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ENERGY EFFICIENT AIRCRAFT ENGINES

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Abstract

The three engine programs that constitute the propulsion portion of NASA's Aircraft Energy Efficiency Program are described, their status indicated, and anticipated improvements in SFC discussed. The three engine programs are (1) Engine Component Improvement--directed at current engines, (2) Energy Efficient Engine--directed at new turbofan engines, and (3) Advanced Turboprops--directed at technology for advanced turboprop--powered aircraft with cruise speeds to Mach 0.8. Unique propulsion system interactive ties to the airframe resulting from engine design features to reduce fuel consumption are discussed. Emphasis is placed on the advanced turboprop since it offers the largest potential fuel savings of the three propulsion programs and also has the strongest interactive ties to the airframe.

Introduction

One of the major reasons the United States was able to develop into a country of world dominance was the possession of unlimited energy producing natural resources and in particular fossil fuels. In the last two decades, our growth and consumer demand have begun to exceed our own supplies. The result has been an increasing dependence on abundant foreign reserves. The effect of this perilous dependency began to be felt in 1973 with the OPEC oil embargo. With supplies suddenly and drastically reduced, the price of fuel took an equally sudden and dramatic increase. The impact was felt by most elements of business including the air transport industry. Fuel suddenly became the major portion of the direct operating cost (D.O.C.) of an aircraft as shown in Fig. 1. Until 1973, the various elements that together make up D.O.C. (fuel, maintenance, crew, and others) were all increasing at only a modest rate. However, between 1973 and 1975 the price of fuel more than doubled. Using a domestically operated Boeing 727 as a representative aircraft (Fig. 2) fuel accounted for 26% of D.O.C. in 1973 and by 1977 had increased to 41% and is probably a higher percentage today. Every indication is that fuel prices well continue to increase rapidly in the near future, as the demand is still continuing to grow even at the higher prices. Some conservative estimates have projected that demand for fuel for air transport use may double by the year 2000. In order for the airlines to remain economically viable, reduced fuel consumption has become a prime objective for the near term and an absolute necessity for the future.

NASA Aircraft Energy Efficiency (ACEE) Program

In response to this need for greater fuel efficiency the National Aeronautics and Space Administration (NASA) in 1976 began the Aircraft Energy Efficiency (ACEE) program. This program is broken into two major areas, propulsion, or engine related efforts, and aerodynamic, or aircraft related programs (Fig. 3). The aircraft related projects - the Energy Efficient Transport, Laminar Flow Control, and Composite Components and Primary Structures - are managed by the Langley Research Center. The three propulsion related areas are managed by the Lewis Research Center. These three programs and how they will impact future aircraft design is the topic of this paper.

The potential fuel savings and technology availability of these programs is shown in Fig. 4. The Engine Component Improvement (ECI) project is directed at improving the fuel efficiency of future production of current engines; the General Electric Company CF6 and the Pratt & Whitney Aircraft Group JT8D and JT9D. These engines power the majority of todays commercial jet aircraft. The E.C.I. project is devoted to both improving the performance of engine components as well as devising means to retain high engine performance as engine flight hours accumulate. This program offers the promise of near-term fuel savings of about 5%. These are improvements to current engines powering today's aircraft and those of the near future. The impact of these improvements on future new aircraft designs will be small and therefore the E.C.I. effort will not be discussed further.

The second ACEE propulsion effort is the Energy Efficient Engine (E^3) project which involves developing and demonstrating the technology base for achieving a potential fuel savings of 15-20% over current engines. Derivative engines incorporating elements of this program could appear on the market in the mid 1980's, depending on the evolving market needs. This program, because it is aimed at new engine designs of the future, will have an impact on and provide new challanges to engine/aircraft integration.

The third ACEE propulsion effort is the Advanced Turboprop (ATP) project. This effort is directed at establishing the feasibility of radically improving propeller driven propulsion systems to the point where they can be effectively applied to future commercial air transports. Such propulsion systems, when developed, are expected to provide at least a 15% fuel savings over a new turbofan powered aircraft, where the turboshaft engine driving the propeller has the same level of technology as the new E^3 turbofans. Thus an advanced turboprop system could offer about 30-35% fuel savings over current engines. Based on an agressive technology development program, the advanced turboprop technologies could be available by the late 1980's, thus starting to appear in commercial air transports in the mid 1990's. The challenge of a $M_o = 0.8$, 30,000 ft turboprop opens a whole new area in engine/aircraft integration and aircraft design.

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Energy Efficient Engine (E^3)

Figures 5 and 6 show schematics of the General Electric and Pratt & Whitney energy efficient engine baseline designs respectively, using components to be investigated in the E^3 program. Both engines are high bypass ratio turbofans (G.E.: $\beta = 6.9$; P & W: $\beta = 6.6$). Aggressive technology advancements are incorporated in most of the components in both engines.

General Electric Configuration

The General Electric design utilizes a low tip-speed fan with a low placement of the mid-span damper to achieve over 88% efficiency. The novel quarter stage booster design serves a dual function. It aids matching of the fan and core streams, and additionally centrifuges any foreign objects away from the core stream thus reducing F.O.D. erosion in the core. The compressor produces a 23:1 compression ratio in only 10 stages with a polytropic efficiency of over 90%. The combustor is a two-zone, double annular design. This rather complex configuration is required to meet the stringent emission goals. The two stage high pressure turbine is designed to achieve an efficiency of 92% and incorporates active clearance control and advanced materials. The low pressure turbine has five stages and was designed to be a low noise configuration.

Pratt & Whitney Configuration

The Pratt & Whitney engine design has a very aggressive fan design which incorporates unshrouded hollow blades. This will require advanced design and manufacturing techniques to keep the blades of a nominal size while still being strong and light weight. The Pratt & Whitney design has low and high pressure compressors. The high pressure compressor has 10-stages and a 14:1 compression ratio. It incorporates supercritical airfoils, trenched cases, and active clearance control to help achieve a polytropic efficiency of over 90%. The P & W combustor is also a two zone design for low emissions, but the two burning zones are arranged axially in series. The high pressure turbine is a single stage design to gain the cost and maintenance benefits associated with fewer hot section parts. To achieve the required high efficiency of 88% will require advances in several areas including advanced airfoils improved cooling schemes, and advanced materials. The 4-stage low pressure turbine is counter-rotating and incorporates low leakages and active clearance controls.

