FUEL CONSERVATIVE AIRCRAFT ENGINE TECHNOLOGY

GL-01

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Abstract

A major new thrust in NASA's aeronautical research is the Aircraft Energy Efficiency Program. This program, initiated in an effort to minimize the adverse impact of the world wide fuel crisis on the aviation industry, will develop technology for more fuel-efficient subsonic transport aircraft. It includes three major propulsion projects: (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. This paper reviews each project, describes some of the technologies and recent accomplishments, and summarizes their respective status.

Introduction

Following the world fuel crisis in 1973, precipitated by the OPEC oil embargo, aviation fuel prices rapidly escalated. Figure 1 illustrates this point.(1) From 1973 to 1975, fuel prices essentially tripled. As a result, fuel cost became a much larger percentage of airplane direct operating cost (DOC). Taking the Boeing 727 as an example, fuel cost in 1973 amounted to 25 percent of DOC; by 1975 it had risen to 38 percent. For airlines to remain economically viable under such circumstances, reduced fuel consumption became a primary objective.

Projections for the future indicate that fuel will remain the most important element of aircraft operating cost.(2) This element could become even larger if fuel prices continue to increase at a rate faster than labor costs or inflation. Such escalation seems likely in view of the projected increases in air travel which are directly opposed to our dwindling supplies of petroleum - a finite natural resource. Indeed, fuel conservation in itself may become a primary consideration in the future. Although future fuel usage is uncertain, conservative projections indicate more than a doubling of the fuel required for air transportation by the year 2000.(3)

In response to the growing importance of fuel efficiency, from the standpoint of fuel conservation as well as the impact on commercial aircraft operating economics, the Aircraft Energy Efficiency (ACEE) program was formulated and implemented in 1976 by the National Aeronautics and Space Administration (NASA). This program represents an aggressive, focused approach to the development of technology for more fuel-efficient aircraft for commercial airline use. Six major technology projects constitute the program. By disciplinary area, they are:

Propulsion
- Engine Component Improvement
- Energy Efficient Engine
- Advanced Turboprop

Aerodynamics
- Energy Efficient Transport
- Laminar Flow Control

Aircraft Structures
- Composite Components and Primary Structures

Within NASA, Langley Research Center has management responsibility for the three aircraft-related projects while Lewis Research Center manages the three propulsion projects. The remainder of this paper describes these propulsion projects along with some recent results.

Engine Component Improvement

The CF6 aircraft engine manufactured by the General Electric Company and the JT8D and JT9D engines manufactured by the Pratt & Whitney Aircraft Group (fig. 2) power the majority of the commercial jet fleet. They are expected to do so throughout the 1980s. For this reason, there is a strong interest in reducing the fuel consumption of these engines, and it is toward this end that the Engine Component Improvement (ECI) project is directed.

Fuel savings can be achieved through both improved engine performance plus improved performance retention. Thus, the ECI project is divided into two subprojects: (1) Performance Improvement and (2) Engine Diagnostics. The objective of the Performance Improvement part of the project is to develop fuel saving component technology in the next few years so that the engine manufacturers can plan for certification and introduction by 1980-1982 into the JT8D, JT9D, and CF6 engines. Components could be introduced either on new production engines or through retrofit, depending on the economics. The Engine Diagnostics part is directed at identifying, quantifying, and understanding the performance degradation that occurs with operational use of the CF6 and JT9D high-bypass-ratio engines. When such data are obtained, it will be used to establish design, operational, or maintenance criteria for these engines - or future advanced engines - that would economically minimize the rate of deterioration throughout engine life.

Performance Improvement

In Performance Improvement, NASA is supporting and participating with both General Electric and Pratt & Whitney in the evaluation, selection, and technology development of a number of engine component improvements. The general approach was to first have an industry team conduct an extensive feasibility, technical, and economic analysis of component improvement concepts. Both General Electric and Pratt & Whitney were assisted by Boeing and Douglas, representing U.S. domestic operators of the engines. TWA was also used by Pratt & Whitney to perform analyses involving fleet modeling, route structures, and airline economics (such analyses were performed by Boeing and Douglas for the General Electric team). Eastern Airlines and Pan American World Airways also served as consultants to NASA to provide independent comments on the merits of the concepts, particularly in the maintenance and retrofit areas.

The feasibility analysis was started with a conceptual/preliminary design by each engine manufacturer for a number of promising concepts. These concepts were based on improvements in areas such as component aerodynamics, flowpath seals, blade tip clearance control, turbine cooling effectiveness, materials and coatings, duct/nozzle/nacelle aerodynamics, forced exhaust mixers, and controls. The initial list of concepts (over 60 at General Electric and over 100 at Pratt & Whitney) were subjected to a preliminary screening based on qualitative engineering judgment. Concepts deemed to have a small fuel saving potential, high development risk, or various practical limitations were eliminated.

Following the concept definition and initial screening, a detailed evaluation procedure was used to simulate the decision-making process that normally occurs when engine and airplane manufacturers offer new concepts or improvements to airline operators. A general flow chart for the procedure is shown in figure 3. For each remaining concept, the impact on engine price, maintenance cost, performance (thrust and specific fuel consumption), weight, and noise was established. These data were then provided to Boeing and Douglas to enable them to evaluate similar effects on their respective airplanes. Various operational assumptions (fleet models, route structures, mission profiles, engine usage rates) were also input to permit cumulative fuel savings for each concept to be estimated. The next step was evaluation of the economic impact of each concept. Various economic ground rules (useful engine life, airline capital investment hurdle rates, airline tax and depreciation structures, market projections, and fuel prices) had to be established to permit calculation of incremental direct operating costs (DOC), return on investment (ROI), and airline payback periods (the time required by an airline to recover its full investment cost). Finally, a ranking was made, with final selection by NASA, based on fuel savings, economic benefits (a concept required a minimum of 15 percent after-tax ROI or a payback period of no more than 5 to 6 years to be acceptable to the airlines), production potential, retrofit potential, development risk, development time, and cost to NASA to develop.

The above evaluation has led to identification of 17 high-payoff concepts for potential NASA support. Three concepts were identified for the JT8D, five concepts for the JT9D, and seven concepts for the CF6. In addition, two concepts which are both engine and aircraft related were identified by Douglas. All concepts had acceptable payback periods, and, in most cases, offered a high degree of retrofit potential as well as being applicable to new production engines.

The concepts are listed in figure 4. Also listed are the reductions in specific fuel consumption (SFC) at cruise and estimates of the total fuel savings which would be accrued if each concept was incorporated into new production, or retrofitted, as soon as possible. These projections involve assumptions of a 15-year new-engine life, production through 1990, various degrees of retrofit (depending on the respective concept and engine model), and - most importantly - projected fleet size. It should be noted that a few concepts, which were screened out or not selected by NASA, did have higher fuel savings (e.g., long duct mixed flow nacelles, increased fan diameter). However, such concepts did not meet the economic criteria.

The fuel savings shown on figure 4 represent a very measurable, worthwhile, and desirable gain to the airlines. In 1976, U.S. domestic trunks used 26.6 billion liters (7043 million gallons) of fuel.(4) At an average price of 8¢/liter (about 30¢/gal) the cost for fuel was over 2 billion dollars. Fuel savings of one percent would have provided a cost savings of over 21 million dollars, an amount equal to approximately 8 percent of the total after-tax income of the U.S. domestic airlines in that same time period.(5) (And, in 1975, a year of losses for the airlines, this amount would have cut their losses in half.)

Based on the results of the feasibility analysis, the selected concepts are now entering a program of rig testing, engine ground testing, and engine flight testing in order to develop their technology and verify their real potential for component improvement. Preliminary results are promising, and it appears early incorporation of these concepts into new production engines, or by retrofit, will be achieved.

