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Abstract

In order for new short-medium range transports to offer significantly lower operating costs than potential derivatives of current designs using advanced technology, the efficiency improvements of high-speed turboprop propulsion systems may be required. Recent studies indicate that the fuel savings of advanced turboprop aircraft appears to be 10 to 20 percent relative to equivalent technology turbofan aircraft. These fuel savings are certainly large enough to warrant further research to establish the viability of turboprop transport aircraft. The studies have identified the technology requirements in propeller design for high efficiency and low noise, fuselage noise attenuation, propeller and gear box maintenance, and engine-airframe integration. This paper presents a review of present research in each of these areas and describes the future plans for continued development of the technology for advanced turboprop transport aircraft.

Introduction

Since 1973 airline fuel prices have tripled (fig. 1). Even though labor costs have also increased substantially over this period, these fuel price increases have resulted in fuel cost accounting for a much larger fraction of direct operating cost. In 1973, fuel cost amounted to 25 percent of the direct operating cost for the average operation of a Boeing 727; in 1975 it had risen to 38 percent. Currently, the U.S. airlines use about 10 billion gallons of fuel. Hence, each 1 cent per gallon increase in the price of fuel will cost the airlines 100 million dollars per year.

Over one-half of the fuel used by the U.S. scheduled carriers is used for stage lengths of less than 1000 statute miles (figs. 2 and 3[1,2]). Also, one-half of the total fuel is used by the short-medium range Boeing 727, 737, and Douglas DC-9 aircraft types. This appears to be a promising market for an advanced turboprop-powered transport aircraft.

In the 1950's, the seemingly unlimited supplies of cheap jet fuel, coupled with the speed and altitude advantages of the turbojet, resulted in its being favored over the 1950's turboprop. Todays environment of higher fuel prices and energy conservation has necessitated a re-examination of the turboprop. This re-examination is based on a new highly loaded, multibladed turboprop using advanced blade structure and aerodynamics technology for efficient, high-speed operation. Because this concept lies somewhat between the conventional turboprop and a high-bypass-ratio turbofan, the Hamilton Standard Division of United Technologies refers to it as the prop-fan. Based on recently completed wind tunnel tests, the installed propulsive efficiency of the advanced turboprop or prop-fan is projected to be about 20 percent better at Mach 0.8 than a high-bypass-ratio turbofan (fig. 4). This efficiency advantage is even greater at lower speeds, increasing to 35 to 40 percent at Mach 0.7.

The purpose of this paper is to review the current status of research on advanced turboprops. This is done by reviewing the results of advanced turboprop aircraft studies, by discussing current research programs, and by reviewing NASA's preliminary plans for continued development of the advanced turboprop concept.

Advanced Turboprop Aircraft Studies

In order to evaluate the advanced turboprop's overall impact on complete aircraft configurations and to identify the critical technology areas, three design studies have been completed.[3-9] The following sections will discuss the configurations used in these studies, the resulting fuel and operating cost savings potential, and passenger acceptance of a new advanced turboprop transport.[10]

Study Configurations

In the first design study, with the Lockheed-California Company,[3-5] a four-engine advanced turboprop-powered aircraft was compared with an equivalent technology level advanced turbofan (JT10D) powered aircraft (fig. 5). These aircraft were both designed to carry 200 passengers in equal comfort for a maximum range of 2778 km (1500 n.mi.) at Mach 0.8 cruise speed. The technology levels reflect 1985 service introduction and include a supercritical airfoil, aspect ratio 10 wing, active controls for longitudinal stability augmentation, and composite secondary structure. The advanced propeller or prop-fan is powered by a Pratt & Whitney study turboshaft engine (STS 476) based on the JT10D engine core. For the design range of 2778 km (1500 n.mi.), the takeoff gross weight of the two aircraft is about equal. This occurs because the prop-fan fuel savings is almost equally balanced by a higher empty weight. The increased prop-fan aircraft empty weight reflects increased wing weight to accommodate prop-fan torsional loads, increased prop-fan nacelle weight, and increased fuselage weight to attenuate the propeller noise in cruise.

The second prop-fan design study was with the Douglas Aircraft Company.[6,7] For this study, the DC9-30 was used as a firm basis of comparison and a derivative of this aircraft using prop-fan propulsion was examined (fig. 6). With mixed class seating, the DC9-30 can accommodate 92 passengers, 12 in first class with 4 abreast and 96.5-cm (38-

in.) pitch seating, and 80 in coach with 5 abreast and 86.4-cm (34-in.) pitch seating. The prop-fan derivative was not resized to the same design range. Instead, the gross takeoff weight and payload were held constant. The takeoff, approach, and cruise performance of the prop-fan derivative were chosen to match the baseline DC9-30 performance and the prop-fan was sized for Mach 0.8 cruise at 9144 m (30 000 ft) altitude. With the exception of moving the wing forward to rebalance the aircraft with wing mounted engines and a 30 percent increase in the vertical tail area for engine out control, the derivative prop-fan aircraft is virtually identical to the current DC9-30. The increase in operating empty weight is due to the heavier prop-fan propulsion system, additional fuselage structure and insulation for propeller noise and vibration attenuation, and slightly higher flight controls and hydraulic system weights for a larger, double-hinged rudder.

The third and most recent design study was with the Boeing Commercial Airplane Company.(8,9) In this study, two prop-fan powered configurations were compared with an equivalent technology level advanced turbofan-powered aircraft (fig. 7). These aircraft were designed to carry 180 passengers in equal comfort for a maximum range of 3334 km (1800 n.mi.) at a cruise speed of Mach 0.8. All three configurations are twin-engine, wide-body aircraft using 1976 design airframe technology and engine technology corresponding to 1980-1985 certification. One prop-fan design has the engines mounted on the wings, the other has the engines mounted on struts attached to the fuselage aft-body. The higher operating empty weights of the two prop-fan aircraft reflect the heavier prop-fan propulsion system. Also, for the wing-mounted prop-fans, a substantial weight penalty, 2667 kg (5880 lb), is included for cabin noise suppression to the interior levels of the turbofan aircraft. The arrangement with the aft-body mounted prop-fans was designed to reduce that penalty. However, for this aircraft, additional structure is required for the engine struts, heavier skin gages must be used in the region of the propeller to prevent acoustic fatigue, aircraft balance requires moving the wing aft, and the shorter tail moment arm necessitates larger horizontal and vertical tails. The increased gross takeoff weights for the prop-fan aircraft result from the higher empty weights and the inability to counter this completely with fuel weight savings for the 3334 km (1800 n.mi.) mission.

Fuel Savings

Because of different study ground rules and assumptions, the prop-fan aircraft fuel savings range from as low as 8 percent to a high of 28 percent in comparison with their turbofan counterparts for a 1852 km (1000 n.mi.) stage length (fig. 8). In all cases, the increased efficiency advantages of the prop-fan compared to the turbofan at lower altitudes and speeds results in greater fuel savings at shorter stage lengths. This is one reason why the prop-fan looks particularly attractive for the short-medium haul markets currently being served by the DC-9, B-737, and B-727 aircraft.

The largest fuel savings are for the prop-fan derivative DC9-30.(6,7) The fuel savings are larger than obtained in the other two studies because the comparison is with the current DC9-30 using low-bypass-ratio JT8D turbofan engines. In the Douglas study two levels of prop-fan performance were examined. One prop-fan design was based on performance levels corresponding to an 8-bladed prop-fan with a rotational tip speed restricted to 219.5 m/sec (720 fps), corresponding to the Lockheed Electra, and current technology turboshaft engine performance. This resulted in a propeller efficiency of 0.73 and an installed cruise thrust specific fuel consumption (TSFC) of 0.0738 kg/hr/N (0.65 lb/lb/hr). The other prop-fan design was based on an 8-bladed prop-fan with a 243.8 m/sec (800 fps) tip speed and turboshaft engine performance corresponding to the STS-476, a Pratt & Whitney study turboshaft engine based on the JT10D engine core. This resulted in a propeller efficiency of 0.80 and an installed TSFC of 0.0602 kg/hr/N (0.53 lb/lb/hr). Depending on the assumed propulsion system efficiency, the derivative prop-fan uses from 27 to 33 percent less fuel than the DC9-30 at its average operational stage length of 537 km (290 n.mi.). For the same takeoff gross weight and a passenger load factor of 58 percent, this fuel savings translates into a maximum range capability improvement of 41 to 73 percent, depending on the propulsion system efficiency assumed.

Admittedly, the fuel savings shown for the prop-fan derivative are higher because the comparison is with an older technology low-bypass-ratio turbofan rather than a comparable technology turbofan. However, the prop-fan derivative does not include the application of any of the other advanced aerodynamics, structures, or active controls technologies that can improve the efficiency still further. Also, the low-bypass-ratio engines are the ones that are currently in-service and being sold in large quantities on this airplane type.

In the Lockheed design study,(3-5) both the prop-fan and the turbofan were developed using 1985 technology levels. The resulting fuel savings for the prop-fan aircraft were 20.4 percent for a typical in-service stage length of 880 km (475 n.mi.) and a 58 percent passenger load factor.

The fuel savings for the Boeing prop-fan aircraft compared with an equal technology turbofan (8,9) were more modest, amounting to 13.5 percent for the wing-mounted configuration at a 926 km (500 n.mi.) stage length and 13 percent for the aft-mounted configuration. These smaller fuel savings reflect the Boeing study assumptions of a prop-fan noise level in cruise 10 dB higher than the long range noise goal, suggested by Hamilton Standard, resulting in a larger acoustic treatment weight penalty, and an increase in drag due to the effect of the propeller slipstream on the wing aerodynamics. These are two of the critical technology areas that are currently being investigated and will be discussed again later in this paper.

Operating Cost Savings

The direct operating cost (DOC) savings identified in these studies (fig. 9) reflect the differences identified in the fuel savings comparisons. The largest DOC savings were obtained for the DC9-30 prop-fan derivative, even at the lower propulsion system efficiency with a TSFC = 0.0738 kg/hr/N (0.65 lb/lb/hr). The DOC savings for this aircraft at a stage length of 537 km (290 n.mi.) were 5.5 percent for fuel at 7.92 ¢/liter (30 ¢/gal) and 9.9 percent for fuel at 15.85 ¢/liter

(60 ¢/gal). The Lockheed prop-fan aircraft obtained a DOC saving for a stage length of 880 km (475 n.mi.) of 5.9 percent for fuel at 7.92 ¢/liter (30 ¢/gal) and 8.5 percent for 15.85 ¢/liter (60 ¢/gal) fuel. For the Boeing wing-mounted prop-fan, the DOC savings for a 963 km (520 n.mi.) stage length were 4.3 percent with 7.92 ¢/liter (30 ¢/gal) fuel and 6.5 percent with 15.85 ¢/liter (60 ¢/gal) fuel. The variation in the DOC savings percentage with stage length reflects the trade between the fuel savings percentage decreasing with increasing stage length while fuel cost, as a fraction of DOC, increases.

