation and for stability augmentation with a smaller horizontal tail.

Work is proceeding in all these areas. For example, a comprehensive series of wind-tunnel tests has recently been completed on advanced supercritical wings. Variations in aspect ratio, thickness, sweep, camber, and twist were investigated to establish a firm aerodynamic data base for design and off-design conditions. Results to date have been promising. Compared to an existing aspect ratio 7, 35-deg swept wing, an advanced supercritical wing with aspect ratio 12 and 27-deg sweep provides more than a 25 percent improvement in cruise lift-to-drag ratio.

In the area of active controls technology (8), the main efforts are directed toward integrated analysis and design techniques and reliable, maintainable flight controls. As indicated in Figure 8, a high-aspect ratio wing for advanced transport application has recently been tested on a BQM-34E/F (Firebee 2) wind-tunnel model. Subsequent flight tests of the drone aircraft will include evaluation of an active control system for gust load alleviation, maneuver load control, and active flutter suppression. The wing has been fabricated so that the structure directly reflects the advantages of incorporating active controls in the early design phase. The wind-tunnel and flight tests will provide an early but realistic assessment of integrated design procedures resulting in flight hardware. Other efforts in the area of active controls include work on advanced fault-tolerant computer systems, assessment of sensor and actuator technology requirements, and development of trade-off models for optimizing flight control system designs.

These activities are coordinated with several efforts selected jointly by NASA and the commercial air transport manufacturers with specific application to derivative and next-generation transport aircraft. Some of the concepts being investigated are shown in Figure 9. Boeing is currently evaluating the performance benefits of adding wing-tip extensions or winglets to the 747, using the 747-200 as a baseline, and is working on a program aimed at the maximum-benefit application of active controls technology for a new-generation commercial transport aircraft. The goal is to reduce the technical risk and provide an in-depth assessment of the performance benefits of active controls technology for commercial application.

Douglas has recently completed flow-field analyses and model design and fabrication of mixed flow, long-duct nacelles for application to DC-10 derivative aircraft. A new high-aspect ratio supercritical wing for advanced transport aircraft, such as the DCX-200, has also been designed. Wind-tunnel tests of this supercritical wing will include the investigation of new leading-edge devices and large extension trailing-edge flaps as part of an improved high-lift system.

The main emphasis of the Lockheed program (9) is on the investigation of active controls for application to an extended-wing version of their new long-range aircraft,

Figure 8. Active controls technology.

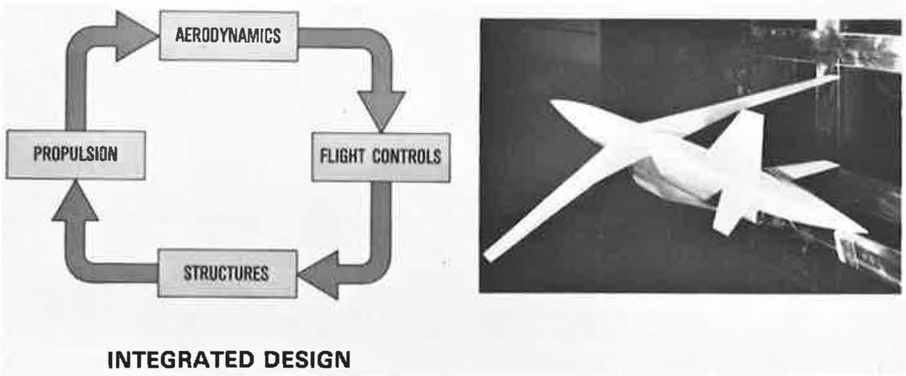
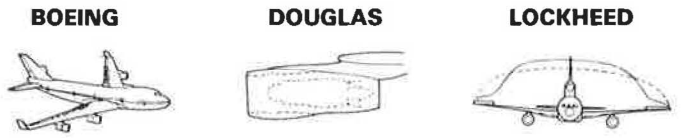


Figure 9. Energy-efficient transport, selected concepts.



- 747 WINGLETS/WING TIP EXTENSIONS WITH WING LOAD ALLEVIATION
- MAXIMUM BENEFIT OF ACTIVE CONTROLS

- ADVANCED INTEGRATED LONG-DUCT NACELLE
- HIGH ASPECT RATIO SUPERCRITICAL WING
- DC-10 WINGLET

- L-1011 WITH WING-TIP EXTENSION AND ACTIVE CONTROLS
- REDUCED HORIZONTAL TAIL SIZE AND STABILITY AUGMENTATION

Figure 10. Laminar flow control–surface contamination.