Engine Diagnostics

The Engine Diagnostics activity is directed toward investigating performance deterioration of the CF6 and JT9D high-bypass-ratio engines. Deterioration occurs in service with these engines as illustrated in figure 5. During initial operation, rapid performance degradation on the order of 1 to 2 percent in SFC occurs. This is called "short term deterioration." Such degradation occurs on the first flight or flights of the aircraft as the engine structure responds to the flight environment, permitting tip rubs and seal wear, hence increasing operating clearances. In the longer term, other types of deterioration occur, such as erosion, warpage of parts, or foreign object damage, which cause another loss of 2 to 3 percent in SFC. Partial restoration of these losses is achieved as the engine is overhauled. In general, however, there is an increasing degradation in performance which is called "long-term deterioration."

Our general approach in this area is to:

(1) Gather existing flight data, ground test data, and used parts information to establish historical trends.

(2) Augment available data with new data from in-service engines, both from in-flight trending and from ground tests.

(3) Assess causes of short-term performance degradation through systematic testing of new or low-time engines.

(4) Assess causes of long-term degradation by collecting in-service trend data on high-time engines and through systematic ground tests of the same engine (both before and after refurbishment or periodic repair).

(5) Determine sensitivity and effects of deteriorated parts on performance of specific components.

(6) Establish statistical trends, analytical

models, and design criteria, with associated correlation of the impact of maintenance practices on SFC losses, and provide recommendations for both current and future engines.

Again, NASA is supported and participating with both General Electric and Pratt & Whitney in this activity. Historical performance data and trends from airlines, based on in-flight measurements as well as test stand calibrations, will be analyzed. The effect of specific repairs will be determined based on pre- and post-repair test data. Also, the condition of specific parts will be examined to determine wear and clearance changes with time, cycles of use, and performance levels. This historical data will be augmented by new, specific data from current in-service engines. For example, new JT9D engines on the Pan American 747SP aircraft will be monitored, both in-flight as well as through engine tests run while the aircraft is on the ground, to attempt to obtain more data on engine deterioration.

Specialized back-to-back testing will also be accomplished, using both low-time and high-time engines. Systematic module replacements between old and new engines and subsequent performance testing will be performed by General Electric. Pratt & Whitney will apply simulated aerodynamic loads to the JT9D nacelle and monitor the engine running clearances by X-ray techniques. Within modules, sensitivity of components to wear and erosion will be determined by both companies through back-to-back tests and measurements. Underlying this entire effort will be a continuing analytical activity to understand the data, to establish analytical models for prediction of deterioration, to evaluate the impact of maintenance procedures, and to establish design criteria for future JT9D and CF6 engine models as well as newer engines of the future.

To date, the Engine Diagnostics activity has concentrated primarily on data-gathering. Analysis of the large amount of data is still somewhat tentative and inconclusive. The historical data, as might be expected, are limited in their suitability for assessment of the specific causes of deterioration, but they are useful for establishing trends, effect of cycles versus hours of operation, and differences in engine deterioration between operators because of maintenance and repair practices. Component performance losses (and potential for recovery) versus usage are still being evaluated, and final models and design criteria will be developed as the controlled specialized back-to-back tests augment the historical data.

One example of progress in this area, however, is the development of an analytical procedure by Pratt & Whitney for predicting the effect of flight loads on short-term performance deterioration. As mentioned earlier, it is believed the primary cause of early, rapid deterioration is the increase in operating clearances due to seal wear. The analytical procedure that has been developed investigates this effect. The damage mechanism considered was the increase in local clearances caused by relative wear of rotating blade tips and stationary seals. Such wear, or interference, is considered to be caused by loads imposed through engine deflections resulting from flight loads affecting the engine-nacelle-pylon structure. The procedure starts with a flight profile description and a definition of maximum flight loads, as developed by Boeing. Pratt & Whitney then develops baseline clearances at the conditions corresponding to points in the flight profile. A NASTRAN finite element structural model, jointly developed by Pratt & Whitney and Boeing, is then used to calculate engine deflections due to the external loads - e.g., aerodynamic loads (inlet lift), maneuver loads, and thrust. Figure 6 shows the NASTRAN model. Local interferences resulting from the engine deflections (plus abradability and wear factors) then establish the new clearance. Loss in component performance is calculated from the average clearance increase, and this result is used to calculate loss in SFC.

Figure 7 compares predicted performance losses as a function of flight cycles against actual data on short-term deterioration. In this case, the model was used to predict effect of minimum and maximum build clearances on performance deterioration. Most of the actual data falls within the predicted band with the average data line showing the same increase in SFC with flight cycles as does the NASTRAN data.

Another indication of the accuracy of this model is shown in figure 8. Fan rub patterns for a Pan-American engine on the Boeing 747SP after 141 flights, and for a 747 certification engine, after 150 flights, are compared to the NASTRAN predicted fan rub wear after 150 flights. The correlation is quite good. It should be mentioned that patterns for other components did not correlate as well, although in all cases there was still a good correlation between the average actual wear and the average of the predicted wear (i.e., total area increase was correlated).

The schedule for the ECI project is shown in figure 9. In the Performance Improvement area, feasibility analyses have been completed and concept technology development is now underway. Engine diagnostics is very active, with a number of tests underway. Component sensitivity tests are in the planning stage. Short-term deterioration tests of a JT9D engine under simulated flight loading conditions, in Pratt & Whitney's X-ray test facility, are also being defined.

Energy Efficient Engine

The second ACEE propulsion effort, the Energy Efficient Engine (E^3) project, involves developing and demonstrating the technology base for achieving higher thermodynamic and propulsive efficiencies in future commercial turbofan engines. Specifically, the project is aimed at achieving technology readiness by 1983 in the areas of advanced components and systems. At that time, such technology could be selected by an engine manufacturer for incorporation into a new or derivative engine development program with an acceptable degree of risk. Derivative engines could thus appear on the market in the mid-to-late 1980s, or in new turbofan engines by the late 1980s or early 1990s - depending on the evolving airline market needs. E^3 core technology could also be used in future advanced turboprop propulsion systems.

NASA has recognized that future new engines must not only be fuel-efficient but also must be economically attractive to the airlines as well as being environmentally acceptable. For these reasons, NASA established a set of goals to provide guidance for engine cycle and concept selections and for subsequent development of E^3 component and systems technology. These goals are:

(1) There should be a significant performance improvement over current high-bypass-ratio engines. Specifically there should be (a) at least a 12 percent improvement in SFC accompanied by (b) at least a 5 percent improvement in DOC along with (c) at least 50 percent lower deterioration rates than experienced by current engines.

(2) There should be no degradation in environmental quality. Any new engines of the late 1980s or early 1990s must meet noise and emission standards that might be in force at that time. Currently, of course, the minimum standards are the FAR-36 noise requirements (as amended March 1977) and the EPA emission standards for engines certified after January 1981.

(3) There should be a thrust growth capability in the E^3 technology that reflects (a) the uncertainty as to thrust size of any future engine based on E^3 technology and (b) the realization that commercial engine models will undergo a wide range of thrust upratings and downratings. Such growth capability must be accomplished without compromising the other goals.

To arrive at engine designs to meet these goals, NASA awarded engine definition contracts to both domestic manufacturers of large commercial turbofan engines (General Electric and Pratt & Whitney). Candidate engine configurations and cycle conditions were selected by each contractor after extensive refinement and tradeoff studies.(6,7) Assistance was provided by Boeing, Douglas, and Lockheed in evaluating the impact on thrust levels, cycle conditions, and engine configuration due to integration with possible future aircraft designs. Pan American World Airways and Eastern Airlines also provide independent evaluations of the engine configurations.

Four basic types of turbofan engines were considered in these studies:

(1) Direct-drive fan with a separate core and fan stream exhaust

(2) Direct-drive fan with mixed core and fan stream exhaust (long duct nacelle)

(3) Geared fan with separate-flow exhaust

(4) Geared fan with mixed-flow exhaust (long duct nacelle).