Passenger Acceptance

In considering the introduction of a new generation of advanced turboprop transports, one nontechnical area of concern involves the question of passenger acceptance of such an aircraft. Would airline passengers perceive the advanced turboprop as a step backward and hence be reluctant to fly on an aircraft with exposed propellers? In order to answer this question and to provide some guidance on the relative importance of different aspects of an airline flight, an in-flight passenger survey (10) was conducted by United Airlines (fig. 10). Some 13 500 questionnaires were circulated on 127 flights over 119 route segments covering stage lengths from 370 to 4260 km (200 to 2300 n.mi.). A total of 4069 passengers responded to the survey. The first part of the questionnaire included general questions on trip purpose, previous flying experience, and the relative importance of different aspects of the flight. Averaging the responses, of the seven aspects of flight that were listed, seating comfort was ranked most important, followed by speed, smoothness (lack of vibration), ride (lack of bumpiness), quietness, flight attendants, and food. Overwhelmingly, the most desired change was less expensive fares, and the least acceptable change was slightly closer seating.

After reading a description of the prop-fan and looking at a picture of it, the passengers were asked how they would feel about flying in a prop-fan airplane for a trip such as the one they were on. In response to this "baseline" question, almost half (49 percent) indicated they would not care one way or the other, 37 percent would like to try the prop-fan airplane, and 14 percent would not. The passengers were then told to suppose that the prop-fan airplane used 20 to 30 percent less fuel than a jet aircraft. With fuel conservation in mind, 76 percent indicated they would like to try the prop-fan airplane, 17 percent were neutral, and 7 percent would rather not. Finally, when told that air fare increases of the future might be avoided because of the savings associated with the new prop-fan airplane, 85 percent indicated they would like to try the prop-fan, 9 percent were neutral, and 6 percent would rather not.

From an analysis of the survey results, United Airlines reached the following conclusions: "Though preferring a jet today, a passenger would fly an advanced prop-fan having jet equivalent speed, seating comfort, and ride quality if he perceived a significant fuel savings attendant with the prop-fan. The passenger would fly an advanced prop-fan with a trip time measurably longer than jets if a direct financial advantage was associated with the prop-fan; e.g., a posted discernible jet/prop-fan fare differential."

Summary of Study Results

The results of the design studies conducted thus far (fig. 11) indicate a potential fuel savings of 10 to 20 percent for a prop-fan powered aircraft relative to a comparable technology turbofan for the same mission cruising at Mach 0.8. This corresponds to a fuel savings of 20 to 40 percent relative to current turbofan aircraft, depending on the current aircraft against which the comparison is made. Accounting for all the design differences between the prop-fan and turbofan-powered aircraft, these fuel savings would result in a savings in direct operating cost ranging from 3 to 6 percent with 7.92 ¢/liter (30 ¢/gal) fuel to 5 to 10 percent with 15.85 ¢/liter (60 ¢/gal) fuel.

The results of a passenger survey indicate that passengers would accept the introduction of a new prop-fan transport. In fact, they would welcome it if it saved fuel and held fares down while providing equivalent comfort levels.

All of the design studies recommended research and technology efforts in four major areas; propeller efficiency, propeller noise and fuselage noise attenuation, airframe/engine integration, and propeller and gearbox maintenance. The following sections will discuss the current research programs in each of these areas and NASA's preliminary plans for continued development of the advanced turboprop concept.

Current Research Programs

Propeller Efficiency

In the past, propellers were very efficient at cruise speeds up to about Mach 0.65. Above this speed, increased drag due to compressibility losses on the propeller blades caused efficiency to fall rapidly. One way to lower compressibility losses is to increase the Mach number at which drag rise occurs by using thinner airfoil sections than employed in the past. In the 1950's, when fabrication was limited to all metal blades, full-scale construction of very thin blades was not possible. Now, however, with the use of composite materials and advanced construction techniques it is possible to construct blades with thinner airfoil sections and more optimum shapes. Compressibility losses at the blade tips can be reduced further by sweeping the blade leading edge so as to keep the flow subsonic, normal to the leading edge. This reduces shock strength at the blade tips and thus reduces compressibility losses. Still a third way to lessen compressibility losses is by proper contouring of the spinner and nacelle to reduce the axial Mach number in the hub region of the propeller. In this region, thick blade sections and closely spaced blades could result in local flow choking. By carefully area ruling the spinner, however, compressibility losses in the propeller hub region can be minimized.

The desire to cruise at Mach 0.8 above 9.144 km (30 000 ft) altitude, as in current turbofan-powered aircraft, not only requires propellers with low compressibility losses but in addition requires a propeller power loading several times higher than that of conventional propellers in order to keep propeller diameter at a reasonable value. In order to achieve the higher power loading most efficiently, the number of propeller blades is increased from 4 to 8 or 10. From studies of highly-loaded, eight-bladed propellers designed for low compressibility losses, it has been estimated that an advanced turboprop could be designed with an installed propulsive efficiency at Mach 0.8 cruise that would be about 20 percent higher than that for the best advanced turbofan.[11] In making this estimate, a propeller net efficiency of 80 percent was used.

Two advanced propeller models 62.23 cm (24.5 in.) in diameter were designed and wind tunnel tested to evaluate their performance. The work was done by Hamilton Standard under contract to NASA-Lewis Research Center. The two models are shown in figure 12 installed on a 373-kW (500-hp) propeller test rig in the United Technologies Research Center large subsonic wind tunnel. The models were composed of blades, spinner, and a simulated axisymmetric nacelle. Both propellers used the same nacelle geometry, which had a ratio of maximum diameter to propeller diameter of 0.35. The two configurations were essentially the same except that SR-1, the swept-bladed propeller model (fig. 12(a)), included 30° of aerodynamic sweep at the tips of the blades while the blades of SR-2 were straight (fig. 12(b)).

A summary of the cruise performance at Mach 0.8[12,13] is shown in figure 13 for both the swept-bladed propeller (SR-1) and the straight-bladed propeller (SR-2). Comparisons are made between the experimentally measured efficiency and the analytically predicted efficiency. In both cases the measured efficiency was close to the predicted value. These propeller models are now under test at NASA Lewis Research Center to confirm these preliminary test results. In addition, an improved version of the swept model will be tested that should show a higher efficiency than the initial swept model. From the tests conducted to date of two highly-loaded, high-speed propeller models, it appears likely that the goal of 80 percent propeller net efficiency at Mach 0.8 will be attained.

Propeller Noise and Fuselage Attenuation

Propeller noise. In order for an advanced turboprop aircraft to be competitive with an advanced turbofan aircraft, the turboprop cabin interior during cruise should be equivalent in comfort (low levels of noise and vibration) to that of the turbofan aircraft. A quiet cabin interior will be more difficult to achieve in the turboprop aircraft. This is because its fuselage is in the direct noise field of the propeller whereas the inlet duct of a turbofan shields the fuselage from fan noise.

Some preliminary noise tests of SR-1 and SR-2 were completed in 1976 in the UTRC Acoustic Research Tunnel (fig. 14). In order to simulate Mach 0.8 cruise operation, the tunnel is operated at its maximum throughflow Mach number (Mach 0.32) and the propeller model is oversped so that the blade tip relative Mach number is the same as for the Mach 0.8 cruise condition. In simulating Mach 0.8 cruise, the propeller model has only two blades because of the limited horsepower of the electric drive rig. Microphones were located on a line parallel to the propeller axis of rotation at three radial distances in the near field and one radial distance in the far field. Measured noise levels in the tunnel were compared with levels predicted by a theoretically based computer program. Empirical adjustments were made to the noise prediction program, which was then used to predict full scale propeller noise at the desired altitude and cruise speed.

The results of these tests and the application of the empirically adjusted propeller noise prediction program are shown in figure 15. With conventional, straight, thick blades (t/c = 6 percent at the blade tip), the overall near field sound pressure level (SPL) would be about 151 dB at Mach 0.8. The SPL of SR-1 and SR-2 was 146±3 dB. At the blade tips, thickness to chord ratio was 2 percent. For SR-1 sweep was 30°. SR-1 was designed for good aerodynamic performance with little compromise for low noise. The reduction in SPL was mostly due to using thinner blades.

Based on the acoustic testing and analysis of SR-1 and SR-2, a third propeller model (SR-3) is currently being designed for low noise. By improving the sweep and planform of the SR-3 blades, a SPL of 140±3 dB is predicted. (Another approach to achieving a SPL of about 140 dB with no change in propeller efficiency is to lower design tip speed from 243.8 m/sec (800 ft/sec) to 201.2 m/sec (660 ft/sec). This would lower design power loading from 301 kW/m^2 (37.5 SHP/ft^2 to 216.8 kW/m^2 (27 SHP/ft^2) and increase propeller diameter by 17 percent.) The bar on the right of figure 15 indicates a long range SPL goal of about 136 dB. This might be achieved by further optimization of blade sweep and planform and by the use of new airfoils, or by reducing tip speed and power loading. Achievement of this goal would tend to minimize the fuselage weight penalty associated with making the cabin noise level of the turboprop airplane comparable to that of the turbofan airplane.

The propeller models SR-1 and SR-2 were also tested at low forward speeds corresponding to takeoff and landing conditions. These noise levels scaled from the test data were close to those predicted from empirical equations.

Fuselage attenuation. The propeller noise levels indicated in figure 15 will require a substantial amount of fuselage acoustic treatment in order to obtain an internal cabin noise level comparable to that for the advanced turbofan aircraft. In the Boeing study,[8,9] a prop-fan noise level 10 dB higher than the long range goal (approximately the levels indicated in the initial anechoic chamber tests) was assumed. Using this noise level, the maximum additional fuselage noise attenuation required for the Boeing wing-mounted prop fan aircraft was 25 dB (fig. 16). Because this noise is primarily low frequency, it is very difficult to attenuate with conventional lightweight acoustic treatment.

The approach used in the Boeing study involves technology advances in attenuating low frequency noise. For the high noise areas of the fuselage, Boeing used a combination of tuned structure, laminated skin and highly damped doubled frames and stringers to achieve the desired attenuation. The additional structural weight penalty for this noise attenuation amounts to 2267 kg (5880 lb) for the Boeing prop-fan aircraft (fig. 17) reducing the potential fuel savings by 2 percent. With conventional noise attenuation techniques using mass damping, this weight penalty could be as high as 3630 to 4540 kg (8000 to 10 000 lb). On the other hand, if the propeller source noise could be reduced by 10 dB, to the long range noise goal of 136 dB, the acoustic treatment weight penalty could be as low as 680 kg (1500 lb).

An alternative method of reducing the cabin noise is by moving the engines to another location, as with the Boeing aft-mounted configuration. At this location, the propeller plane is behind the aft fuselage pressure bulkhead and only a very small portion of the passenger cabin requires additional acoustic treatment to get down to turbofan cabin noise levels (fig. 18). However, because the propeller tip clearance is reduced, some additional structure is required to prevent acoustic fatigue for the 60 000 hour design life. The added skin thickness results in a weight penalty of 807 kg (1780 lb), costing 1 percent in potential fuel savings, and further aggravating the balance problem for this configuration.