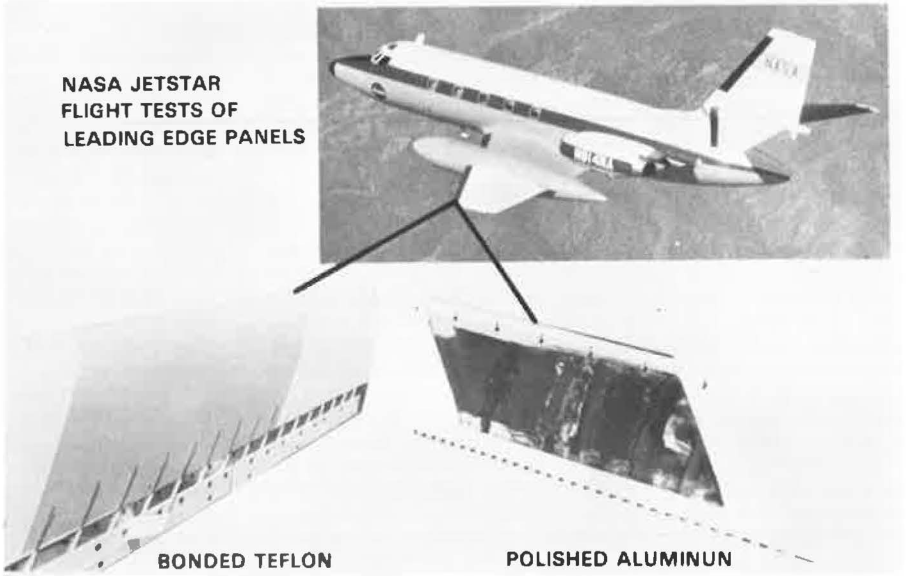
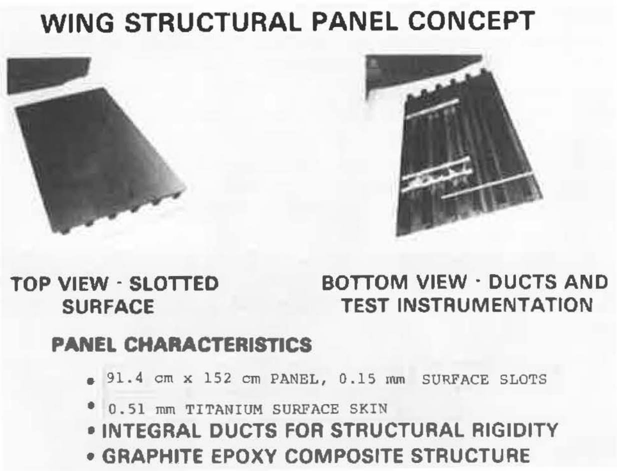


Figure 11. Laminar flow control–wing structural panel concept.



the L1011-500. Flight test hardware required for horizontal tail and outboard aileron control is currently being evaluated, and approximately 20 flight test hours have recently been completed for functional tests, flutter checks, and maneuver loads. The L1011 aircraft will next be modified with 1.3-m ($4\frac{1}{2}$-ft) wing-tip extensions; the flight tests will be repeated to evaluate the performance improvements that can be achieved with an active control system for maneuver load control, elastic mode suppression, and gust load alleviation.

Lockheed is also investigating another active control concept, longitudinal stability augmentation with application to derivative aircraft. Significant fuel savings are possible with smaller horizontal tail size, and early incorporation of augmented-stability systems for this non-flight-critical application is expected. This work and the efforts described above will contribute to the evolutionary development and integration of advanced aerodynamics and active controls into the design of a new generation of energy-efficient transport aircraft.

LAMINAR FLOW CONTROL

Laminar flow control (LFC) promises to significantly reduce the drag of aircraft by using a suction system to maintain smooth, or laminar, flow over the wings and empennage. Fuel savings of from 20 to 40 percent appear possible, depending on the extent of application and the aircraft design range. NASA's LFC program builds on experiments performed in the mid-1960s with the U.S. Air Force-Northrop X-21A airplane and is aimed at the development of a practical, reliable, and maintainable system for boundary-layer control. This requires attention to all of the factors that affect laminar flow such as surface contamination, suction distribution manufacturing tolerances, and configuration variables such as wing sweep, airfoil section, and location of the propulsion system. The major emphasis of the ongoing program is on the engineering investigations and component tests necessary to evaluate alternative LFC system concepts.