Long Duct-Mixed Flow

As can be seen, both engines are long duct mixed flow designs. Both engine manufacturers independently selected mixed flow designs as a means of both improving performance and reducing noise. Figure 7 shows the potential performance improvement due to mixing. The gains in SFC are shown as a function of mixer pressure drop for constant values of mixing effectiveness. The objective is to achieve a high mixing effectiveness with a low pressure loss in a short mixing length and without any large weight penalties. Large SFC benefits (3-4%) are potentially realized with a mixed flow system. Improvements as high as 2.5% have been demonstrated on an engine in a test cell at NASA Lewis with a moderate tailpipe length $L/D_{eff} = 1.2$.[1] The two E^3 goals of 75% and 85% mixing effectiveness with a very low (0.2%) pressure loss would yield 3.1% and 3.5% SFC improvements and are to be achieved with very short mixing chamber lengths, $L/D_{eff} = 0.5$ and 0.6, respectively.

In addition to improving performance, it is anticipated that the mixed flow engine with its reduced jet velocity will also provide a 2-5 dB noise reduction. Model parametric test programs are currently underway investigating both the performance and the acoustics of a matrix of mixer designs.

The mixed flow does require a long duct nacelle which will require new ideas for wing/pylon/nacelle design. In order to address this area, a cooperative test program will be run envolving NASA Lewis, NASA Langley, and the General Electric Company. A model of the E^3 nacelle, housing a turbofan simulator, will be tested at Langley under a supercritical wing as shown in Fig. 8. Also shown is a photograph of the model E^3 nacelle. To establish interference drag, the half span model will be tested without the nacelle and the nacelle will be tested isolated mounted on a strut. The nacelle will then be mounted under the wing and the combined installed performance determined. This will be done for five different nacelle locations relative to the wing as shown in Fig. 9. The reference point is the center of the nozzle exit and the nacelle is shown in position No. 1. The other four positions are denoted by their respective reference points with variations being in both the vertical distance below the wing and the horizontal distance relative the wing leading edge. This will help determine how the interference drag varies with various positions of the wing/nacelle combination. Each of the three major airframe companies (Boeing, Douglas, Lockheed) were asked where the best location for an E^3 type nacelle would be. The five test locations provide a perturbation around the resulting position selections. All the test data will be made available to the airframe companies for their independent analysis. Figure 10 shows a drawing and crossection of the Langley designed pylon for these tests.

Advanced Turboprop

The Advanced Turboprop project is the most challenging of the three A.C.E.E. propulsion efforts, but also has the largest potential fuel savings. It must, of course, compete with current and new turbofan engines and so must be able to fly at high speed (Mo = 0.7-0.8) and at high altitudes 30,000 ft and above). The objective, therefore, is to develop enabling technology to permit efficient, reliable acceptably operational turboprop aircraft that can fly at these conditions.

The ATP effort is broken down into phases, as shown in Fig. 11. The first phase involves subscale model testing in several different areas including propeller performance, propeller acoustics and propeller/nacelle/aircraft interaction effects. Propeller efficiencies above 80% have been demonstrated to date at high Mach numbers in model tests. The next logical step beyond phase I is large scale component verification leading to flight tests.

The four major elements of phase 1 are shown in Fig. 12. The various elements are not always in harmony with each other. For example, a propeller with high propulsive efficiency may have acoustic properties that are close to the natural frequency of most aircraft structures thus creating a natural resonance; or the engine or gearbox may be too large in some local areas, thus requiring undesirable contour changes in an otherwise promising nacelle/wing design. The various elements must be drawn together and tradeoffs made to achieve the optimum system design.

Propeller/Nacelle

The first element, propeller/nacelle, involves the aerodynamic and acoustic performance of the new designs. The advanced propeller/nacelle designs are considerably different from past turboprop configurations. Figure 13 shows a comparison of an advanced propeller with the four bladed propeller used on the Electra. The scale is the same, emphasizing the smaller size propeller and radically different blade shape of the new design. The advanced configuration has 8 or 10 highly loaded blades to keep propeller diameter relatively small. The blades are very thin and highly swept (possibly as high as 60°) and twisted to minimize compressibility losses and propeller noise during high speed cruise. An area-ruled spinner and an integrated nacelle shape would also be used to minimize compressibility losses in the propeller hub region.

The measured performance of three new propeller designs is shown in Fig. 14 for a power loading of 37.5 horsepower per square foot of disc area. All three were tested as 2-ft diameter models in the NASA-Lewis 8×6 Foot Wind Tunnel. As can be seen, high levels of efficiency were measured at Mach numbers up to 0.85. The new long chord highly swept (45°) blades yielded the higher performance. The highly swept blades also resulted in lower noise as shown in Fig. 15. The configuration with 45° of sweep was 6 dB quieter than the straight blade configuration.

The experimental propeller noise levels measured to date involve some degree of uncertainty because of the limitations of measuring noise in a wind tunnel. Two tests have been run. The first was run at Mach 0.8, but had possible wall reflection interferences. The second was in an acoustic tunnel but was limited to a Mach number of 0.3. As a result, NASA is proceeding with a program to record propeller noise in flight. The test vehicle will be a NASA owned Jet Star, shown in Fig. 16, modified to carry a small (2-ft diam) propeller and its air-turbine drive on the top of the fuselage. The turbine will be powered with main engine bleed air. The near field noise will be measured by microphones mounted on the fuselage and data recorded at conditions from takeoff to Mach 0.8 cruise. Testing will begin next year. The results from these tests will be used to upgrade the noise prediction programs and to provide input for the fuselage attenuation studies.

Cabin Environment

The second element on Fig. 12 is cabin environment. In order for an advanced turboprop powered aircraft to be viable, it must provide equal cabin comfort with that of current turbofan powered transports. In order for the advanced turboprop to do this, it must overcome the problem of its high near field noise. This may be the most challenging part of the program and could have a big impact on the airframe design.