Airframe-Propulsion System Integration

The initial systems studies[3-9] identified the integration of the turboprop propulsion system with the airframe as one of the areas of high uncertainty that requires additional research. The integration of a turboprop is more critical than that of a turbofan because of the large interaction between the slipstream and wing. As outlined in the studies, the combination of a supercritical swept wing and the highly loaded propeller can give rise to a considerable level of aerodynamic interference. Inherent in the slipstream are Mach number and swirl increments of approximately 0.05 and 6.0°, respectively. Both of these flow perturbations can significantly affect the flow over a supercritical wing which has been designed to operate at a specific Mach number. Either can cause the section of the wing within the slipstream to operate well into 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.

To reduce the uncertainties associated with the installation of these advanced turboprop propulsion systems, a combined experimental and analytical research program has been initiated. The primary objectives of the effort, as enumerated in figure 19, are to assess the magnitude of the aerodynamic interference, to understand the aerodynamic phenomena associated with the installation, and to develop an analytical and experimental data base. The determination of the aerodynamic interference between the propulsion system and airframe will significantly contribute to the technology base required to establish the overall performance potential of the proposed high-speed turboprop aircraft; thus providing a more concrete basis upon which to establish the future program effort. The design and optimization of the propulsion system installation requires a detailed understanding of the aerodynamic and flow characteristics associated with this type of installation. The development of the analytical and experimental data base will contribute to this understanding.

The near term experimental effort includes two complementary test programs. The first uses a simulated propeller slipstream while the second employs an active propeller. The first program, referred to as the slipstream simulator program, is schematically illustrated in figure 20. The objective of the test is to acquire fundamental force and pressure data on the interaction of a representative slipstream and a supercritical wing. The slipstream will be generated using an ejector driven nacelle strut mounted in front of a transonic wing-body model. The ejector driven nacelle is powered by 20 sets of ejector nozzles which control the energy and hence the velocity of the slipstream. The nacelle also includes a set of swirl vanes to induce swirl into the slipstream. The wing-body model is mounted on a force balance and the wing is pressure instrumented. With this arrangement, the effects of slipstream Mach number and swirl on the wing-body forces and pressure can be determined. To provide a more detailed understanding of the interaction between the slipstream and wing, a wake rake is being used to measure the wake characteristics along the span of the wing. This information will provide a detailed description of the local drag characteristics along the wing and identify the local drag increments resulting from the slipstream-wing interaction. The wing-body model along with the wake rake installed in the Ames 11- by 11-Foot Wind Tunnel is shown in figure 21. The actual test program using the slipstream simulator will be conducted in the latter part of FY'77 in the Ames 14-Foot Wind Tunnel.

To provide a more accurate estimate of the interference between the propulsion system and the airframe including the effects of the installation on the actual propeller performance, a second test program using an active propeller mounted on a semi-span wing-body model is being pursued. A schematic of the proposed model is shown in figure 22. To ensure consistency between these results and those of the isolated propeller tests and also to allow the propeller blades to be interchangeable between the two test programs, the wing-body model was sized to match the 62.2 cm (24.5 in.) diameter propellers previously tested. Furthermore, the semi-span wing-body model is a scaled version of the full-span model used in conjunction with the slipstream simulator. This will allow a detailed comparison of the data from both the slipstream simulator and active propeller tests. The propeller on the semi-span model will be powered by an air turbine motor and be instrumented for propeller thrust and power. The wing-nacelle combination will be mounted on a floor balance and be extensively pressure instrumented. The tests are planned for the Ames 11- by 11-Foot Wind Tunnel in the early part of FY'79.

The relative merits of these two test programs to assess the airframe-propulsion system interference effects are outlined in figure 23. The slipstream simulator program, although providing only an approximate simulation in terms of slipstream Mach number and swirl, does allow the individual interactions to be investigated separately and/or in combination. Due to the necessity of maintaining the alignment between the ejector nacelle and the free-stream flow direction, only measurements corresponding to the conditions around the cruise angle of attack can be obtained. However, the relative position of the slipstream and wing can be easily varied. In contrast the powered semispan model provides an accurate and complete simulation of the flow field over the full angle-of-attack range. Under this condition, however, it is more difficult to identify the effects of the various flow perturbations and to vary them to establish trends that can be used to optimize the installation. Jointly though, these two test programs should provide a detailed understanding of the various interference effects and establish an accurate assessment of installed performance of these high-speed turboprops.

To provide an analytical base for the integration of these advanced turboprop propulsion systems, two approaches are being pursued. The first is to apply existing linear paneling techniques to the wing-nacelle-slipstream combination along the lines described in reference 14. Although these techniques are applicable only subcritically, it is believed that many of the potential transonic flow problems can be identified by examining the local pressure distributions at subcritical conditions. A number of different paneling techniques are being applied to this area and include those described in references 14 to 16. The accuracy of these methods will be evaluated using the experimental results obtained from the test programs. As a long-range analytical effort, the development of a transonic computational technique will be supported. The objective of this effort will be to develop a computational tool capable of analyzing a wing-nacelle-slipstream combination under transonic flow conditions.

Propeller and Gearbox Maintenance

A study of turboprop systems reliability and maintenance costs was completed in May 1977 by Detroit Diesel Allison (DDA) for NASA-Lewis Research Center. The objectives of the study were to understand the overall reliability and maintenance costs (R&MC's) of past and current turboprop systems and then to project the R&MC improvements that could be expected from these levels to those of new turboprop systems for the 1985-1990 IOC time period. Hamilton Standard (HS) was a subcontractor to DDA and provided information on past, current, and new propellers.

The aircraft studied were the Lockheed L188 Electra and the Convair CV580. These aircraft were powered by the DDA 501-D13 turboshaft engine and either the DDA 606 propeller or the HS 54H60 propeller. The data used in the study were obtained from airline records, repair facilities, CAB Form 41, and the DDA reliability department records.

The fully burdened turboprop maintenance cost was found to be quite high. Using data from the 1966 through 1969 time period for Electra L188 operations averaging 0.80 hours per flight, the turboprop (DDA 501-D13/HS 54H60) maintenance cost was $42.30 per flight hour (FH) (CY 1976 economy). The cost drivers were found to be scheduled overhaul, lack of modularity (particularly in the propeller and the reduction gearbox), and lack of inherent reliability of some parts.

In figure 24 the high maintenance cost of the DDA/HS turboprop is compared with the maintenance cost of the JT8D turbofan that powered B737 aircraft during the 1971 through 1973 time period. The higher turboprop maintenance cost ($53.18/FH rather than $42.30/FH) resulted from scaling the turboprop so that its thrust equaled the thrust of the JT8D turbofan at Mach 0.8 climb and 10.67 km (35 000 ft) altitude. In this comparison, turboprop maintenance cost exceeds turbofan maintenance cost by $14.28 per engine flight hour or by 37 percent. Most of the difference ($9.59) is due to the higher maintenance cost of the older-technology turboprop core. The remaining difference ($4.69) comes from the higher maintenance of the turboprop's propeller and gearbox as compared with the maintenance cost of the turbofan's fan and thrust reverser.

The study of past and current turboprops indicated that an advanced turboprop for the 1990 era must incorporate many changes. On-condition maintenance must replace scheduled overhauls. This alone has the potential of eliminating about 45 percent of the current turboprop maintenance cost. The entire propulsion system must be designed using modular concepts so that failures and resulting removal and repair can be done on small equipment packages with little or no disturbance to the rest of the engine. Improved hardware reliability must be achieved through simplification as measured by lower parts count and through the use of improved materials and designs.

Based on a preliminary design of an advanced turboprop that incorporated the above features, a mature engine maintenance cost was calculated. The engine maintenance cost of the 1990 era turboprop can be compared with engine maintenance costs of the 1960 era turboprop and the JT8D turbofan in figure 25. Maintenance cost of the 1990 turboprop is only 35 percent of that for the 1960 turboprop. It was outside the scope of the study to do a preliminary design of a 1990 turbofan and estimate its maintenance cost. But, it is likely that the maintenance cost of an advanced core in a 1990 turbofan would be about the same as that for an advanced core in a 1990 turboprop. The difference between the two engines would then be in the maintenance cost of the advanced propeller plus gearbox versus the maintenance cost of the fan plus thrust reverser. The maintenance cost of the 1990 propeller and gearbox was calculated to be $0.98 per engine flight hour. Since it is not likely that fan and reverser maintenance costs would be much below $1.00 per engine flight hour, the inference is that the maintenance costs of advanced turboprops and turbofans should be competitive.

Plans for Continued Development

The Advanced Turboprop Program is one of six major technology programs that comprise the NASA Aircraft Energy Efficiency Program. These technology programs will have application to current transport derivatives in the early 1980's and to all-new aircraft of the late 1980's and early 1990's. Successful development of the six elements will greatly contribute to the design of a new generation of aircraft that are significantly more energy-efficient than today's transports.

The objective of the Advanced Turboprop Program is to demonstrate technology readiness for efficient, reliable, and acceptable operation of turboprop-powered commercial transports at cruise speeds up to Mach 0.8 and at altitudes above 9.144

km (30 000 ft) (fig. 26). This technology would also apply to possible new military aircraft requiring long-range and long-endurance subsonic capability. A major goal of the program is to achieve a fuel savings of at least 15 percent relative to turbofans with an equivalent level of core technology. Using current turbofans such as the P&W JT9D and the GE CF6 as a reference, a new advanced turbofan might achieve a fuel savings of 10 percent while a new advanced turboprop has the potential of achieving a 25 percent fuel savings.

The four major areas involved in the Advanced Turboprop Program are shown in figure 27. These areas interact with each other and all contribute to the program goals of low fuel consumption, low operating cost, and passenger acceptance.

Starting with the sketch in the upper right, the propeller and its nacelle must be designed to achieve a high level of efficiency for cruise at Mach 0.8 above 9.144 km (30 000 ft). The propeller blades are very thin and have swept leading edges in order to minimize compressibility losses. The spinner and nacelle are shaped to minimize choking and compressibility losses especially near the blade roots. Successful application of these concepts will result in a high level of propeller efficiency. This, of course, will contribute to both low fuel consumption and low operating cost, since fuel accounts for such a large fraction of operating cost.

The sketch at the lower right labeled cabin environment is a reminder that the fuselage is in the direct noise field of the propeller (whereas the inlet duct of a turbofan acts to shield the fuselage from fan noise). The propeller tips may be slightly supersonic at the Mach 0.8 cruise condition resulting in a relatively high noise level. The noise level must be attenuated by the cabin wall in order to provide a quiet cabin environment. Since it is likely that additional airframe weight will be needed to achieve the required attenuation, the quiet cabin environment is achieved at the expense of some degradation in fuel consumption and operating cost.

At the lower left, the sketch labeled installation aerodynamics depicts an accelerated, swirling propeller slipstream flowing over a wing. Here, there is a potential for higher drag which would adversely affect fuel consumption and operating cost. The increased Mach number of the flow over the wing segments washed by the propeller slipstreams and the flow rotation in the propeller slipstreams may cause large interference drag penalties in cruise. On the other hand, there is the possibility that fuel consumption and operating cost can be improved by special tailoring of the wing segments washed by the propeller slipstream. The magnitude of swirl in the propeller slipstream results in very substantial losses in propeller efficiency which are attributed to the swirl component of slipstream momentum. A properly designed wing in the slipstream can be expected to straighten the flow and to experience a corresponding thrust force. This resulting thrust force may offset or even exceed the drag penalties due to propulsion system/airframe interference. Because of the complexity of the aerodynamic processes involved, detailed wind tunnel testing will be required to provide reliable answers.