One of the difficulties in maintaining smooth flow over the surface is caused by the adhesion of dirt or insects to the leading edge of the wing. NASA recently concluded a series of flight tests using a Lockheed JetStar (Figure 10) to investigate various leading-edge materials that show promise of alleviating this problem. Tests were made of nonstick and hydrophobic materials at high Mach number and high altitudes and included investigation of a water-spray system with nozzles located beneath the wing leading edge. The flight program demonstrated that a combination of Teflon tape and the washer system was effective in reducing excrescence size below the critical values for laminar flow.

One of the accomplishments of the early phase of the LFC program was the completion of studies by Boeing, Douglas, and Lockheed to select a design mission and define a baseline LFC transport aircraft configuration for operation in the early 1990s. These baseline transport configurations and missions are being used to better define requirements in aerodynamics, structures and materials, suction pumps and propulsive systems, leading-edge cleaning and protection, and auxiliary systems.

In other related work, recently developed analytical techniques have been used to design a series of supercritical shockless airfoils for LFC applications. One of the airfoils has been selected for high Mach-number testing in the Ames 3.7-m (12-ft) tunnel in a swept configuration with full-span suction through slots in the upper and lower surfaces. Computer codes have also been developed to calculate the optimum suction rates required to prevent the boundary layer from becoming turbulent. These computational tools are an important

Figure 12. Aircraft energy efficiency program composite components.

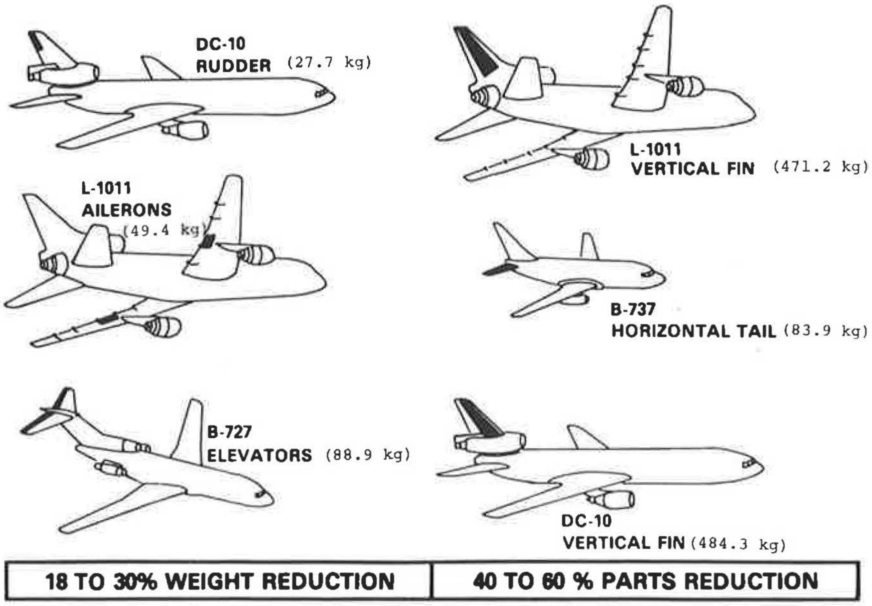


Figure 13. DC-10 composite upper aft rudder segment.