Three new propeller designs as previously stated, have been tested in the wind tunnel for both aerodynamic and acoustic performance. The resulting near field noise levels fall in the band shown on Fig. 17, and have a lower limit of about 140 dB. With the aircraft operating at a cruise Mach number of 0.8, transonic propeller tip speeds result. This is the prime source of noise. Some of the new designs have incorporated varying degrees of sweep which, as would be expected, does lower the noise because of lower relative tip Mach numbers. With further improved propeller design techniques, it may be possible to lower the propeller noise still further to about 130 dB.

The desired sound level in the cabin is based on a value of 75 dB on the A scale at 160 Hz. This frequency corresponds to the blade passage frequencies for these designs, and this is where the major noise source occurs. Converting this 75 dB from the A scale to sound pressure level yields a value of 90 dB (shown on the bottom of Fig. 17). Conventional fuselage acoustic treatment can provide noise suppression of about 15-20 dB. This would permit the noise level outside the cabin to be approximately 110 dB. With improved fuselage treatment, it is estimated this permisable level could be as high as 140 dB. As seen on Fig. 17, the two bars overlap indicating that it should be possible to achieve the desired noise level inside the cabin. The solution, however, is not a simple one, and it involves several aircraft trades. Engine location can provide benefits, but with some possible penalties. Moving the engines further outboard on the wing, increases the distance to the cabin, but would have associated structural and weight drawbacks. Placing the engines at the rear of the aircraft behind the passenger compartment may achieve similar benefits with lesser penalties.

While careful placement of the engines can provide some benefits, extensive fuselage suppression will still be required. It appears possible to further attenuate the noise using conventional treatment techniques, but the fuselage and cabin weight penalties begin to erode the potential fuel savings. Therefore, new ideas are necessary. Figure 18 shows the relationship between the fuselage suppression and frequency level. For a conventional fuselage, the suppression has a minimum in a discrete frequency band. Unfortunately, this minimum suppression area is very close to the propeller blade passage frequency. Three possible concepts to improve suppression are shown. Increasing the stiffness will reduce the amplitude of the excited vibrations and shift the natural frequencies to higher values away from the blade passage frequency. Another concept is structurally tuning and damping, where the structure is designed to excite at preferred modes of vibration that can be easily damped. The double link wall concept involves a modification of current fuselage and cabin walls to optimize the distribution of mass, stiffness, and damping. This concept thus becomes more effective at higher frequencies, and it may be advantageous to increase the number of blades. To date, some limited experimental results have been obtained for

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all three concepts. The final optimized configuration to yield maximum suppression with minimum penalty may involve some combination of each of these concepts.

Studies were recently completed by Bolt, Beranek and Newman and the Lockheed California Company to identify fuselage design concepts for obtaining low cabin noise levels with minimum acoustic weight penalty to the aircraft. The Lockheed concept is shown in Fig. 19. It is a double walled design that incorporates the benefits of mass-like behavior, increased stiffening and damping. The estimated weight penalties for three possible transports are also listed. The planning effort is now underway to define small scale and large scale model test programs in order to conduct the tests required to validate the analytical tools used to compute acoustic weight penalties and interior noise levels.

Installation Aerodynamics

The third element shown on Fig. 12 is Installation Aerodynamics. This involves the challenge of integrating propeller design with wing design to achieve the best combination of engine efficiency and aircraft lift to drag ratio, while at the same time maintaining adequate stability and control. The initial aircraft studies identified the integration of the turboprop propulsion system with the airframe as one of the areas of high uncertainty, particularly because of the possible large interaction between the slipstream and wing. These interactions could be particularly severe for a supercritical wing. The section of the wing in the slipstream can operate in drag-rise, effectively reducing the installed performance of the propeller. In addition, the propeller will be subject to a nonuniform flow field created by the airframe, thus potentially reducing its performance. Conversely, there is a possibility for swirl recovery, thus increasing the performance of the installed propulsion system.

To reduce the uncertainties associated with the installation of these advanced turboprop systems, a combined experimental and analytical research program has been initiated by the Ames Research Center.[2] This consists primarily of two wind tunnel programs, one with a wing body and a slipstream simulator and the other a powered semispan test. Only results from the former are available to date. Figure 20 shows the slipstream simulator and the wing body model installed in the Ames 14-Foot Wind Tunnel. The slipstream was generated using an ejector driven nacelle mounted in front of the supercritical wing. The nacelle was powered by 20 sets of ejector nozzles which controlled the velocity and swirl of the slipstream. The wing/body model was mounted on a force balance. The simulator was designed to simulate the slipstream characteristics of an advanced propeller design previously tested. A comparison of both swirl angle and total pressure profiles from the slipstream simulator and values measured behind a model propeller are shown in Fig. 21. The agreement in both variables is fairly good. The only disagreement is seen at radius ratios which lie directly downstream of the nacelle walls. The viscous wakes shed from these surfaces cause a deficit in the total pressures at these locations.

The changes in aircraft drag with swirl angle for two Mach numbers are shown in Fig. 22. The change in drag is relative to the drag of the wing/body alone with no slipstream. When the slipstream was turned on with zero swirl an increase in drag of about 2.5% was seen. This increased drag remained until swirl angles somewhere in excess of 7°. Between 7° and 11° the drag dropped, and at 11° a benefical effect was seen. The new propeller designs are highly loaded and swirl angle generally increases with higher power loading; this effect thus becomes an important consideration in overall system design, and indicates the wing should be tailored for optimum swirl recovery. Although this phenomena is not fully understood yet, it indicates that the installation drag of an advanced turboprop system has the potential of being better than that of a comparable turbofan.

Mechanical Components

The last of the four elements in Fig. 12, mechanical components, includes the propeller, gearbox and engine. The components must be designed and packaged in such a way that maintenance and reliability will be much improved over that experienced by the past older technology turboprop aircraft. An analysis of Electra propulsion system data by Detroit Diesel Allison[4] has indicated the major area where improvements are required. Preliminary concepts for gearboxes and propellers have indicated that drastic reductions in maintenance cost may be possible. Even with the very high maintenance costs of the Electra system, however, the fuel savings of the advanced turboprop still yields large savings in DOC. As was shown in Fig. 11, future phases of the ATP program will address this area further, including full scale propeller fabrication and test and gearbox system analysis.