Both engine manufacturers selected the direct-drive, mixed-flow engine configuration.

Mixers clearly provided advantages in SFC, fuel burned, DOC, and noise. For example, Pratt & Whitney (and the aircraft manufacturers who assisted them) estimated SFC advantages of 3-1/2 to 4 percent, fuel burned (block fuel) advantages of 2 to 4 percent, and DOC reductions of 1/2 to 2 percent over a separate-flow exhaust. Noise advantages over a 3/4-length duct configuration ranged from 0.4 to 1.1 EPNdB. Moreover, the mixer was considered a mechanically simple, high reliability system of low development risk.

The geared engine versus direct-drive engine evaluation was not as conclusive, particularly for fuel burned and DOC. Fuel burned for geared engines was sensitive to gearbox efficiency and weight, while DOC was sensitive to initial cost, maintenance cost (e.g., gear replacement frequency), and fuel burned. For a range of reasonable estimates for these values, a wide-spread variation in fuel burned and DOC was achieved, particularly when both U.S. domestic and international missions were considered. Typically, however, there was always a DOC penalty for the geared versus direct-drive engine case. Also, it was believed that (a) the high degree of mechanical complexity of a geared engine (e.g., in addition to the gearbox, more main bearings were required), coupled with (b) the relatively unknown and unpredictable durability and reliability of a lightweight, high-power gearbox under flight load conditions, would require a very extensive and expensive commercial development program to substantiate gearing durability for a future commercial energy efficient engine. The impact of the large performance sensitivities, giving marginal or no benefits under some circumstances, along with the mechanical uncertainties which could affect future commercial acceptability, led to selection of the direct-drive engine configuration for the E^3 program.

A wide variety of engine cycles were assessed in the engine definition studies. The selected cycles are shown in figure 10 in comparison to the current production engines used as reference engines in estimating performance improvements of the E^3 design. Improvements in all areas were realized, leading to the desired improvements in thermodynamic and propulsive efficiencies. The cycle conditions as shown in figure 10 are based on extensive optimization and tradeoff studies of the effect on fuel burned and DOC when varying parameters such as overall pressure ratio, turbine inlet temperature, and bypass ratio. The cycles selected are not the optimum from the standpoint of fuel efficiency alone. It was recognized that engine first cost, life. and maintenance cost must be traded off against fuel efficiency, while also providing for a realistic growth margin if a cost effective airline acceptable design is to be the final result.

Associated with the engine cycles are advancements and improved efficiencies in every component. While the selected engine design of each engine manufacturer was the same (two-spool, direct-drive, mixed-flow exhaust), each had different approaches to component design, reflecting his own level of component technology. Figure 11 illustrates the engine design configuration of General Electric. Some of the major advanced technology features are also indicated on the figure.

The fan is an advanced aerodynamic design with mid-span dampers located near the trailing edge of the titanium blades. A fan hub quarter-stage booster is used to permit low fan tip speeds for best fan performance while maintaining proper core boost pressure at a high efficiency. The booster also offers a reduction in foreign object damage to the core by allowing such objects to be centrifuged into the bypass stream. The high-pressure compressor is an extremely advanced machine incorporating high efficiency, low aspect ratio (long chord) blades to minimize number of blades and to provide ruggedness for reduced performance deterioration with time (both factors in maintenance cost). Active clearance control is used for the last five stages, while the inlet guide vanes and first four vane rows are variable. The basic design of the compressor was based on the NASA Advanced Multi-Stage Axial Flow Core Compressor Program.

The combustor is a double-annular, low emission design derived from the NASA Experimental Clean Combustor Program. This design concept provides the staged burning necessary to meet emissions requirements, but in a short compact design. The high-pressure turbine is a two-stage, cooled, high efficiency design incorporating ceramic tip shrouds and active clearance control. Directionally solidified René 150 material is planned for the airfoils, along with improved cooling technology. The low-pressure turbine is a five-stage uncooled design. Improvements were projected as a result of improved concentricity, sealing, and roundness control (e.g., an unsplit impingement cooled case is used). The mixer consists of 24 chutes contoured for effective, low-loss mixing of the hot, high velocity core gas with the low-velocity fan stream.

The Pratt & Whitney configuration is illustrated in figure 12, along with associated key component technologies. The fan is a single-stage, shroudless design with hollow-titanium blades having an aspect ratio of 2.8. A four-stage, 1.77 pressure ratio low-pressure compressor supercharges the core. It uses supercritical, canted airfoils to minimize losses and provide high surge margin. The high-pressure compressor is a high inlet corrected tip speed design with low aspect ratio (1.7:1 average) blades and variable stators in the first four stages. The rotor tips extend into grooves (trenches) in the abradable rub strips for reduced losses. A modulated, active clearance control system is used on the last seven stages. Multiple circular arc airfoils are used for the supersonic and transonic front stages, while supercritical airfoils are used for the rear stages.

The combustor is a low emissions vorbix (staged vortex burning and mixing) design using two axial stages. It is derived from the NASA Experimental Clean Combustor Program. The high-pressure turbine is a single-stage design with single crystal alloy blades permitting high metal temperatures, hence minimizing compressor bleed cooling air. High efficiencies are expected, with the design incorporating large annulus area, low loading coefficients, high rotor speed, high rim speed, contoured endwalls, preswirled coolant flow injection, hot/cold modulated active clearance control, and ceramic outer air seals coupled with abrasive blade tips. The low-pressure turbine has four uncooled stages and is counterrotating relative to the high-pressure turbine to reduce camber of the first-stage airfoils and improve performance. It also has active clearance control. To reduce weight, the rear stages will be fabricated from titanium aluminide. The mixer consists of a 12-lobe scalloped configuration. A flight mixer would be made in one piece through superplactic forming and diffusion bonding of titanium.

Both engine manufacturers paid particular attention in their designs to minimizing performance deterioration and maintenance costs. Both engine configurations feature a short, stiff, straddle mounted core with easily accessible bearing compartments. Both used five main bearings and two bearing compartments. Special attention has been given to structural load carrying to minimize engine bending forces encountered furing flight. Structurally integrated composite fan ducts, core cowls, and fan frames are used to stiffen the engine cases and reduce inner casing distortions. Nacelle load-sharing is augmented by extensive use of active clearance controls on the compressor, high-pressure turbine, and low-pressure turbine. This permits clearances to be opened up at operating conditions where maximum flight loads and critical transients occur, while permitting tighter clearances during cruise - hence increased efficiency. Another contributing item to reduction of maintenance costs and weight is the large reduction in number of airfoils, primarily in the hot section for Pratt & Whitney and in the compression system of the General Electric design, as compared to the reference engines. This occurs because of the use of low-aspect-ratio blading as well as a reduction in number of stages.

Acoustic reduction features of the two engine designs are also similar. A large chord-spacing is used between the fan rotor and outlet guide vanes to minimize fan noise. The mixer is expected to reduce jet noise considerably. Low-pressure turbine noise is reduced by selection of numbers of blades. Extensive nacelle treatment is utilized in the fan inlet and along the fan duct walls.

The conceptual engine designs offer the potential for exceeding the SFC and DOC goals established by NASA for the E^3 project. Predicted benefits are summarized in figure 13. These values reflect the projections of both engine manufacturers as well as the aircraft manufacturers. As can be seen, the goals are exceeded in all cases. Other goals for performance deterioration, emissions, noise, and growth capability were also exceeded, hence providing margin for an advanced technology program such as the E^3 project.

These engine definition studies established the basic design parameters around which the current component development and integration program was planned. Schedules for the current activity are shown in figure 14 for both contractors, showing the major project elements. A continuing design and analysis effort will be conducted to support the component, core, and integrated core/low spool efforts and to use data from those efforts for refinements of the previous engine definition studies.