The sketch in the upper left shows the mechanical components of an advanced turboprop propulsion system. Two of the components are singled out as being especially important in achieving a low operating cost; the advanced propeller and its gearbox. Their maintenance costs must be greatly reduced relative to values experienced previously in operation of commercial turboprop aircraft. In the advanced turboprop transport studies, the estimates of propeller and gearbox maintenance costs took credit for advanced design features providing better modularity and increased mean time between failure of components. The estimates were much lower than the maintenance costs experienced on the propellers and gearboxes of the Lockheed Electra. Measures planned to reduce propeller and gearbox costs are, therefore, crucial to achieving the low operating cost potential of advanced turboprop transports.

The Advanced Turboprop Program must address all of these areas, to some extent, if the large fuel-saving potential of turboprop-powered aircraft is to be realized in the future. While not yet fully defined, a preliminary approach to the Advanced Turboprop Program is shown in figure 28.

Enabling Technology

The Enabling Technology phase is an effort that is estimated to require approximately 3 years to accomplish. This effort is in current NASA planning for initiation in FY 1978. The work labeled "propeller aerodynamic/acoustic design and test" will establish a propeller aerodynamic and acoustic design for future scale-up effort. Wind tunnel tests will be performed to determine the aerodynamic and acoustic performance of two-foot-diameter models. Since only a limited number of models can be tested, it is important to develop reliable analytical programs in conjunction with the testing to enable prediction of propeller noise and aerodynamic performance.

The next effort, called "propeller structures/materials," will establish the propeller structural design for future scale-up effort. The effort includes performing preliminary designs of advanced large-scale propeller blades; screening of blade materials and structural concepts for feasibility and aeroelastic effects; model tests of blade segments; and wind tunnel tests of propeller/nacelle models, both alone and mounted on an aircraft model, to determine aerodynamic excitations forces on the propeller blades.

Under "installation aerodynamics," analysis and wind tunnel tests will be performed to evaluate propeller-nacelle-wing interactions in order to develop a data base for propeller slipstream swirl recovery and the avoidance of excessive installation drag.

In the next effort, "cabin acoustics," there would be studies of fuselage-wall acoustic attenuation concepts, model tests of promising concepts, and an investigation of the feasibility of scaling fuselage acoustics.

The "aircraft studies" would be continued to provide guidance for the program and, as better input becomes available, to more accurately evaluate the performance and economy of future shortrange and medium-range transports powered by advanced turboprop engines. The studies to date show fuel-savings and operating-cost advantages with uncertainty bands. These bands will be narrowed as the advanced turboprop program yields more precise knowledge in such areas as propeller noise generation, engine-aircraft installation aerodynamics, and fuselage-wall noise attenuation.

Under "mechanical components and engines," existing gas-turbine shaft engines and cores of existing turbofan engines will be screened for use as large-scale propeller drives. Also, design concepts for advanced gearboxes and pitch change mechanisms will be developed and evaluated in order to select the concepts for possible follow-on efforts with large-scale components.

The Enabling Technology phase of NASA's Advanced Turboprop Program is a multicenter endeavor with the Lewis Research Center having total program responsibility. The Lewis, Ames, Langley, and Dryden Flight Research Centers will have combined in-house/contractual efforts in work areas wherein center expertise resides. In general, the required work is carried out at small scale in order to reduce costs and achieve results quickly. Another characteristic of this first phase is that theory and experiment are brought along together. This also is expected to reduce cost and should save time.

Future Plans

Based on continued success in the Enabling Technology effort, and on the usual budgetary approvals, the next step in the program would be a second phase labeled Advanced Components in figure 28. In this effort, propeller diameter would be scaled to a more realistic size over the two-foot-diameter models of the Enabling Technology effort, possibly to a diameter of 8 to 14 feet. Under "advanced propeller development," this larger diameter propeller would undergo aeroacoustic tests either in a wind tunnel or in a flight test. These tests would verify the aerodynamic and acoustic characteristics of the advanced propeller design established at the end of the Enabling Technology effort. The larger diameter propeller would be driven by a turboshaft engine derived from a current turbofan core or a modified shaft engine. By means of component static tests, an advanced large-scale gearbox and pitch-change mechanism would be developed. The continuing effort in installation aerodynamics would investigate, in the wind tunnel, the stability, control, and loads of turboprop-powered aircraft. In cabin acoustics, an acoustic design concept would be selected and investigated by way of fuselage model and segment tests. The aircraft studies would include potential commercial turboprop-powered aircraft and possible commercial-type test-bed aircraft. Finally, a test-bed aircraft would be selected for use in the next major phase of the program.

This next phase, Systems Integration, would involve flight testing of a complete turboprop engine (or engines) on a test-bed aircraft. The engine would be comprised of the large-scale components developed under the Advanced Components phase. These would be assembled with the appropriate core or shaft engine, and ground tested to evaluate component compatibility and turboprop system performance. The engine would then be mounted on an appropriate test-bed aircraft and flight tested.

Candidate test-bed aircraft might be modified first-generation jet aircraft such as the 707, the DC-8, or the CV-990. Modifications might involve moving the two inboard jets to the outboard locations. With two podded jets at each of the outboard locations, the total jet thrust of the aircraft would thus be preserved. An advanced turboprop propulsion system could then be installed at each of the inboard stations. The aircraft fuselage would be modified to incorporate the acoustic design concept developed under the Advanced Components phase. Using such a test-bed aircraft, flight tests would be conducted to evaluate and verify the system interactions of advanced turboprops. The advanced turboprops would then be operating in a real-world environment that would subject the turboprops to operational conditions such as icing, FOD, cross flow, and thrust reversing. Through these flight tests, two major goals would be demonstrated: (1) the fuel savings potential of advanced turboprops and (2) an acceptable cabin environment.

Concluding Remarks

In order to retain a viable air transportation system in the face of rising fuel prices and diminishing fuel supplies, it is very important to consider all the alternatives that could increase air transportation's energy efficiency. In the recently completed RECAT (Reduced Energy for Commercial Air Transportation) studies,[3-10] alternatives ranging from small changes in operating procedures to the introduction of new advanced technology aircraft were examined. The results of these studies (fig. 29) indicated the improvements that could be obtained by operational procedures (including flight procedures, load factor increases, seating density increases, and fleet mix) in the near-term, aircraft modifications and derivatives in the mid-term, and new advanced technology aircraft in the far-term. The fuel savings potential for an advanced turboprop-powered aircraft looks particularly attractive. If the performance and low maintenance cost goals for the prop-fan can be achieved, the operating cost savings are also significant, particularly at higher fuel prices. It has been suggested that because of the high costs associated with the development and introduction of a new aircraft, a new passenger transport will not be developed unless it offers direct operating cost savings at least 20 percent better than existing designs.[17] The advanced turboprop or prop-fan may provide a large fraction of this savings. Indeed, the advanced turboprop may be required in order to meet this requirement.

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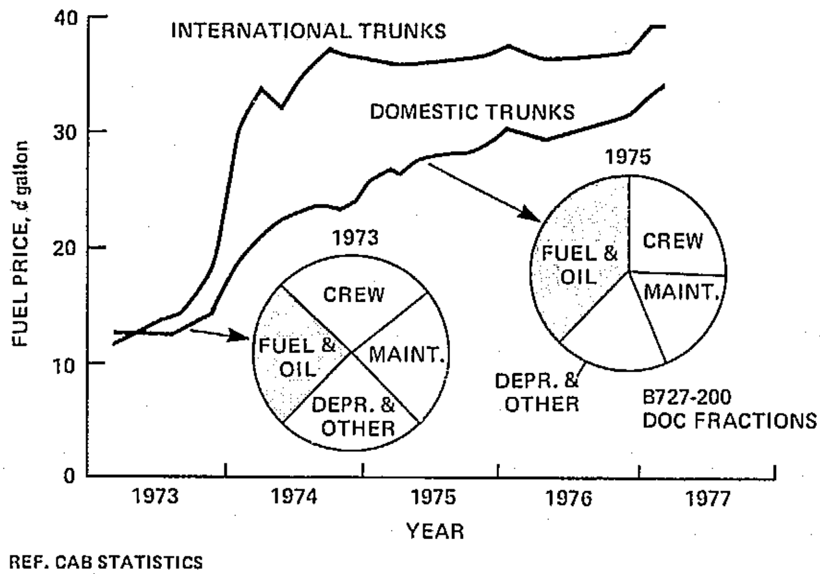

Figure 1. - U.S. airline jet fuel price. Monthly averages.

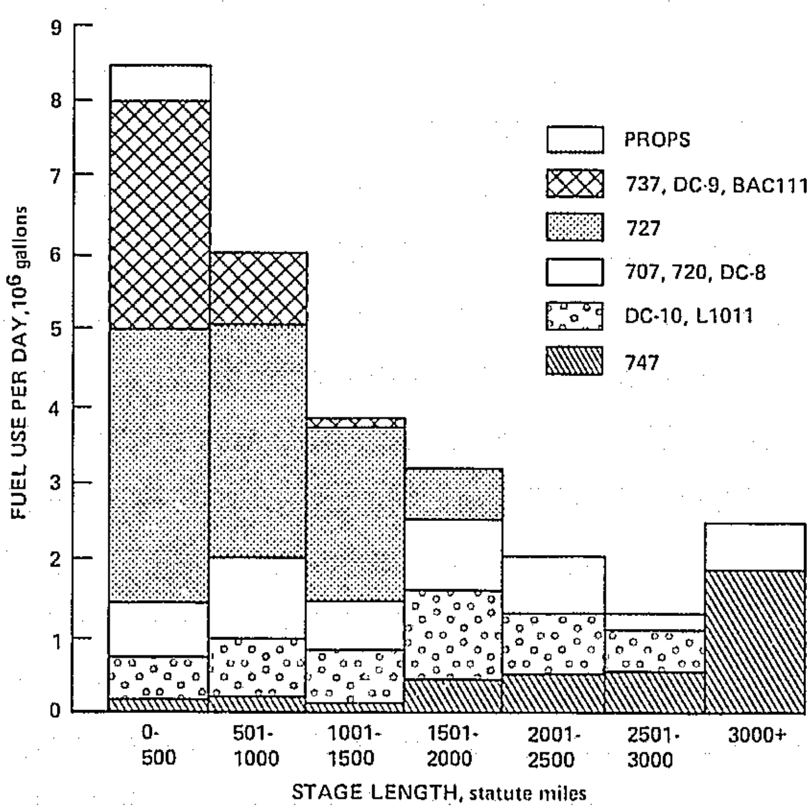

Figure 2. - Aircraft fuel usage. U.S. scheduled carriers, domestic and international operations, average for August 1976.