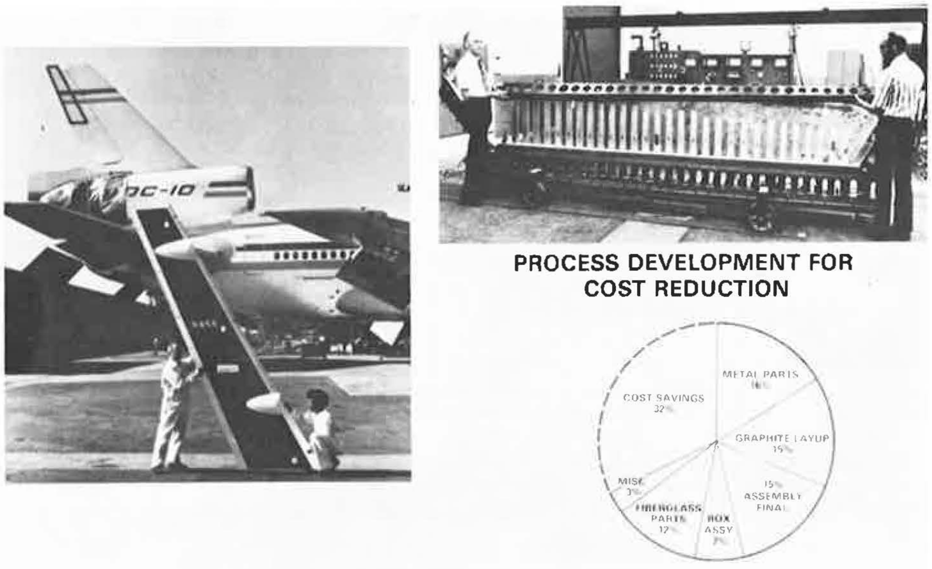
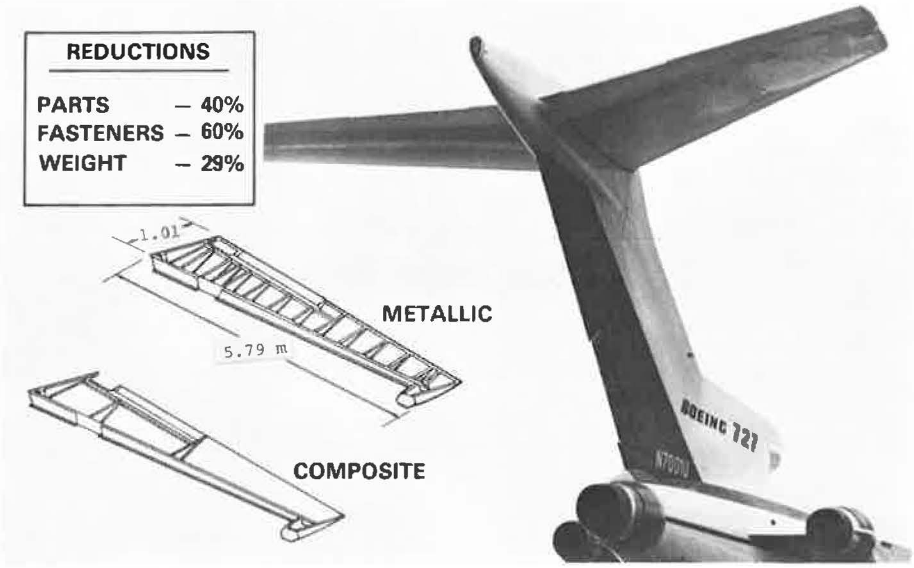


Figure 14. 727 composite elevator.



advance over techniques used during the X-21 program.

One of the major thrusts of the LFC activities has been the definition of suction surfaces and primary structural concepts. Lightweight porous, perforated, and slotted materials have been fabricated and tested to determine static strength, stiffness, fatigue life, flow characteristics, and environmental stability. Structural concepts investigated include skin stringer and sandwich construction of bonded or riveted aluminum, various types of composite materials, and superplastically formed and diffusion-bonded titanium. One of the promising concepts, shown in Figure 11, is a graphite/epoxy composite structure with bonded titanium skin and integral ducts for low weight and structural rigidity. A 0.9 × 1.52-m (3 × 5-ft) section of this structural panel concept is currently being tested to verify requirements for manufacturing tolerances, repair procedures, aerodynamic smoothness, and projected production cost.

Sufficient progress has been made during the first years of the laminar flow control program to increase confidence in the practicality of active boundary-layer control for viscous drag reduction. In the next phase of the LFC program, full-sized and subscale systems and subsystems will be designed and fabricated for extensive tests to provide manufacturing costs derived from representative hardware, maintenance, and repair data, and demonstration of economically viable subsystem concepts. Flight research of a gloved LFC section will also be performed to demonstrate LFC compatibility with supercritical airfoils at cruise Mach numbers, altitudes, and Reynolds numbers representative of commercial transport aircraft.

COMPOSITE PRIMARY AIRCRAFT STRUCTURES

The remaining element of the Aircraft Energy Efficiency Program is the Composite Primary Aircraft Structures (CPAS) program. The objective of this program is to provide the technology required for the use of composite structure in future transport aircraft (10). Potential savings of 25 percent in structural weight are possible, and if composite materials are used throughout an aircraft structure, fuel consumption can be reduced by up to 15 percent.

The principal barrier to the extensive application of composite materials to the next generation of transport aircraft is the lack of confidence displayed in the design and manufacture of composite structures in quantity on a cost-competitive basis. It is also necessary to validate that composite structures will be reliable and economical in commercial airline operations, subject to normal airline maintenance requirements and repair procedures. The required experience can only be obtained through hardware programs conducted in a production environment to demonstrate safety, durability, long-life characteristics, and manufacturing costs.

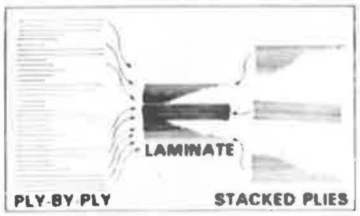
The NASA program, as indicated in Figure 12, includes the design, development, and extensive structural testing of three composite secondary structural components, with a maximum weight of up to 91 kg (200 lb), and three moderately sized primary structures, with a maximum weight over 456 kg (1000 lb). Work to date has indicated that the use of composite materials for these components can provide a weight savings of up to 30 percent as well as significant manufacturing cost savings because of reductions in the number of required parts, attachments, and fasteners (11). Each of the three commercial transport companies is responsible for one of the secondary and one of the moderately sized components to ensure that a wide diversity of structural concepts is investigated.