Summary

In summary (Fig. 23), the current international political and economic environment necessitates that our available energy supplies be used as efficiently as possible. This is especially true for the air transport industry as the price of fuel continues to climb. NASA - through the Aircraft Energy Efficiency program - is developing the technology which will enable a continued reduction in fuel consumption. Specifically, for the propulsion system, three efforts are underway to improve current aircraft engines by about 5%, to develop technology for new engines with 10-15% improvement, and to provide a technology base for future systems with savings as high as 35% above the engines in service today. The new propulsion systems, however, will provide new technical questions that must be answered. Future turbofan engines such as E^3 will probably be long duct mixed flow designs that must be carefully integrated with the aircraft so that the gains due to mixing are not lost through added weight or interference drag. The advanced turboprop system also must face integration problems both for performance and noise. The noise problem in particular appears most challenging, but initial studies have yielded encouraging results. The potential fuel savings are large and with proper installation even higher savings can be realized.

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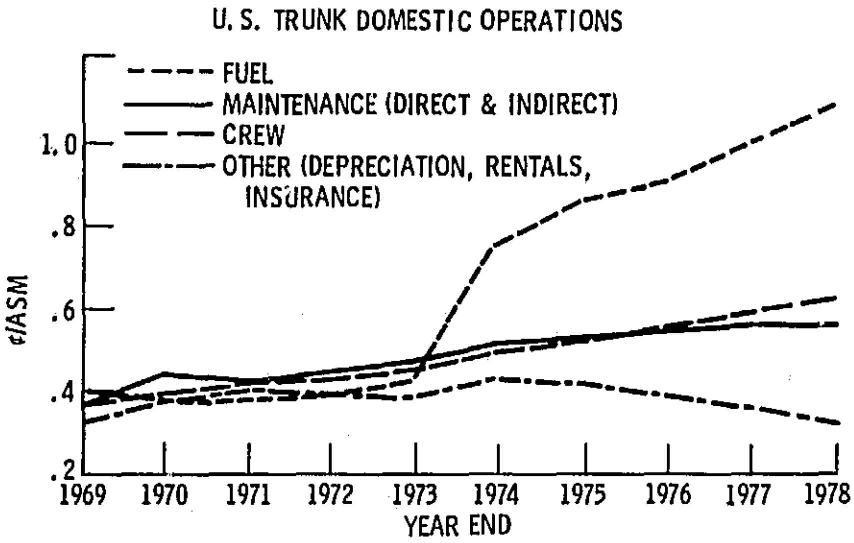


Figure 1. - Elements of direct operating cost.

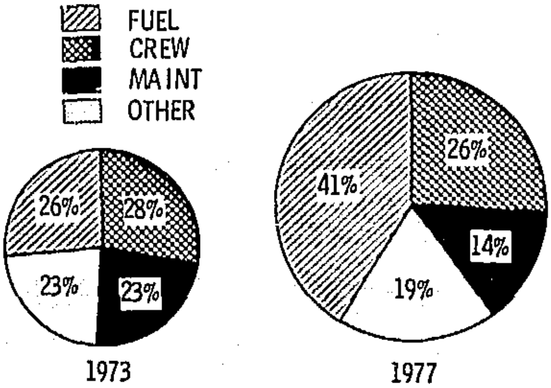


Figure 2. - Direct operating costs B727-200, domestic operation.

PROPULSION

- ENGINE COMPONENT IMPROVEMENT
- ENERGY EFFICIENT ENGINE
- ADVANCED TURBOPROP

AERODYNAMICS AND AIRCRAFT STRUCTURES

- ENERGY EFFICIENT TRANSPORT
- LAMINAR FLOW CONTROL
- COMPOSITE COMPONENTS AND PRIMARY STRUCTURES

Figure 3. - NASA aircraft energy efficiency program.

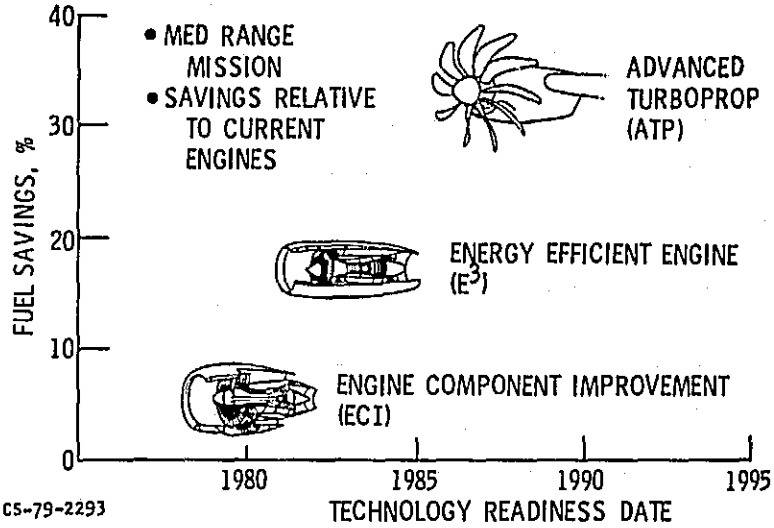


Figure 4. - Fuel savings and technology readiness dates of the ACEE propulsion projects.