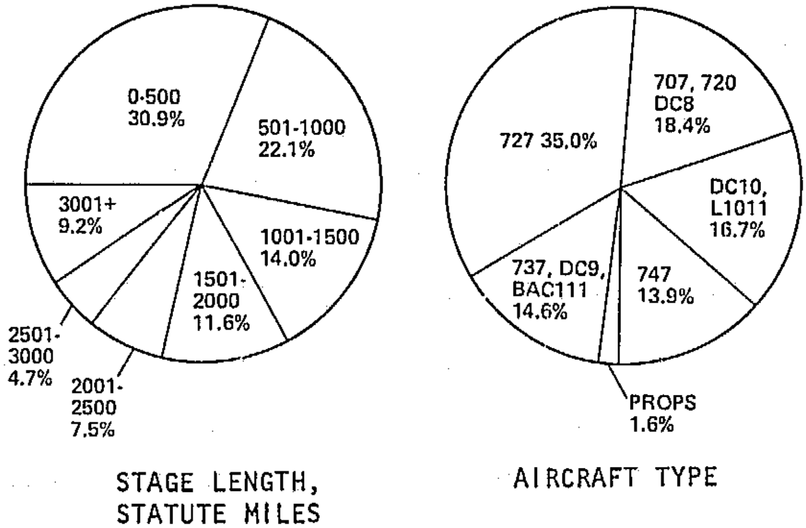

Figure 3. - Aircraft fuel use distribution. U.S. scheduled carriers, domestic and international operations, average for August 1976.

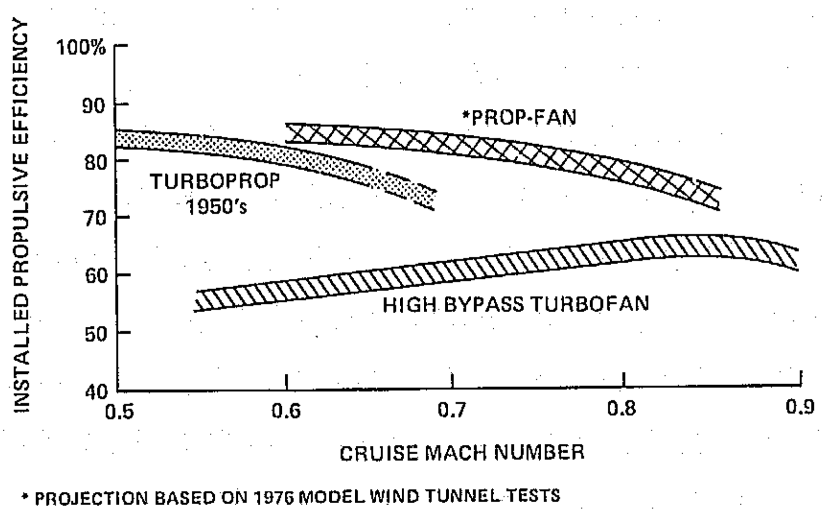

Figure 4. - Propulsive efficiency.

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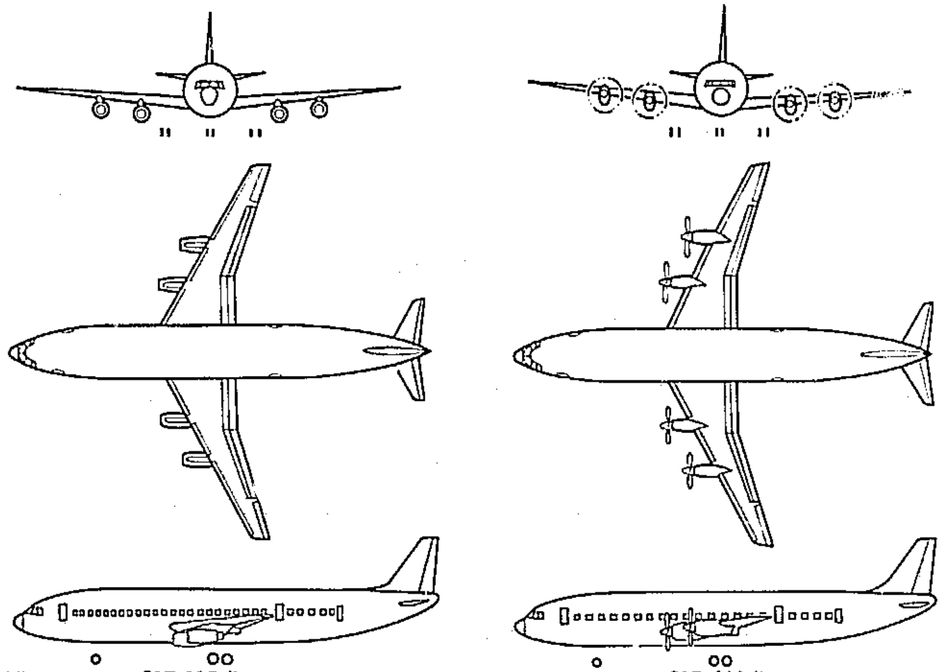
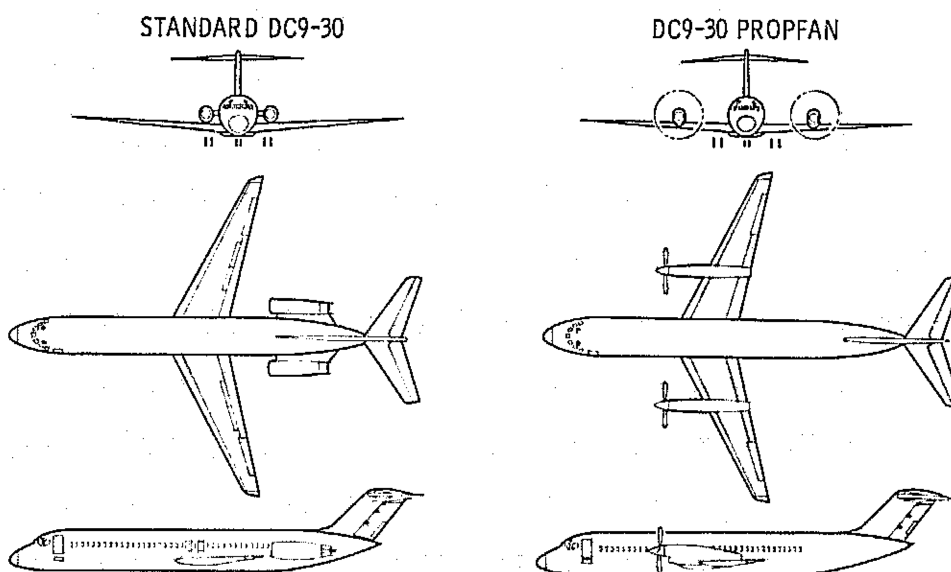


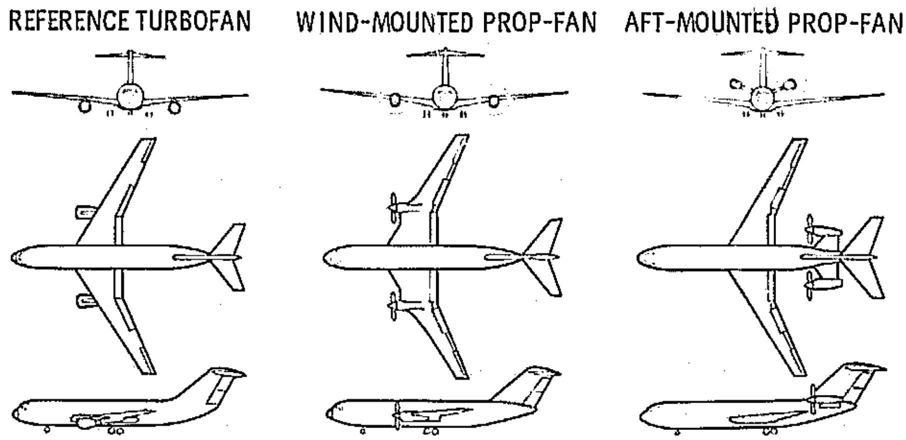
TAKEOFF WEIGHT (MAX)	217 015 lb	217 466 lb
OPERATING EMPTY WEIGHT	138 402 lb	146 417 lb
PROPULSION SYSTEM	(4) 14 672 lb SLST SCALED JT 10D-2 TURBOFANS	(4) 8 863 SHP SCALED STS 476 (REMATCH) TURBOSHAFTS DRIVING 12.6 DIA. PROPFANS

Figure 5. - Lockheed study configurations. 200 passengers, 1500 n. mi. range, Mach 0.8 cruise.



TAKEOFF WEIGHT (MAX)	108 000 lb	108 000 lb
OPERATING EMPTY WEIGHT	57 900 lb	61 220 lb
PROPULSION SYSTEMS	(2) 14 000 lb SLST JT8D-7 TURBOFANS	(2) 13 400 SHP SCALED STS 476 TURBOSHAFTS DRIVING 13 ft. DIA. PROPFANS

Figure 6. - Douglas study configurations. 92 passengers, Mach 0.8 cruise.



	REFERENCE TURBOFAN	WIND-MOUNTED PROP-FAN	AFT-MOUNTED PROP-FAN
TAKEOFF WEIGHT (MAX)	254 300 lb	269 100 lb	273 300 lb
OPERATING EMPTY WEIGHT	165 480 lb	184 550 lb	186 710 lb
PROPULSION SYSTEM	(2) 37 400 lb SLST BPR 6 TURBOFANS	(2) 30 470 SHP SCALED STS 476 TURBOSHAFTS DRIVING 19.6 ft. DIA. PROP-FANS	(2) 30 990 SHP SCALED STS 476 TURBOSHAFTS DRIVING 19.8 ft. DIA. PROP-FANS

Figure 7. - Boeing study configurations. 180 passengers, 1800 n. mi. range, Mach 0.8 cruise.

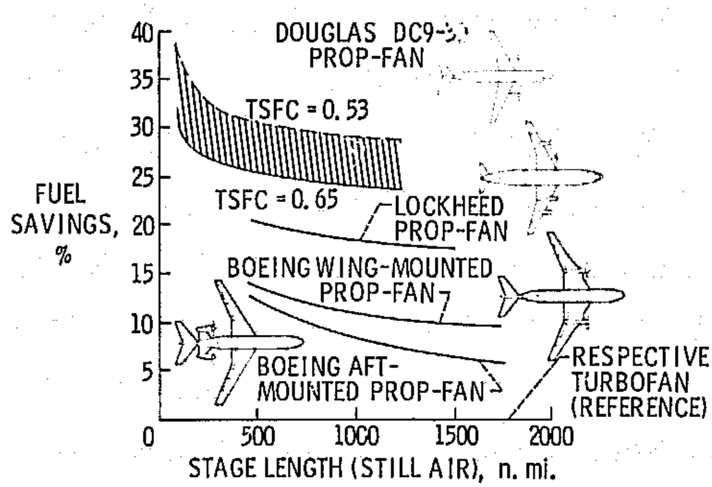


Figure 8. - Prop-fan aircraft fuel savings.