The component technology and development activity will be conducted on all components of the engine (excluding the composite nacelle which is not a part of the experimental effort of the E^3 project). When sufficiently developed, the high pressure components will be assembled and tested to evaluate component interactions and core performance. Upon satisfactory core demonstration, the low-spool components (fan, low-pressure turbine, and mixer) will be assembled with the core and a metal boilerplate nacelle. This integrated package will then be tested to evaluate uninstalled performance, interaction, and mechanical systems (e.g., active clearance control) operating characteristics.

Advanced Turboprops

The third ACEE propulsion effort is the Advanced Turboprop project. This project has the objective of providing technology readiness for efficient, economic, and acceptable operation of turboprop-powered commercial transports at cruise speeds up to Mach 0.8 and at altitudes above 9144 m (30 000 ft). This technology would also apply to cargo aircraft, short-haul operation, and to new military aircraft requiring long-range and long-endurance subsonic capability. The goal is to achieve at least a 15 percent fuel savings relative to a turbofan engine with an equivalent level of core technology. This goal, of course, must be achieved with a cabin environment which is acceptable (i.e., as comfortable and quiet as today's jet-powered commercial transports).

Previously, in the 1950s, turboprop-powered aircraft were in commercial service at speeds of Mach 0.6 to 0.65 and at altitudes about 7600 m (25 000 ft). These were replaced by jet-powered aircraft which offered higher speed, above-the-weather cruise, better passenger comfort, and simpler maintenance. In an era of inexpensive fuel, efficiency was not a critical factor and was offset by the higher productivity of the jets. Now, however, the application of several advanced technologies (e.g., advanced aerodynamic capabilities and understanding; improved structural concepts permitting thin, high-speed, swept-tip blade fabrication; etc.) permits the turboprop propulsion system to once again be considered. An example of this evolution in turboprops, in this case a scale model mounted in the Lewis Research Center 8- by 6-foot wind tunnel, is shown in figure 15.

A number of aircraft and propulsion system studies have indicated the potential of this concept.(8-19) Results from three of the earlier studies are shown in figures 16 and 17. Boeing and Lockheed examined 1985 technology level turboshaft engines versus equivalent technology level turbofan engines (i.e., JT10D level of technology). The Boeing aircraft design was based on 1976 technology levels, while Lockheed used 1985 technology levels (i.e., supercritical airfoil, active controls, etc.). Douglas used the DC9-30 as a basis of comparison and compared both current technology level turboshaft engines (TSFC=0.65) and 1985 technology level engines (TSFC=0.53) to the current DC9-30 configuration using low-bypass-ratio JT8D turbofan engines. As can be seen, a wide spread in fuel savings and DOC was achieved, reflecting various assumptions (e.g., propeller efficiency, fuselage concepts and weight for noise attenuation, aircraft configurations, design stage lengths, maintenance costs, etc.) of the three different approaches. In all cases, however, there is a very significant improvement for the turboprop-powered aircraft as compared to the turbofan-powered aircraft. This is especially true at the shorter stage lengths and is one reason why advanced turboprops look particularly attractive for the short- and medium-range flight markets currently being served by the DC-9, B-737, and B-727 aircraft.

These studies identified four major areas as being important for low fuel consumption, low operating cost, and passenger acceptance. These areas - propeller/nacelle, cabin environment, installation aerodynamics, and mechanical components - are all being addressed in Phase I of the Advanced Turboprop project. This phase is an enabling technology effort, directed at evaluation of concepts, development of theory, and acquiring supporting data for the four key technical areas. Lewis Research Center manages this effort with support of Ames (Installation aerodynamics and aircraft studies), Dryden (flight testing), and Langley (cabin environment).

In the propeller/nacelle area, the goals are to establish aerodynamic and acoustic design methodologies for high-speed propellers (and associated nacelle and engine inlet) and to select a viable baseline propeller design (including fabrication technique) for future phases in which effects of scaling will be evaluated. For the cabin environment area, the goals are to identify merits and tradeoff characteristics of various fuselage noise attenuation concepts along with identification of the impact of propeller noise characteristics on fuselage design. Efforts in installation aerodynamics will establish the effect and extent of propeller/nacelle/wing interactions and will identify improvements available through nacelle/wing tailoring. Finally, mechanical component goals are to establish conceptual designs for turboprop engines with improved gearboxes and pitch change mechanisms, and to identify potential improvements relating to the reliability and maintenance costs. Some results and status of the areas are described as follows.

Propeller/Nacelle

The propeller and its nacelle must be designed to achieve high efficiency at cruise speeds up to Mach 0.8 and 9144 m (30 000 ft) altitude. The propeller blades must be very thin and will require swept leading edges in order to minimize compressibility losses. The spinner and nacelle will require shapping to minimize choking and compressibility losses, especially near the blade roots.

At this time, four propeller models have been tested (designated by the model numbers SR-1, SR-1M, SR-2, and SR-3). These models were all 62.23 cm (24.5 in.) diameter and were designed by Hamilton Standard under contract to Lewis Research Center. Planform and significant design characteristics are shown in figure 18. The models all had eight blades and were designed to operate at Mach 0.8, a tip speed of 244 m/sec (800 ft/sec), and a disk power loading of 301 kW/m^2 (37.5 shp/ft^2). Tip sweep was varied, however, for values of 0° (SR-2), 30° (SR-1, SR-1M), and 45° (SR-3) as shown in figure 19. SR-2 was basically a baseline design against which the effects of sweep were to be evaluated. SR-1 and SR-1M differed primarily in the blade twist and camber distribution from hub to tip. SR-1 was modified into SR-1M when results of initial wind tunnel testing showed radial loading differed from design distribution. The changes were designed to increase loading in the outboad region of the blade. SR-3 was the first model to be designed with acoustic consideration (fig. 15). Because of this and other refinements in the blade design procedures (taking advantage of previous testing on SR-1, -1M, and -2), the design efficiency of SR-3 was higher and the estimated cruise near-field noise level was lower than for the other designs. Two types of spinners were also designed and tested - one was conical and the other was area ruled to lower flow velocities in the hub region where choking could be a problem.

Initial testing of SR-1 and SR-2 was conducted by Hamilton Standard (under NASA contract) in a wind tunnel at United Technologies Research Center.(20,21) These tests gave the first experimental confirmation of the expected propulsive efficiency gains for advanced turboprops. A comparison to 1950-era turboprops (e.g., Lockheed Electra) and to high-bypass-ratio turbofans is shown in figure 20.

Subsequently, all models have been tested in the Lewis Research Center 8- by 6-foot wind tunnel. Test data are shown in figure 21 for a range of Mach numbers. SR-3 is seen to have the best performance above Mach 0.75. Also, preliminary results indicate the predicted reduction in noise was achieved. Further, the area-ruled spinner performed better than the conical spinner. (Note that retwisting of SR-1 to SR-1M did not affect the performance at the design Mach number as predicted.) Other tests, not shown, varied tip speed and power loading from design conditions. Efficiencies above 80 percent were achieved with the lower power loadings (but in actual operation, this would give a larger propeller diameter which must be considered in the aircraft optimization).

Other propeller models are currently in the program to investigate effects of designing for different tip speed, loading, and number of blades, along with advanced airfoils. Results to date, however, from an efficiency standpoint, are considered promising. The previously mentioned studies assumed a value of 80 percent for propeller efficiency. Improvements continue to be made in propeller aerodynamic design methodology based on test results and analysis. Such improvements are expected to result in achieving or bettering the value of 80 percent efficiency at design loading and Mach number. Results, as they are obtained, will also continue to be factored into aircraft studies to provide guidance as to the optimum design conditions.

In addition to the propeller effort directed at efficiency, work is also planned to evaluate propeller fabrication and aeroelasticity. The basis approach to construction of the thin, highly-swept blades is to use modifications of the metal spar-composite shell approach as commercially developed by Hamilton Standard. Fabrication samples and aeroelastic models will establish the feasibility of using this or other methods.