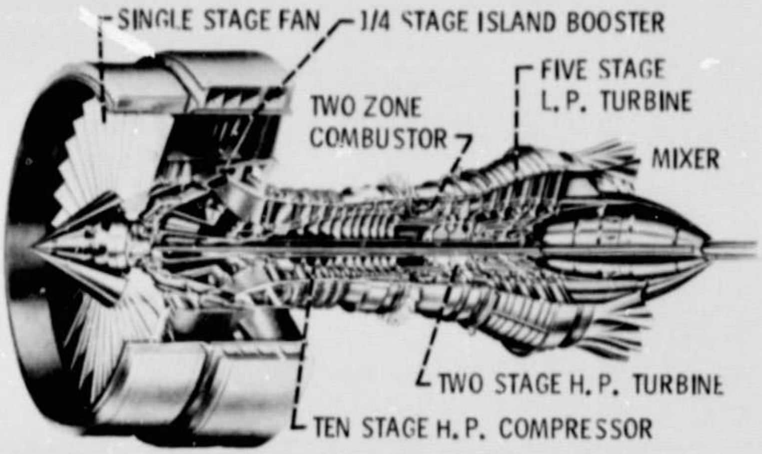


Figure 5. - General Electric energy efficient engine configuration.

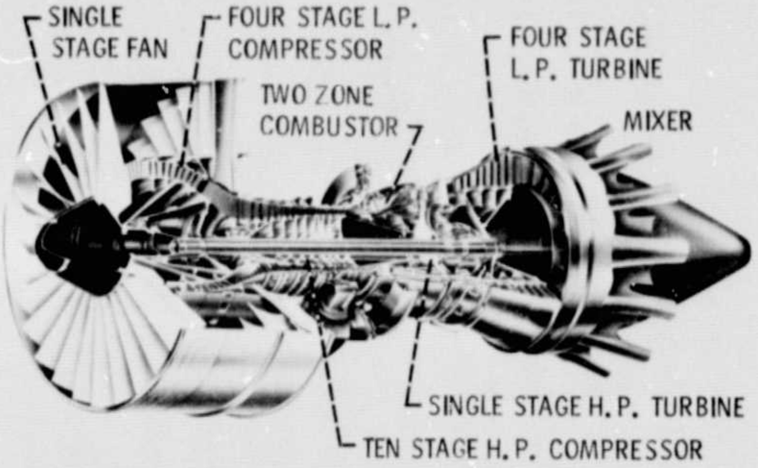


Figure 6. - Pratt and Whitney energy efficient engine configuration.

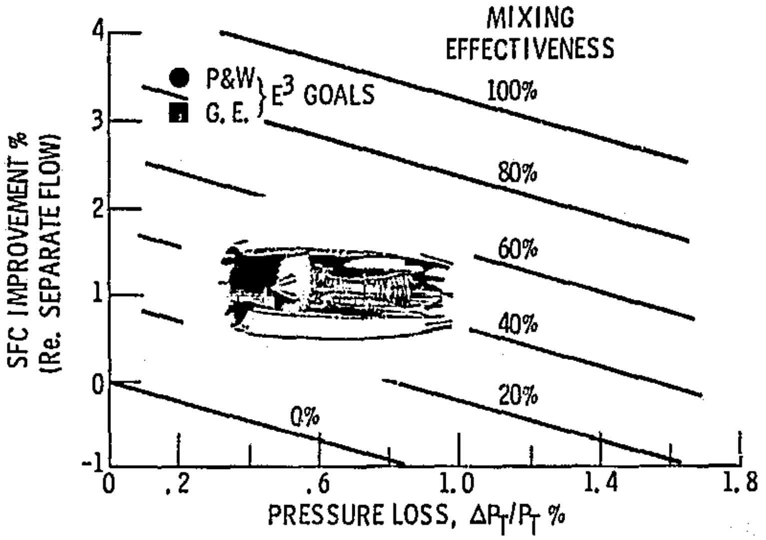
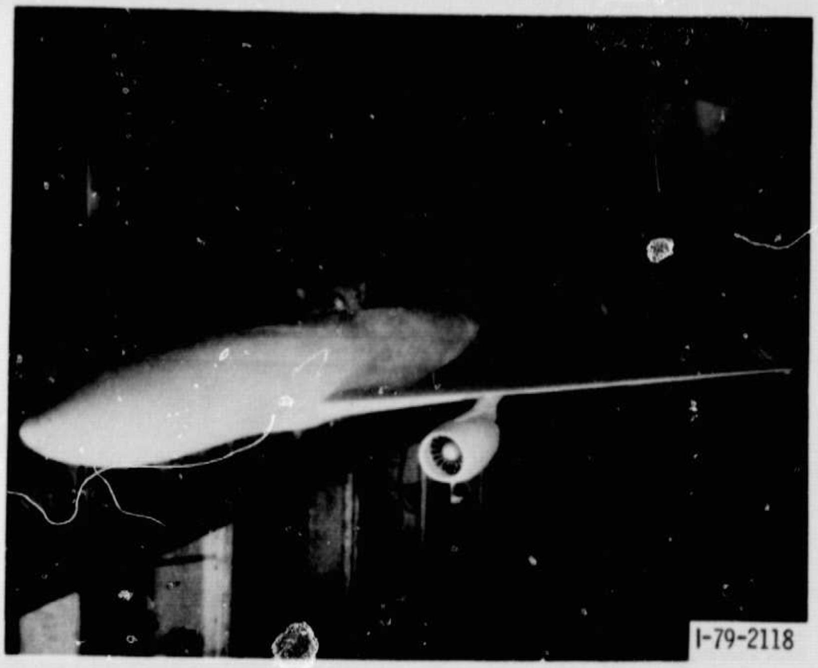
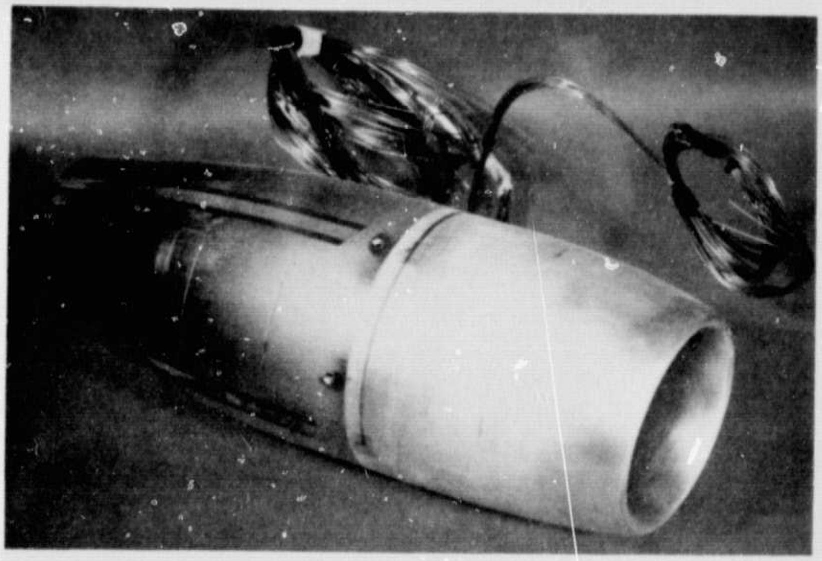


Figure 7. - Potential benefits of a mixed flow system.