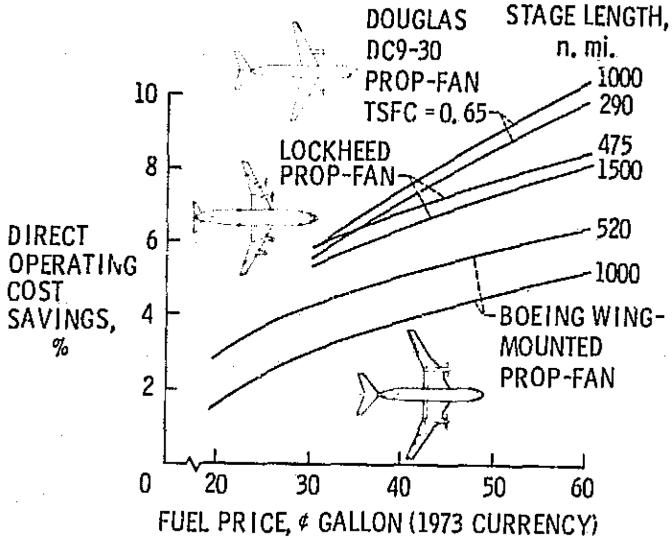


Figure 9. - Prop-fan operating cost savings.

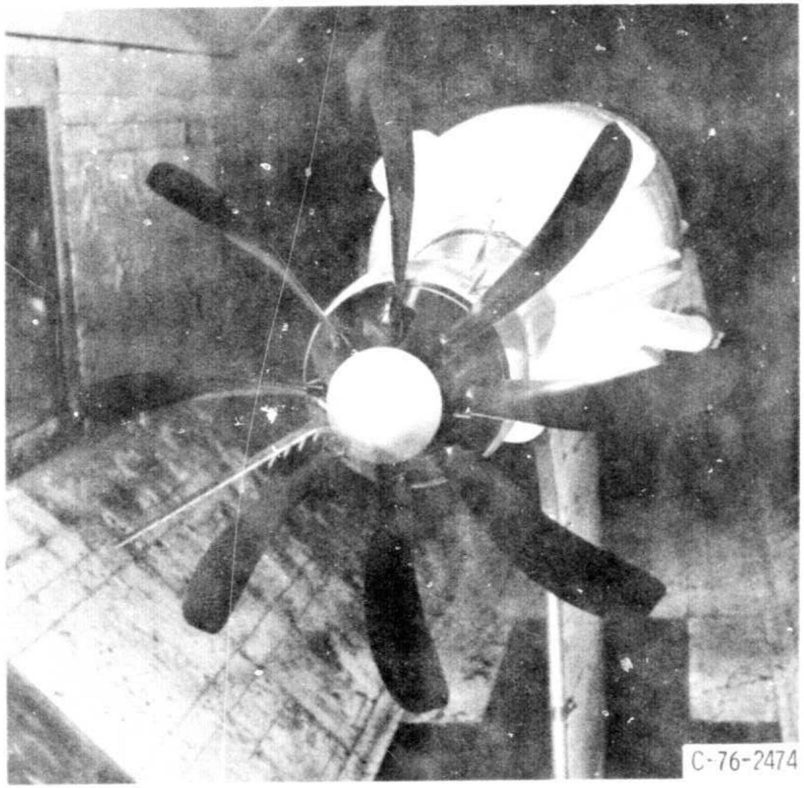
- 127 FLIGHTS/200-2300 n. mi. TRIP LENGTH/4069 RESPONSES
- RELATIVE IMPORTANCE
  1 SEATING COMFORT
  2 SPEED
  3 SMOOTHNESS
  4 RIDE
  5 QUIETNESS
  6 FLIGHT ATTENDANTS
  7 FOOD
- MOST DESIRED CHANGE – CHEAPER FARES
- LEAST ACCEPTABLE CHANGE – CLOSER SEATING
- WOULD YOU FLY A NEW TURBOPROP?

	PROBABLY OR DEFINITELY WOULD	DON'T CARE	PROBABLY OR DEFINITELY NOT
BASELINE	37%	49%	14%
FUEL SAVING	76%	17%	7%
LOWER FARES	85%	9%	6%

Figure 10. - United Airlines passenger survey.

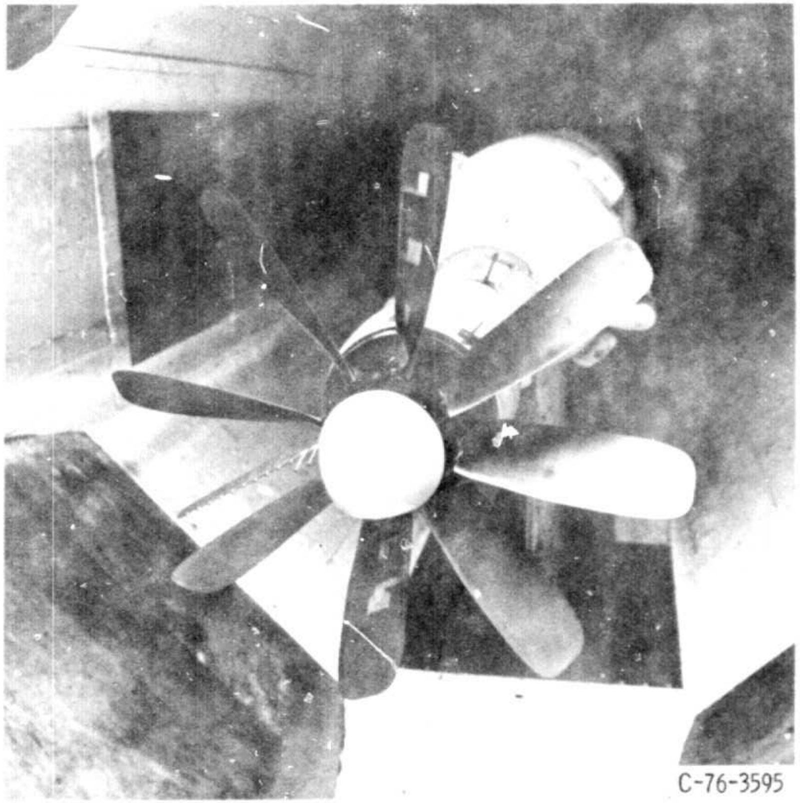
- POTENTIAL FUEL SAVINGS
  - 10 - 20% RELATIVE TO COMPARABLE TECHNOLOGY TURBOFAN
  - 20 - 40% RELATIVE TO CURRENT TURBOFAN AIRCRAFT
- POTENTIAL DIRECT OPERATING COST SAVINGS
  - 3 - 6% WITH 30 ¢/GALLON FUEL
  - 5 - 10% WITH 60 ¢/GALLON FUEL
- PASSENGER ACCEPTANCE INDICATED
- R & T RECOMMENDATIONS
  - PROPELLER EFFICIENCY
  - PROPELLER NOISE AND FUSELAGE ATTENUATION
  - AIRFRAME/ENGINE INTEGRATION
  - PROPELLER AND GEARBOX MAINTENANCE

Figure 11. - Summary of study results.



(a) SR-1, SWEPT BLADE.

Figure 12. - Propeller models in U.T.R.C. wind tunnel.



(b) SR-2, STRAIGHT BLADE.

Figure 12. - Concluded.

CONFIGURATION	DESIGN POINT NET EFFICIENCY, PERCENT	
	EXPERIMENTAL	ANALYTICAL
SR-1 (SWEPT)	78.2	79.5
SR-2 (STRAIGHT)	78.8	77.0

Figure 13. - Comparison of SR-1 and SR-2 propeller performance. UTRC 8-foot wind tunnel, Preliminary data: Mach number, 0.80; $SHP/D^2 = 37.5$ (35 000 ft alt); $C_p = 1.7$; $J = 3.06$; tip speed = 800 ft/sec

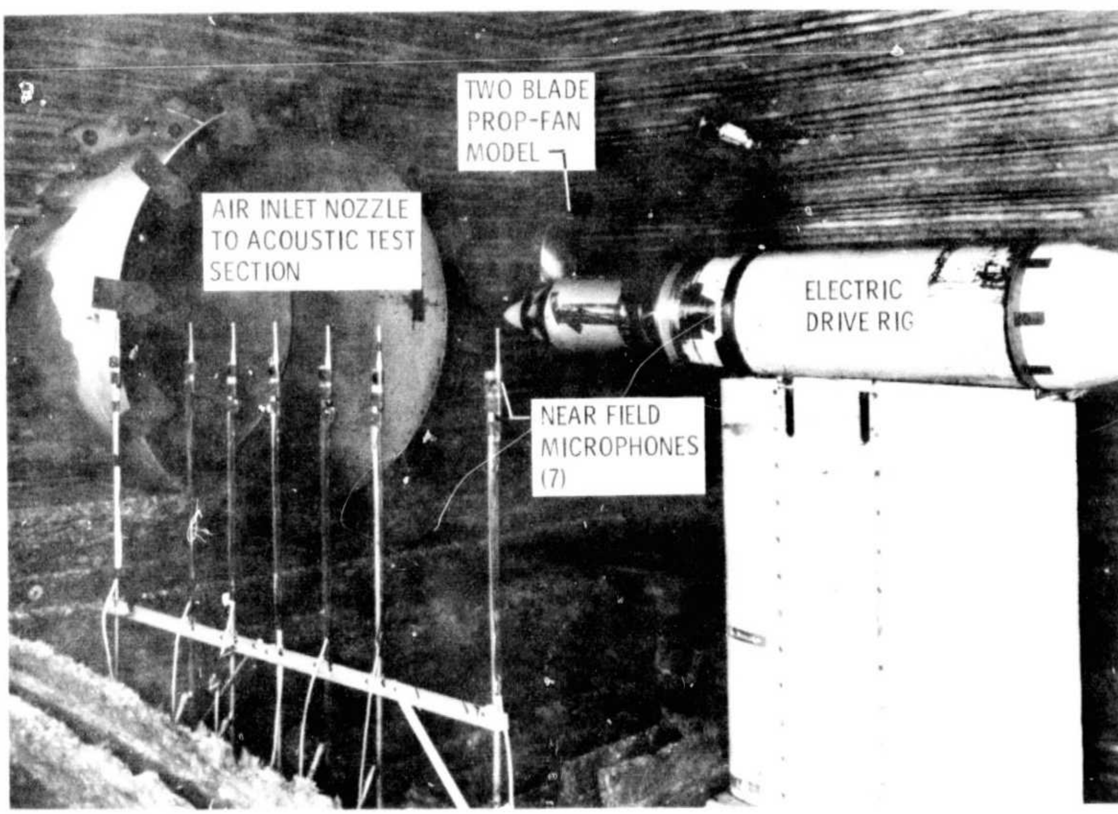


Figure 14. - Model tests in acoustic research tunnel.