Cabin Environment

To be competitive with turbofan aircraft, cabin environment during cruise for an advanced turboprop aircraft should be equivalent in noise and vibration. The noise perceived by the passenger inside the cabin is a strong function not only of the noise generated by the propellers but also of the noise attenuated by the fuselage. Since the propeller tips may be slightly supersonic at the Mach 0.8 cruise condition, the resulting near-field noise level is expected to be quite high. Thus, it is likely that additional airfram weight (over a turbofan-powered aircraft) will be required to achieve the required attenuation. The quiet cabin environment is thus achieved at the expense of fuel economy.

Currently, there are four approaches to this problem: (1) Design propeller tip speed can be reduced to lower the noise generated by the propeller. (2) Fuselage design and can acoustic treatment can be improved over conventional techniques to increase noise attenuation. (3) The propeller and fuselage design can be integrated in the selection of propeller blade passing frequency and fuselage acoustic modes. (4) Finally, the engine location on the aircraft can be optimized; for example, mounting the engines farther outboard on the wing, or on the aft end of the fuselage behind the passenger cabin, would result in less cabin noise. All four approaches, which affect propeller efficiency, diameter, and weight, will require extensive aircraft optimizations and tradeoff studies. First, however, near-field noise data on propellers, as influenced by design parameters, is required.

To obtain high quality acoustic data with respect to noise level, spectral content, and directionality, NASA is planning to conduct flight tests of the 62.23 cm (24.5 in.) diameter propeller models on a JetStar aircraft (fig. 22). The models would be mounted above the fuselage, which would be instrumented with microphones. This approach has been taken because of the uncertainty of high-speed wind-tunnel acoustic data with respect to both level and directionality. Also, such uncertainty is extremely difficult to quantify without comparison to flight data.

For fuselage attenuation, three different fuselage structural concepts have been suggested to date. A conventional fuselage is believed to attenuate noise as shown in figure 23. The least attenuation occurs in the frequency range of several hundred hertz. Unfortunately, the blade passing frequencies of many propeller designs fall in this range. The three concepts to resolve this problem are: (1) Structural tuning and damping, which seems to apply at the blade passing frequencies of current propeller designs; (2) Increasing fuselage stiffness, which is more effective at lower frequencies as could be achieved by lower propeller tip speeds (and, of course, lower tip speeds are also an effective way to reduce propeller generated noise); and (3) Using a double-limp-wall approach to lowering resonant frequencies while increasing damping. This latter concept is more effective with higher blade passing frequencies as could be achieved with increased number of blades. Current plans are to analyze these concepts and run model or panel tests for screening their effectiveness in providing maximum noise attenuation with minimum weight penalty.

Installation Aerodynamics

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 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. 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 propulsion system, a combined experimental and analytical research program has been initiated by Ames Research Center. Both a slipstream simulator model and a powered semispan model will be tested. To date, only preliminary results from tests of the slipstream simulator in the Ames 14-foot wind-tunnel are available (fig. 24). These results do show that the drag penalties associated with the interaction of a turboprop slipstream and a supercritical wing are not excessive, and that the potential does exist to recover some of the propeller swirl losses with the wing. The reason for the apparent anomaly at a 6° swirl is not known, but it will be investigated further with the powered semispan model tests.

Mechanical Components

The fourth area to be addressed in the Advanced Turboprop project involves evaluation of the reliability maintenance costs of the advanced propeller and gearbox, along with conceptual screening and designs for advanced gearboxes, pitch change mechanisms, and engine drive systems. To date, a study of turboprop reliability and maintenance costs has been completed by Detroit Diesel Allison (DDA) under contract to Lewis Research Center.(22) The objectives were to determine actual maintenance costs of past turboprop systems and then project such costs for new turboprop systems in the 1985-1990 time period. Hamilton Standard assisted in the evaluation of the propeller data. The aircraft involved were the Lockheed L188 Electra, Convair CV580, and Lockheed L382 Hercules. These were all powered by the DDA 501-D13 turboshaft engine and either the DDA 606 propeller or the HS 54H60 propeller. Data was obtained from airline records, outside repair facilities, CAB form 41, and the DDA reliability and maintenance department records.

Figure 25 shows the results of this study, as compared to the fully burdened maintenance cost of the JT8D turbofan that powers the B-737 aircraft. In this comparison, the actual turboprop maintenance cost of $42.30 per flight hour in CY 1976 dollars was scaled to $53.18 to reflect the scaling of the turboprop to a thrust capability equal to the JT8D turbofan at Mach 0.8 and 10 670 m (35 000 ft) altitude. It can be seen that the bulk of the maintenance costs reflect the older technology core of the DDA501-D13 engine, although there is still a substantial difference between the propeller/gearbox and fan/thrust reverser. For future engine systems, it can be assumed that the maintenance cost of the core will be no greater for a turboprop than for a turbofan if the same level of technology is used. Thus, if turboprop maintenance costs are to be comparable to those of a turbofan engine, the propeller/gearbox maintenance costs must be reduced to the level of the fan/thrust reverser.

Various cost drivers and design features of the 501-D13/54H60 system were examined to determine where maintenance cost savings could be expected. Then, unburdened costs for that system were projected to an advanced design of 1990, assuming that various design features were incorporated (fig. 26).

Elimination of scheduled removals accounted for 60-percent of the cost saving. Modularity in design contributed another large fraction. For the gearbox, other items included provision for more modern design features such as longer life bearings, removing engine accessories from the gearbox and mounting them on the core as is the case for a turbofan, and using a single shaft drive for aircraft accessories. With all these features, the unburdened maintenance costs were projected to be $0.73, about a six to one reduction.

Values of this order were used in the advanced turboprop aircraft studies previously described. Since such costs could be higher in actual practice, the affect on DOC of doubling the maintenance costs was evaluated using data from two of the studies.(14,19) As shown in figure 26, the effect is small.

Future Effort

Currently, NASA is in Phase I of a multiphased Advanced Turboprop program. Phase I is an enabling technology phase that is estimated to require about 3 years to accomplish. Effort in all four of the major technical areas is being conducted, as previously described. Future phases, to fully establish technology readiness, will evaluate scale effects relative to propeller generated noise, fuselage noise attenuation concepts, propeller flutter, and propeller fabrication. Flight testing will be required to achieve viable data in these areas and to evaluate system interactions under flight operational conditions. In this way, the potential of the advanced turboprop system relative to fuel savings and cabin environment can be established for commercial acceptance.

Concluding Remarks

Potential benefits of the three ACEE propulsion efforts for commercial air transports are shown in figure 28. In ECI, as much as 5 percent fuel savings and 3 percent DOC reduction can be realized by the early 1980s, thus being very applicable to the near-term needs of the airlines. E^3 benefits represent a major reduction in fuel savings and DOC and could be realized in the late 1980s in new engines or in derivative engines by the middle 1980s. Advanced turboprop benefits might be achieved by the late 1980s or early 1990s and represent the largest potential of any ACEE project. Indeed, the advanced turboprop provides an almost unmatched technological opportunity, possibly leading to a step gain in subsonic aircraft efficiency. To realize such gain, however, will require a major change in propulsion systems from those in current use. For this reason, advanced turboprop concepts may first appear in other types of aircraft.

In summary, these three projects represent an aggressive and focused approach to developing fuel efficient propulsion technology. Further, their impact on future aircraft propulsion systems is believed to be large and of major consequence.