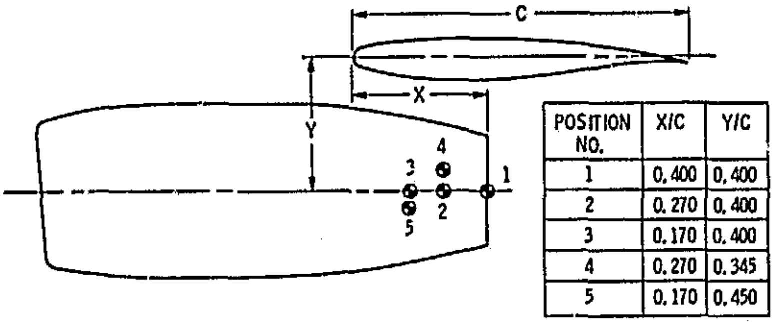


(a) HALF SPAN MODEL.



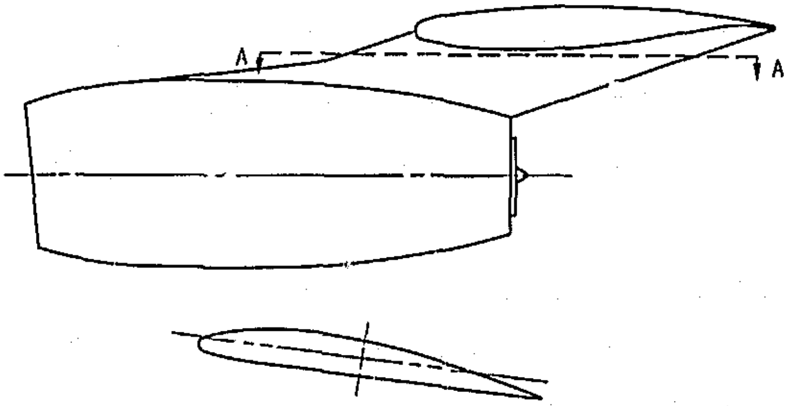
(b) E^3 NACELLE.

Figure 8. - Model hardware for interference drag testing.



POSITION NO.	X/C	Y/C
1	0.400	0.400
2	0.270	0.400
3	0.170	0.400
4	0.270	0.345
5	0.170	0.450

Figure 9. - E^3 nacelle test locations.



SECTION A-A

Figure 10. - Schematic of pylon and nacelle contours.

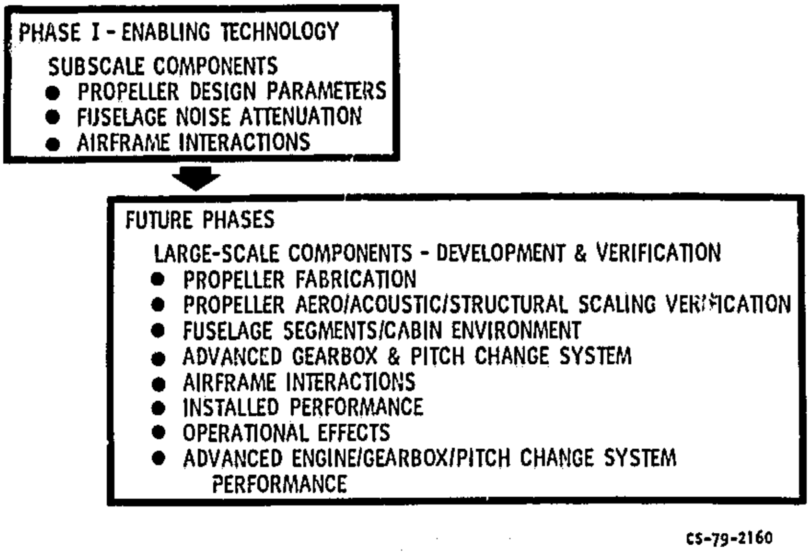


Figure 11. - Phases of advanced turboprop program.

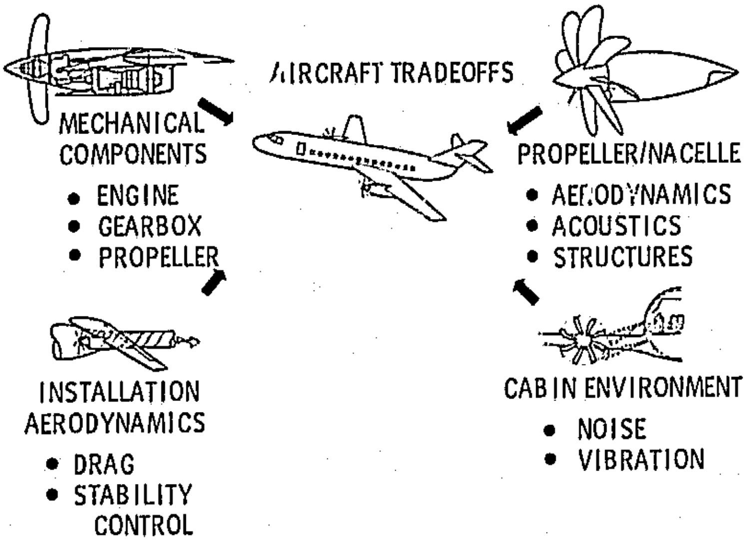


Figure 12. - Major elements of phase I of the advanced turboprop project.

ADVANCED PROPELLER ELECTRA PROPELLER

Figure 13. - New and old technology propellers.