In general, the early steps for each component involve investigation of various materials, selection of the most promising candidates, and extensive properties characterization tests to establish a firm data base. The most appropriate design for the component is selected, and design and fabrication procedures are validated through development and qualification tests. A flightworthy component will then usually undergo ground vibration, flight flutter, and stability and control flight tests as part of the requirements for Federal Aviation Administration certification. The final step is the production of a sufficient number of components to allow verification of the learning curve for manufacturing costs. In some cases the parts are installed on production aircraft and flown in airline service, subject to periodic inspection and maintenance.

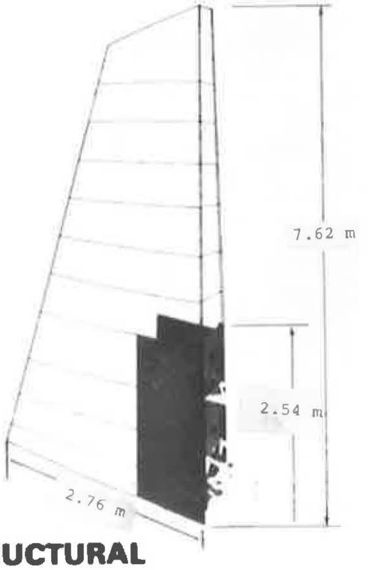
The program on the DC-10 rudder segment, shown in Figure 13, was initiated more than 3 years ago. The components were certificated in May 1976 and ten rudder segments have been produced. Seven of these have been installed on commercial aircraft as replacement parts and one has been installed on the production line. To date, 17 000 total flight hours have been accumulated,

Figure 15. L-1011 composite fin.

COST TREND HISTORY



LOW COST PLY LAYUP



STRUCTURAL VERIFICATION

three rudders have been in service for more than one year, and the high-time rudder has accumulated over 4400 flight hours. No maintenance or repair incidents have been reported. All rudders have been found acceptable for continued service, with inspection visually at 1000 flight-hour intervals and ultrasonically at 3000 flight hours. This program is now in a second preproduction phase to verify reduced-cost fabrication techniques using an expanding rubber tooling process, as shown in Figure 13.

The 727 elevator, shown in Figure 14, is the largest and most heavily loaded of the secondary components. A 29 percent weight reduction is estimated for the structure, with large reductions in the number of parts and fasteners. For this component, the total weight savings come not only from the structure, but also from a reduction in the balance weight of almost 45 percent.

Work on the first of the medium-sized primary components, the L1011 vertical fin, began in June 1975. The vertical fin has progressed through the early portion of detail design and element testing; a large subcomponent, shown in Figure 15, has been assembled to evaluate structural performance. A major effort during the past year has been reevaluation of the design to reduce manufacturing and assembly costs. This effort has resulted in a design with a 39 percent cost savings over the original baseline design and a projected cumulative cost for 100 units that is lower than for the all-metal construction.

Work on the additional medium primary components, the DC-10 vertical fin and the 737 horizontal stabilizer, is under way at the present time. Multiple study contracts for a wing technology program have also been initiated with the three manufacturers. These studies will consider the added requirements for wing structures as compared to the secondary and medium primary components. In addition to higher, repeated loads, consideration will be given to factors such as fuel containment, crash integrity, and lightning effects.

Size, weight, and complexity increase markedly between the secondary and medium primary components, and again between these components and wing. Increasing experience with composite materials is obtained first through structural testing and manufacturing process development for the small components, then through fabrication of the moderately sized components, followed by studies of application to the wing, a large, heavily loaded structure. This step-by-step approach is designed to provide the data required for the application of composite materials to primary structure of future transport aircraft.

SUMMARY

The program elements that form NASA's Aircraft Energy Efficiency Program are described in this paper. Three of the elements—engine component improvement, energy-efficient engine, and energy-efficient transport—are directed toward evolutionary improvements in aircraft propulsion, aerodynamics, and controls. The three remaining elements—advanced turboprop, laminar flow control, and composite primary aircraft structures—involve a substantial departure from current design practices for commercial transport aircraft. Successful technological development of the six elements of the Aircraft Energy Efficiency Program will greatly contribute to fuel-savings improvements for derivative aircraft and engines and to the design of a new generation of aircraft that are significantly more energy efficient than today's transports.

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