References

1. J. F. Dugan, D. P. Bencze, and L. J. Williams, "Advanced Turboprop Technology Development," AIAA Paper 77-1223, Aug. 1977.
2. "The Next Commercial Jet Transport: The Need, Economics, Technology, and Financing," Paper presented at the Air Transportation Research International Forum, San Francisco, May 9, 1977.
3. "Aircraft Fuel Conservation Technology - Task Force Report," NASA-Office of Aeronautics and Space Technology, Washington, D.C., Sept. 10, 1975.
4. "Fuel Cost and Consumption," Civil Aeronautics Board, Washington, D.C., Dec. 1977.
5. "Airline Industry Economic Report," Civil Aeronautics Board, Washington, D.C. Vol. X-4, Feb. 24, 1978.
6. D. E. Gray, et al., "Energy Efficient Engine Preliminary Design and Integration Studies - Final Report," NASA CR-135396, (to be published, NASA Contract NAS3-20628).
7. R. P. Johnston, et al., "Energy Efficient Engine Preliminary Design and Integration Studies - Final Report," (to be published, NASA Contract NAS3-20627).
8. R. E. Neitzel, R. Hirschkron, and R. P. Johnston, "Study of Turbofan Engines Designed for Low Energy Consumption," (R76AEG432,

General Electric Co., NASA Contract NAS3-19201.) NASA CR-135053, 1976.

9. R. E. Neitzel, R. Hirschkron, and R. P. Johnston, "Study of Unconventional Aircraft Engines Designed for Low Energy Consumption," (R76AEG597, General Electric Co.; NASA Contract NAS3-19519.) NASA CR-135136, 1976.

10. D. E. Gray, "Study of Turbofan Engines Designed for Low Energy Consumption," (PWA-5318, Pratt & Whitney Aircraft; NASA Contract NAS3-19132.) NASA CR-135002, 1976.

11. D. E. Gray, "Study of Unconventional Aircraft Engines Designed for Low Energy Consumption," (PWA-5434, Pratt & Whitney Aircraft; NASA Contract NAS3-19465.) NASA CR-135065, 1976.

12. R. L. Foss, and J. P. Hopkins, "Fuel Conservation Potential for the Use of Turboprop Powerplanes," SAE Paper 760537, May 1976.

13. J. P. Hopkins and H. E. Wharton, "Study of the Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," (LR-27769-1, Lockheed-California Co.; NASA Contract NAS2-8612.) NASA CR-137927, 1976.

14. J. P. Hopkins, "Study of the Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commrecial Air Transportation System," (LR-27769-2, Lockheed-California Co.; NASA Contract NAS2-8612.) NASA CR-137926, 1976.

15. J. Stern, "Aircraft Propulsion - A Key to Fuel Conservation: An Aircraft Manufacturer's View," SAE Paper 760538, May 1976.

16. E. F. Kraus, "Cost/Benefit Tradeoffs for Reducing the Energy Consumption of Commercial Air Transportation System. Vol. I: Technical Analysis," (MDC-J7340-Vol.-1, Douglas Aircraft Co., Inc.; NASA Contract NAS2-8618.) NASA CR-137923, 1976.

17. J. C. Vanabkoude, "Cost/Benefit Tradeoffs for Reducing the Energy Consumption of Commercial Air Transportation System. Vol. II: Market and Economic Analyses," (MDC-J7340-Vol.-2, Douglas Aircraft Co., Inc.; NASA Contract NAS2-8618.) NASA CR-137924, 1976.

18. "Energy Consumption Characteristics of Transports Using the Prop-Fan Concept: Summary," (D6-75780, Boeing Commercial Airplane Co.; NASA Contract NAS2-9104.) NASA CR-137938, 1976.

19. "Energy Consumption Characteristics of Transports Using the Prop-Fan Concept: Final Report," (D6-75780, Boeing Commercial Airplane Co.; NASA Contract NAS2-9104.) NASA CR-137937, 1976.

20. C. Rohrbach, "A Report on the Aerodynamic Design and Wind Tunnel Test of a Prop-Fan Model," AIAA Paper 76-667, July 1976.

21. D. C. Mikkelson, B. J. Blaha, G. A. Mitchell, and J. E. Wikete, "Design and Performance of Energy Efficient Propellers for Mach 0.8 Cruise," SAE Paper No. 770458, Mar. 1977.

22. P. C. Stolp, and J. Baum, "Advanced Turboprop Propulsion System Reliability and Maintenance Cost," SAE Paper-771009, Nov. 1977.

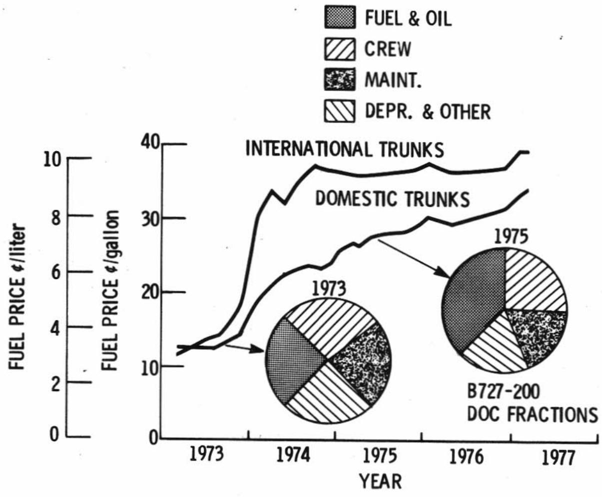


Figure 1. - U. S. airline jet fuel price. Monthly average.

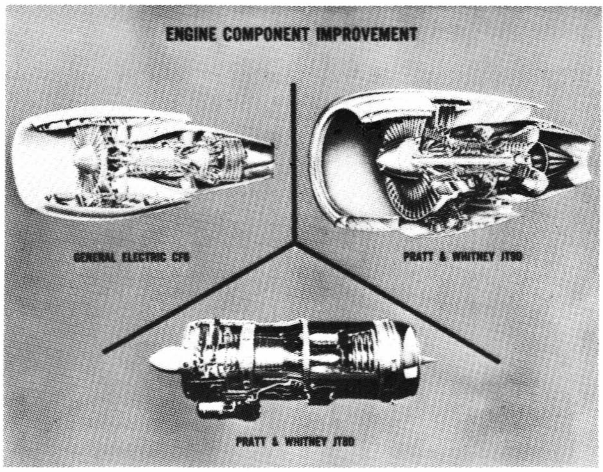


Figure 2. - Engines under investigation in Engine Component Improvement project.

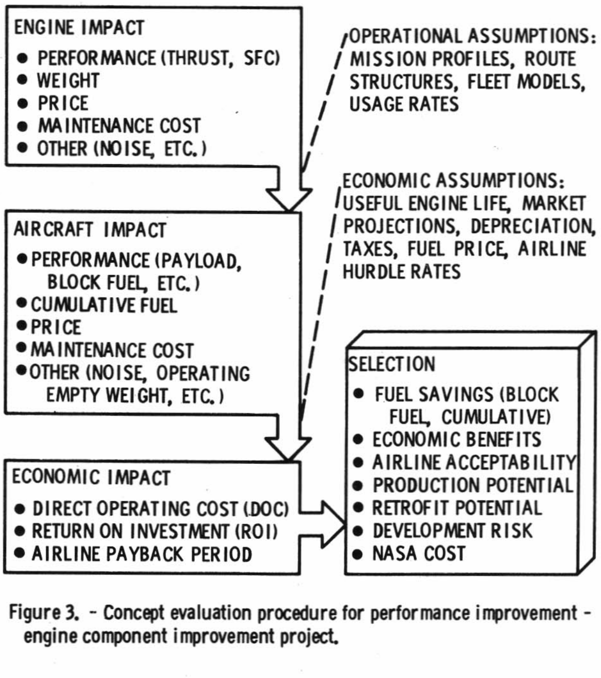


Figure 3. - Concept evaluation procedure for performance improvement - engine component improvement project.