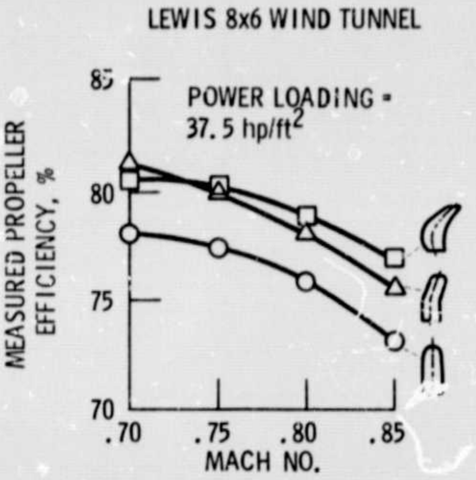


Figure 14. - Measured propeller efficiency.

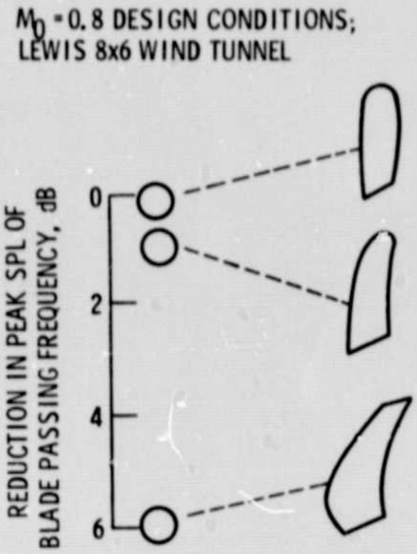


Figure 15. - Noise comparison of advanced propeller models.

Figure 16. - Concept for high-speed propeller mounted on NASA Jet Star aircraft for in-flight acoustic tests.

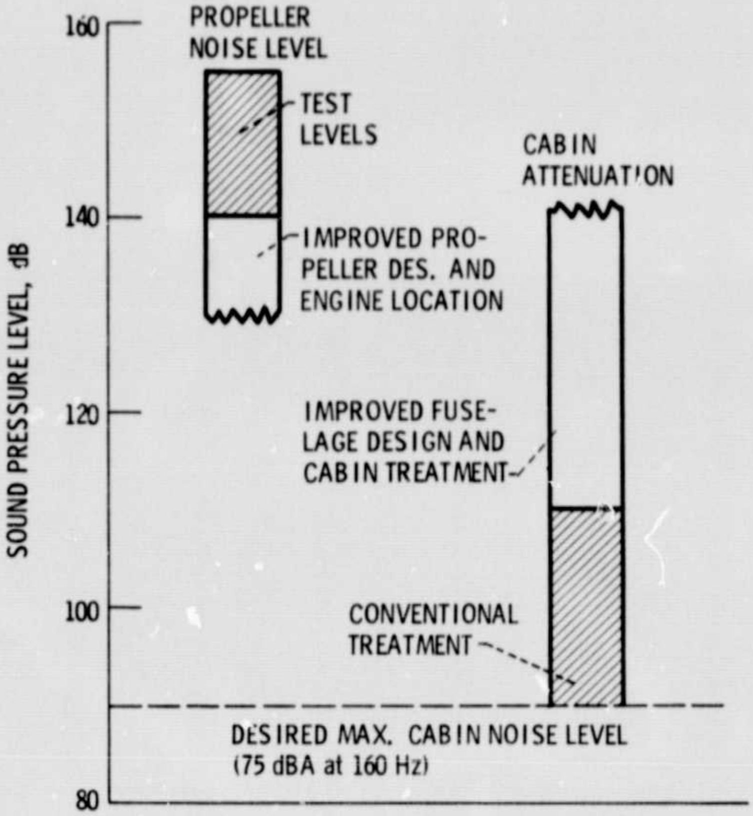


Figure 17. - Cabin noise - propeller aircraft trades.

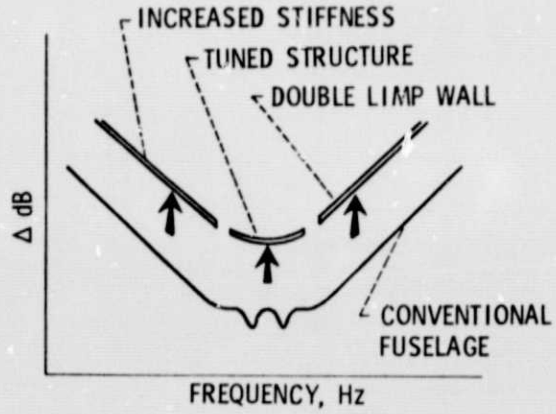
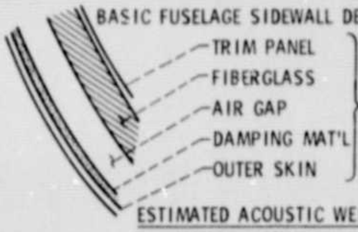


Figure 18. - Fuselage noise attenuation.

STUDY CONCLUSION: INTERIOR CABIN NOISE GOAL OF 80 dBA APPEARS ACHIEVABLE WITH CONVENTIONAL ALUMINUM FUSELAGE STRUCTURE



DOUBLE WALL CONCEPT USES OPTIMUM COMBINATION OF MASS, DENSITY, STIFFNESS AND DAMPING, EXPERIMENTAL VALIDATION REQUIRED

ESTIMATED ACOUSTIC WEIGHT PENALTIES

AIRCRAFT	GROSS WT.	FUSELAGE D	PROP D	WEIGHT PENALTY	% GW
4 ENG WIDE BODY	217,000	20.00 ft	12.6 ft	*5033 lb	2.31
2 ENG NARROW BODY	90,000	12.80 ft	12.4 ft	1635 lb	1.82
2 ENG SMALL A/C	32,000	7.33 ft	7.2 ft	551 lb	1.72

*PENALTY OF 5220 lb USED IN AUGUST 1977 LOCKHEED RECAT STUDY.

Figure 19 - Summary of Lockheed fuselage acoustic design study.