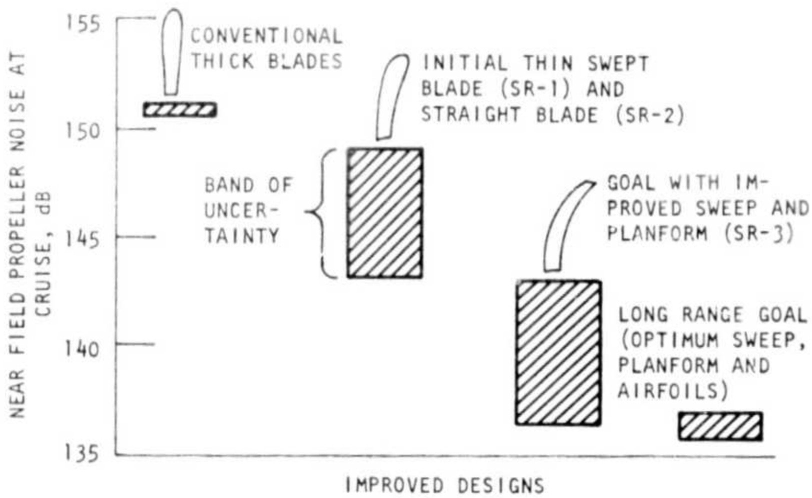


Figure 15. - Propeller noise. Tip relative Mach number greater than 1.

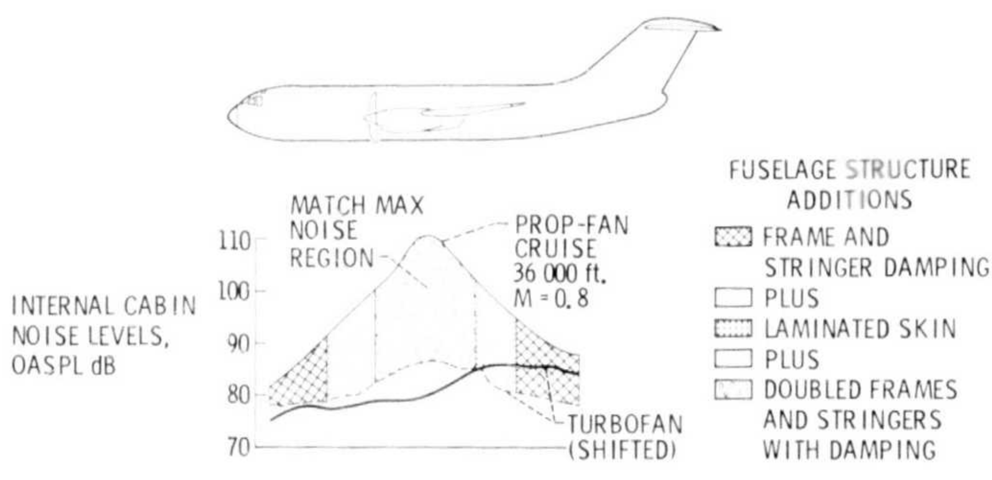


Figure 16. - Boeing wing-mounted prop-fan noise attenuation requirements. Tip clearance, 0.8 D.

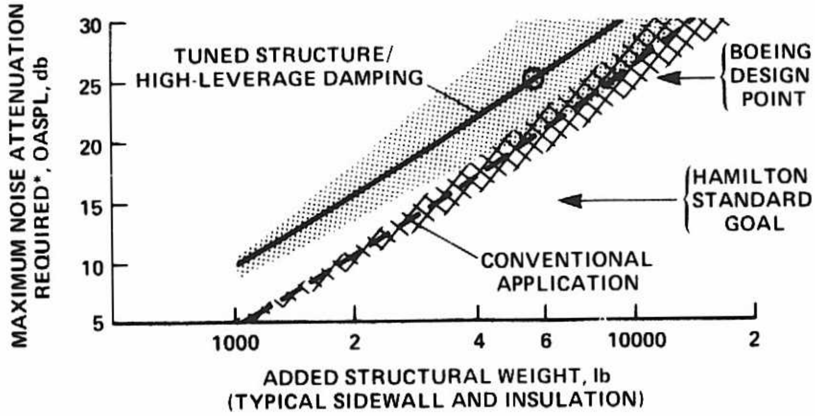


Figure 17. - Acoustic treatment weight. Boeing wing-mounted prop-fan.

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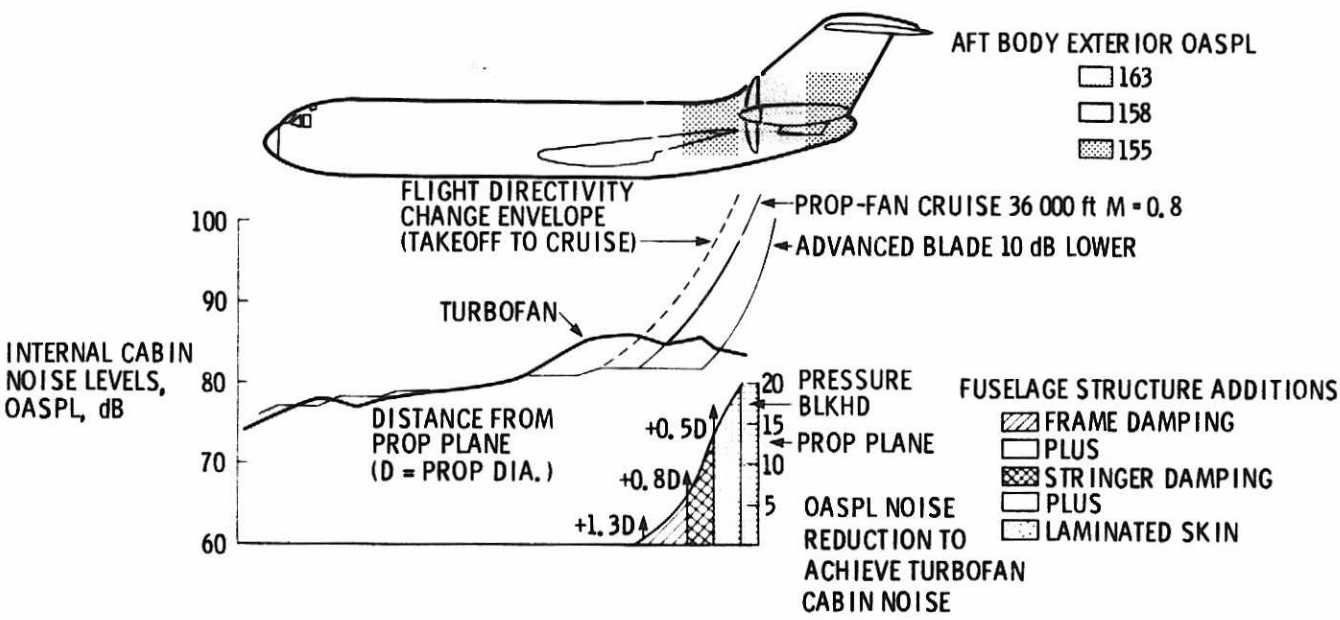
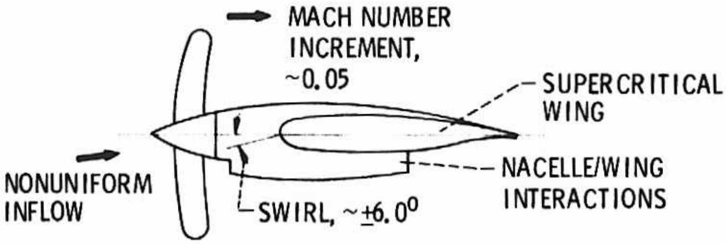


Figure 18. - Boeing aft-mounted prop-fan noise attenuation requirements. Tip clearance 0.2 D.



- ASSESS MAGNITUDE OF AERODYNAMIC INTERFERENCE
- UNDERSTAND AERODYNAMIC PHENOMENIA
- DEVELOP ANALYTICAL & EXPERIMENTAL DATA BASE

Figure 19. - Airframe-propulsion system integration program.

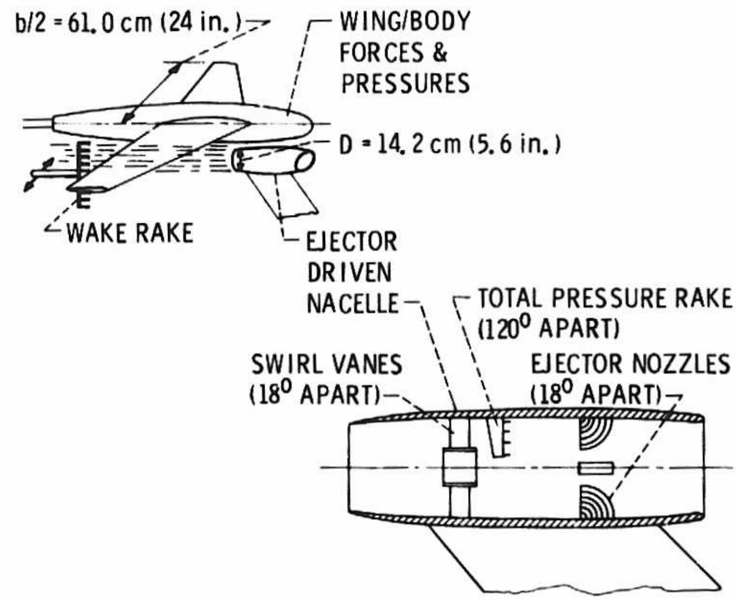


Figure 20. - Slipstream simulator.

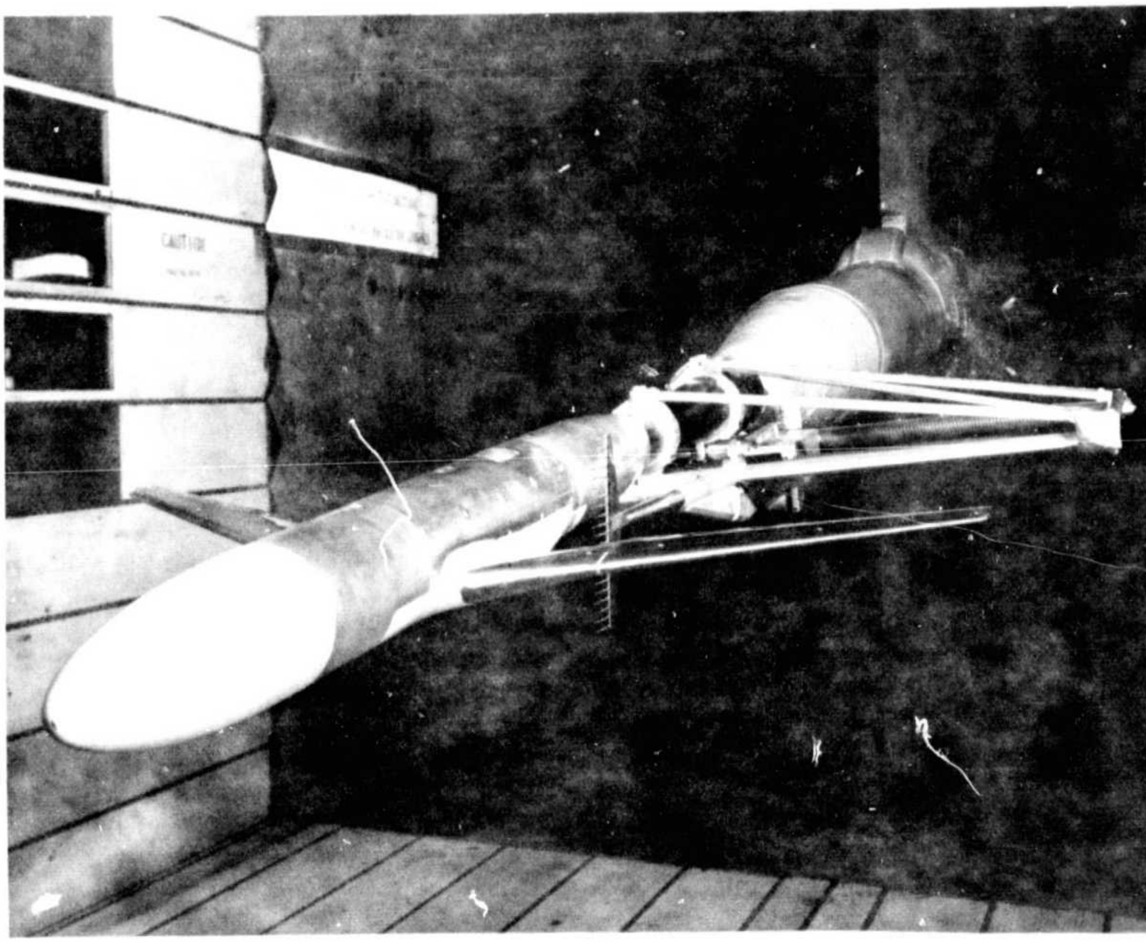


Figure 21. - Wing-body and wake rake installed in Ames 11- by 11-foot wind tunnel.