CONCEPT	ENGINE	SFC REDUCTION @ CRUISE - %	CUMULATIVE FUEL SAVED THROUGH 2005 10^6 LITERS	CUMULATIVE FUEL SAVED THROUGH 2005 10^6 GAL
TRENCHED HPC BLADE TIP	JT8D	0.9	2229	589
REVISED HPT OUTER AIR SEAL	JT8D	0.5	341	90
HPT ROOT DISCHARGE BLADE	JT8D	0.9	980	259
DC-9 NACELLE DRAG REDUCTION	JT8D	0.5	322	85
3.8 ASPECT RATIO FAN	JT9D	1.3	2725	720
TRENCHED HPC BLADE TIP	JT9D	0.3	1865	493
HPT ACTIVE CLEARANCE CONTROL	JT9D	0.9	1771	468
HPT VANE THERMAL BARRIER COATING	JT9D	0.2	980	259
HPT CERAMIC OUTER AIR SEAL	JT9D	0.3	1953	516
IMPROVED FAN	CF6	1.7	3997	1056
NEW FRONT MOUNT	CF6	0.3	800	211
HPT AERODYNAMICS	CF6	1.3-1.6	1120	296
HPT ROUNDNESS/CLEARANCE	CF6	0.4-0.8	1506	398
HPT ACTIVE CLEARANCE CONTROL	CF6	0.6	916	242
LPT ACTIVE CLEARANCE CONTROL	CF6	0.3	348	92
SHORT CORE EXHAUST	CF6	1.0-3.0	1730	457
DC-10 REDUCED ENGINE BLEED	CF6	0.7	3028	800

Figure 4. - Summary of results from evaluation of performance improvement concepts. Engine Component Improvement project.

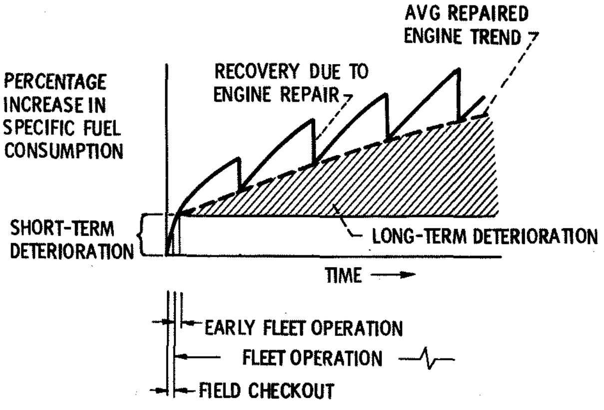


Figure 5. - SFC performance deterioration trends.

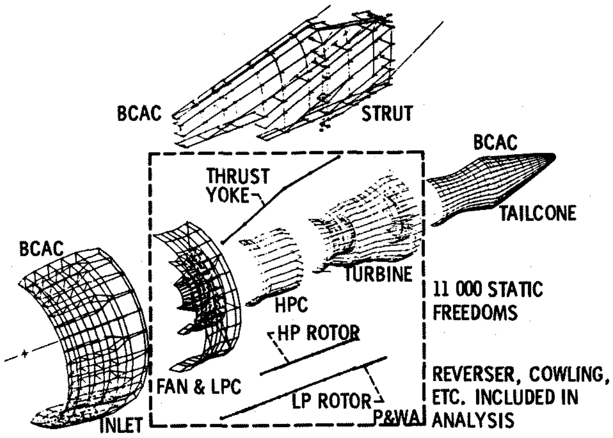


Figure 6. - NASTRAN finite element model for JT9D engine.

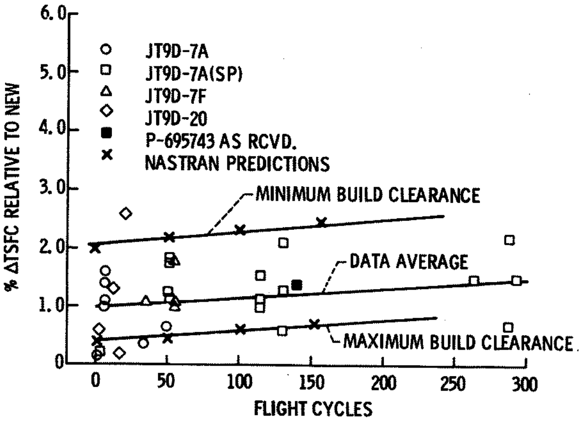


Figure 7. - NASTRAN predictions compared to engine data for short-term deterioration.

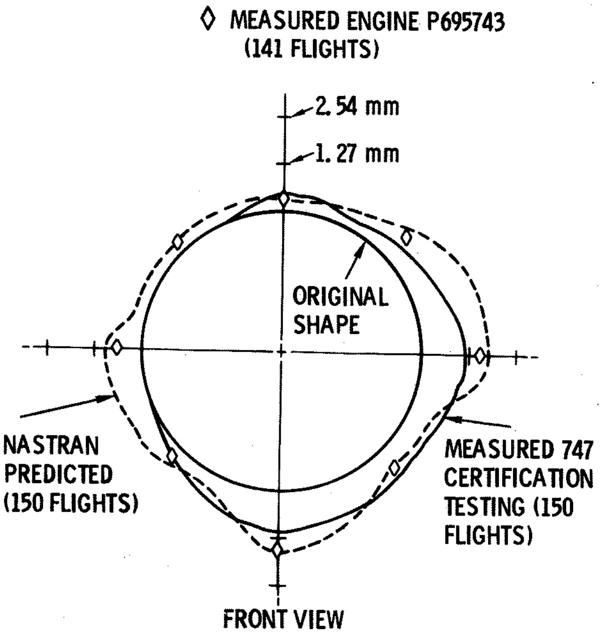


Figure 8. - Fan rub patterns. Analytical versus experimental correlation.

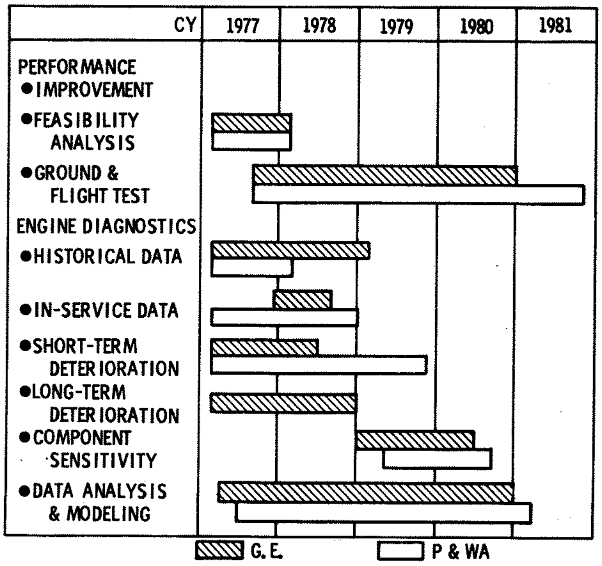


Figure 9. - Engine component improvement project schedule.

	PRATT & WHITNEY		GENERAL ELECTRIC	
	JT9D-7A	EEE	EEE	CF6-50C
FAN DRIVE	DIRECT	DIRECT	DIRECT	DIRECT
EXHAUST CONFIGURATION	SEPARATE	MIXED	MIXED	SEPARATE
BYPASS RATIO	5.1	6.55	7.0	4.3
FAN PRESSURE RATIO	1.58	1.74	1.61	1.72
COMPRESSOR PRESSURE RATIO	10	14	22.2	12.9
OVERALL PRESSURE RATIO	25.4	38.6	36	32
TURBINE TEMPERATURE				
MAXIMUM CRUISE (°C)	1088	1204	1182	1138
" " (°F)	1990	2200	2160	2080
HOT-DAY TAKEOFF (°C)	1252	1343	1338	1316
" " " (°F)	2285	2450	2440	2400
SLS THRUST (LBS)	44,265*	39,250	36,500	39,580*
" " (kN)	197*	174	162	176*

*SCALED VERSIONS OF REFERENCE ENGINES

Figure 10. - Cycles selected for energy efficient engines (maximum cruise conditions).