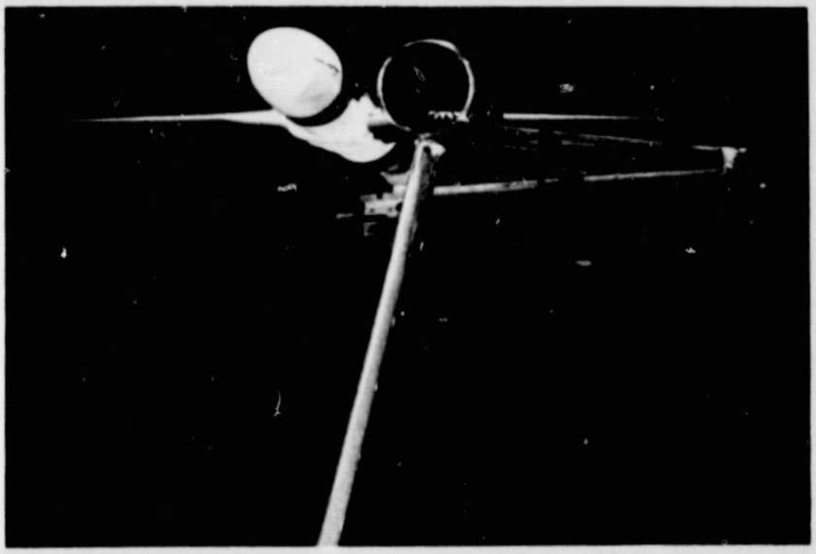


Figure 20. - Slipstream simulator and wing body installed in Ames Wind Tunnel (ref. 2.).

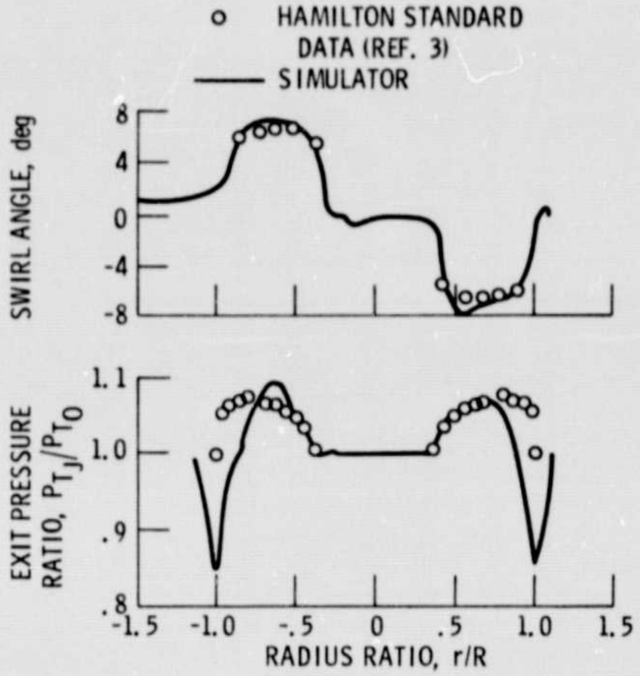


Figure 21. - Comparison of simulator exit flow with model propeller data (ref. 2). $M_0 = 0.8$.

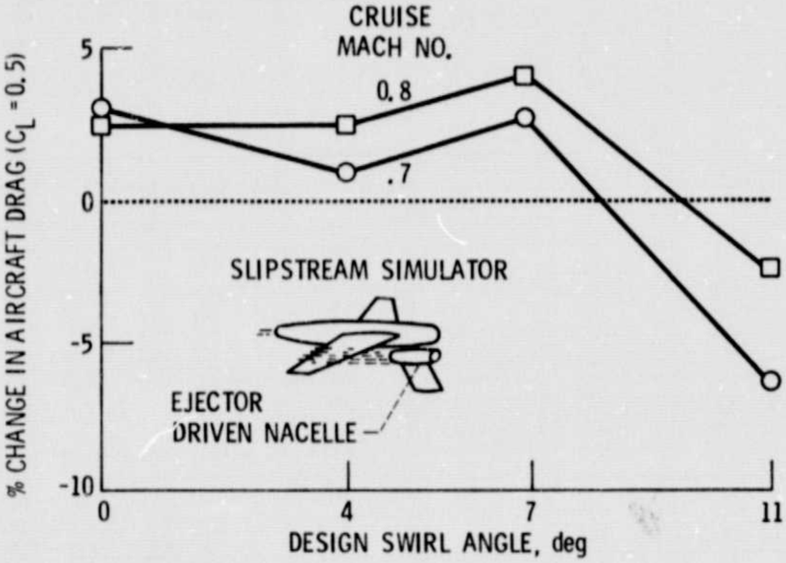


Figure 22. - Effect of simulated slipstream on aircraft cruise drag.

- CURRENT ENVIRONMENT DICTATES MORE EFFICIENT USE OF AVAILABLE ENERGY RESOURCES
- NEW AIRCRAFT PROPULSION CONCEPTS AND SYSTEMS ARE BEING DEVELOPED THAT WOULD REDUCE FUEL CONSUMPTION BY 5 - 35% OVER CURRENT SYSTEMS
- NEW SYSTEMS POSE NEW ENGINE/AIRCRAFT INTEGRATION PROBLEMS
- PROPER INSTALLATION, INTEGRATION AND AIRCRAFT DESIGN CAN YIELD FURTHER FUEL SAVINGS

Figure 23. - Summary.

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16. Abstract

The three engine programs that constitute the propulsion portion of NASA's Aircraft Energy Efficiency Program are described, their status indicated, and anticipated improvements in SFC discussed. The three engine programs are (1) Engine Component Improvement--directed at current engines, (2) Energy Efficient Engine--directed at new turbofan engines, and (3) Advanced Turboprops--directed at technology for advanced turboprop--powered aircraft with cruise speeds to Mach 0.8. Unique propulsion system interactive ties to the airframe resulting from engine design features to reduce fuel consumption are discussed. Emphasis is placed on the advanced turboprop since it offers the largest potential fuel savings of the three propulsion programs and also has the strongest interactive ties to the airframe.

17. Key Words (Suggested by Author(s))
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