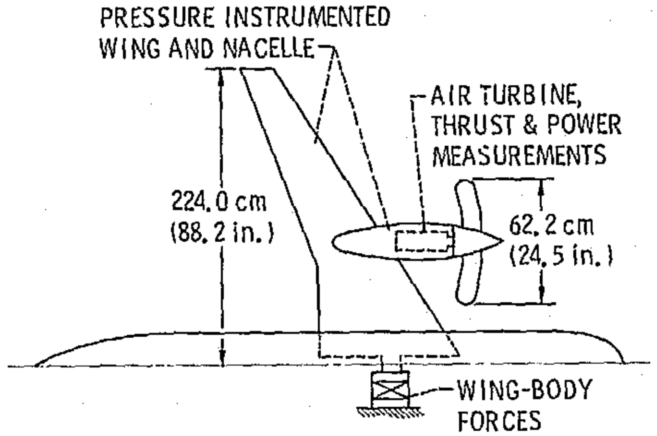


Figure 22. - Powered semi-span model.

SLIPSTREAM SIMULATOR	POWERED SEMI-SPAN
APPROXIMATE SIMULATION	COMPLETE/ACCURATE SIMULATIONS
APPROXIMATE $\Delta M + \alpha_{SWIRL}$	ACTUAL $\Delta M + \alpha_{SWIRL}$
EJECTOR WAKE	PROPELLER WAKE
INDIVIDUAL INTERACTIONS	TOTAL INTERACTIONS
α_{CRUISE}	FULL α
VARIATIONS IN SLIPSTREAM POSITION EASY	. . . DIFFICULT

Figure 23. - Relative merits of experimental techniques for propulsion system integration.

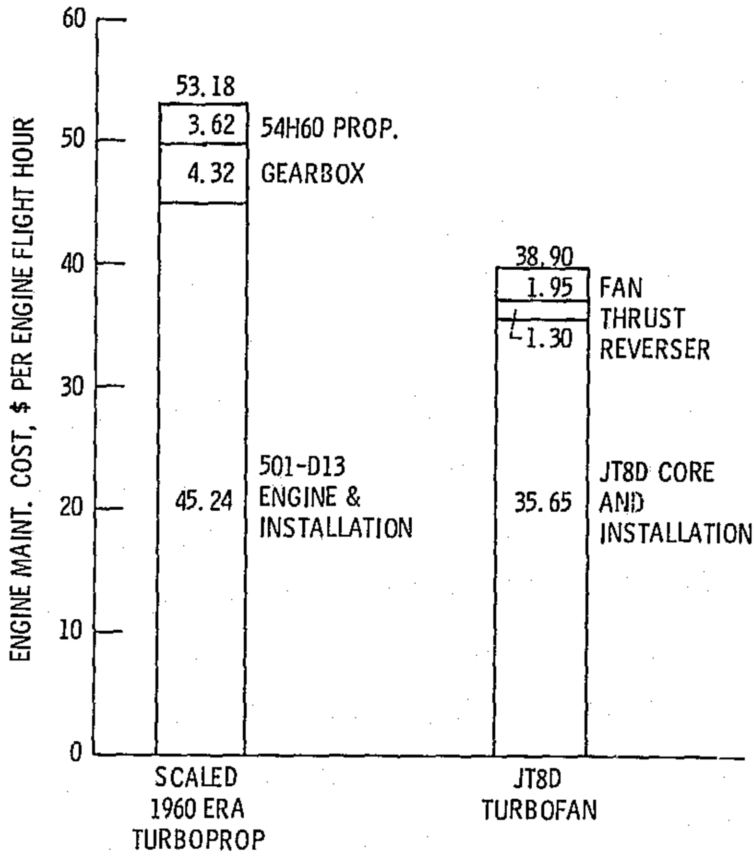


Figure 24. - Comparison of 1960 ERA turboprop and JT8D turbofan maintenance costs. B737 operations, fully burdened, CY1976 $.

	1960 ERA TURBOPROP (0.80 HR/FLT)	JT8D TURBOFAN (0.76 HR/FLT)	1990 ERA TURBOPROP (1.25 HR/FLT)
PROPELLER	3.62	NA	0.79
GEARBOX	4.32	NA	.19
ENG. & INSTALL.	45.24	35.65	17.89
FAN	NA	1.95	NA
THRUST REVERSER	NA	1.30	NA
	53.18	38.90	18.87

Figure 25. - Summary results. Fully burdened maintenance cost per engine flight hour, CY1976 $.

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OBJECTIVE

DEMONSTRATE TECHNOLOGY READINESS FOR EFFICIENT, RELIABLE, AND ACCEPTABLE OPERATION AT MACH 0.8 AND 30 000 FT ALTITUDE

GOAL

15% FUEL SAVINGS MINIMUM OVER TURBOFANS WITH EQUIVALENT LEVEL OF CORE TECHNOLOGY

Figure 26. - Advanced turboprop program.

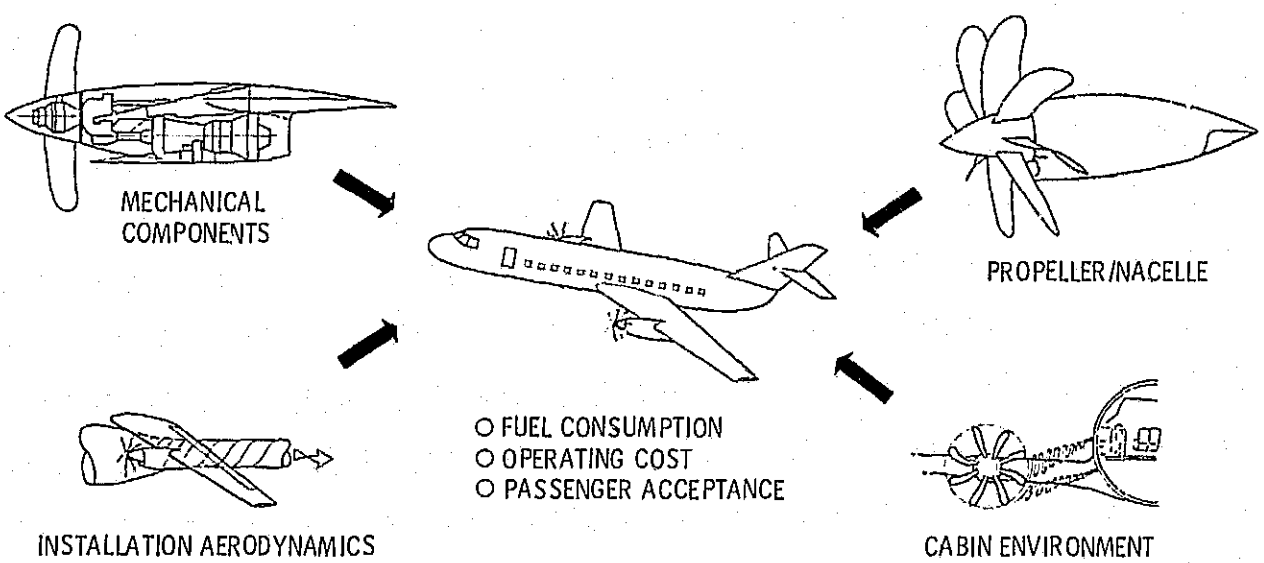

Figure 27. - Major areas of advanced turboprop program.

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ENABLING TECHNOLOGY
- PROPELLER AERO/ACOUSTIC DESIGN AND TEST
- PROPELLER STRUCTURES/MATERIALS
- INSTALLATION AERODYNAMICS
- CABIN ACOUSTICS
- AIRCRAFT STUDIES
- MECHANICAL COMPONENTS AND ENGINES

ADVANCED COMPONENTS
- ADVANCED PROPELLER DEVELOPMENT
- LARGE-SCALE PROPELLER DRIVES
- LARGE-SCALE GEARBOX/PITCH CHANGE DEVELOPMENT
- CONTINUATION OF INSTALLATION AERODYNAMICS, CABIN ACOUSTICS, AND AIRCRAFT STUDIES

SYSTEMS INTEGRATION
- ASSEMBLY AND TEST OF ADVANCED TURBOPROP PROPULSION SYSTEM
- FLIGHT TESTS OF ADVANCED TURBOPROP USING COMMERCIAL-TYPE TEST-BED AIRCRAFT

Figure 28. - Phases of advanced turboprop program.

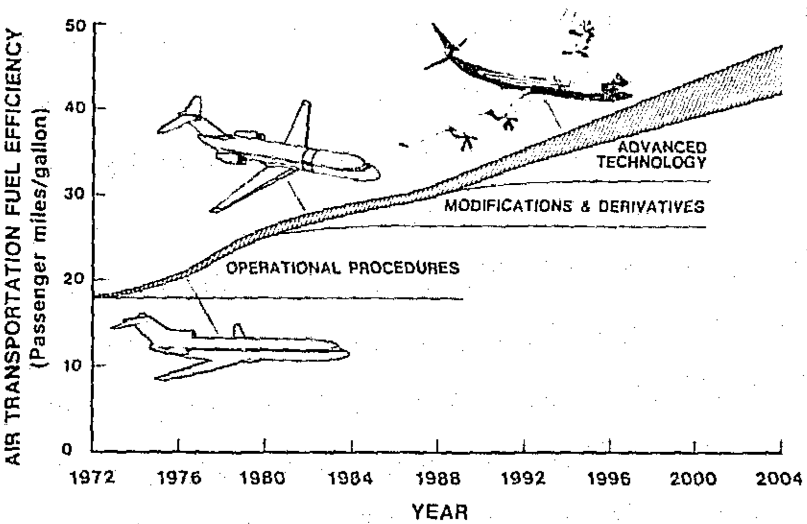

Figure 29. - Air transportation energy efficiency.