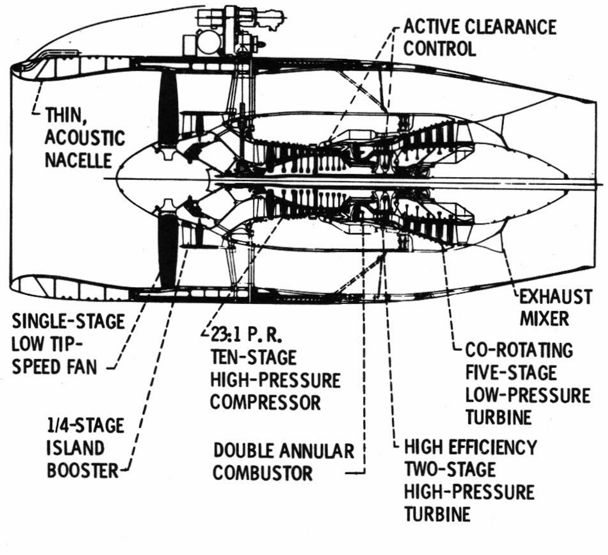


Figure 11. - General Electric's energy efficient engine configuration.

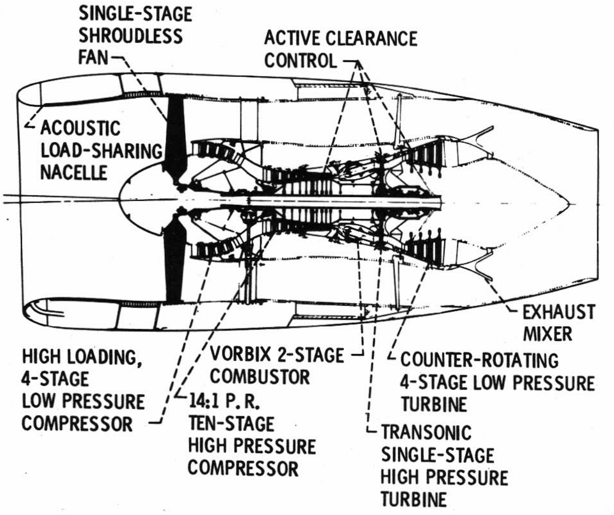


Figure 12. - Pratt & Whitney's energy efficient engine configuration.

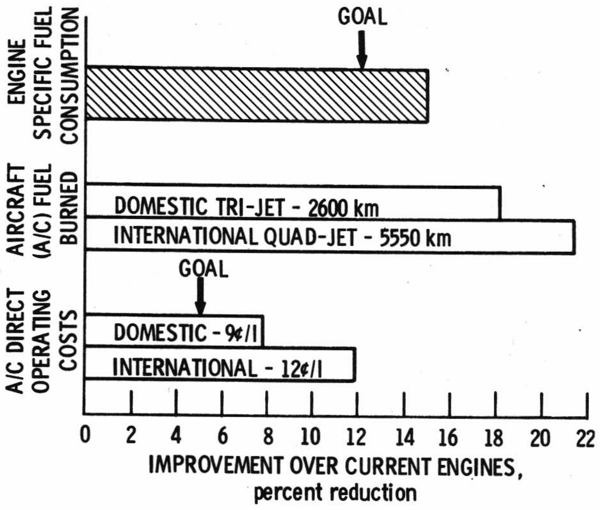


Figure 13. - Potential benefits of energy efficient engines.

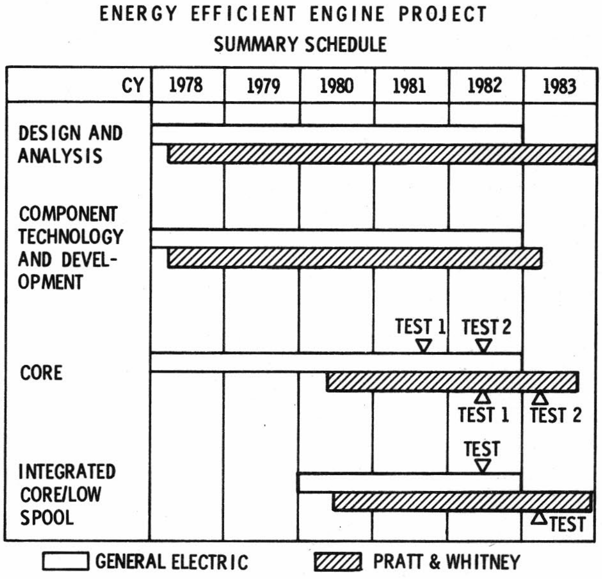


Figure 14. - Summary schedule for energy efficient engine project.

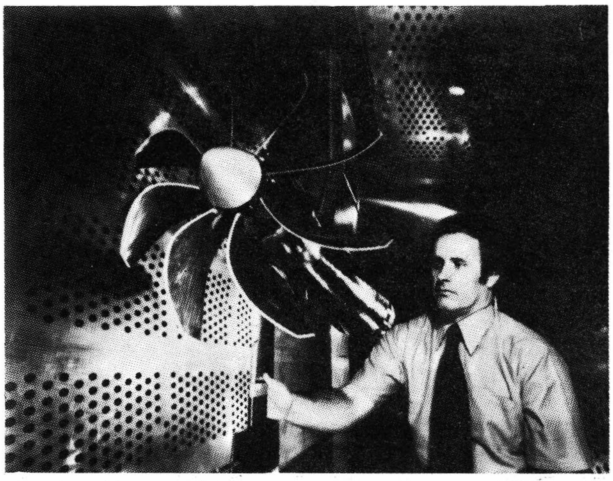


Figure 15. - High-speed propeller model mounted in Lewis Research Center 8- by 6-foot wind tunnel.

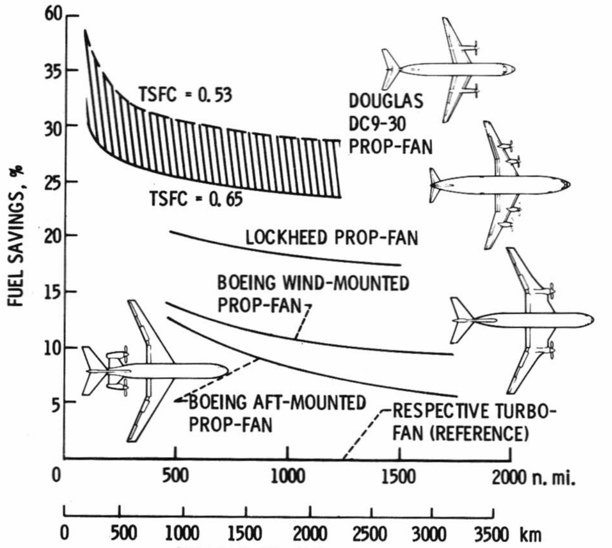


Figure 16. - Advanced turboprop (prop-fan) aircraft fuel savings.

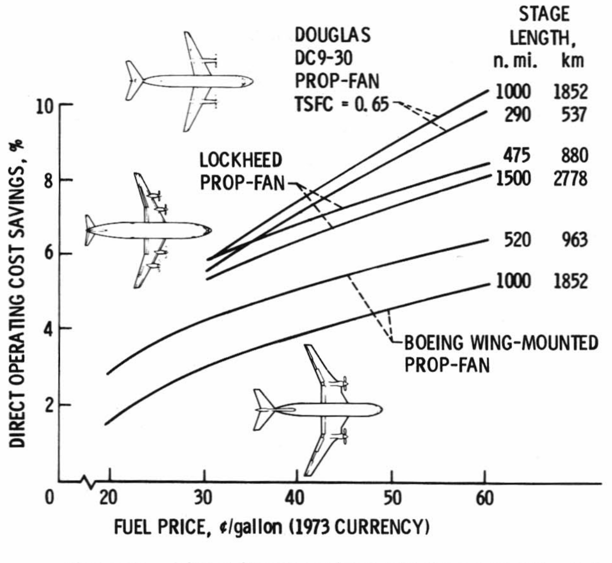
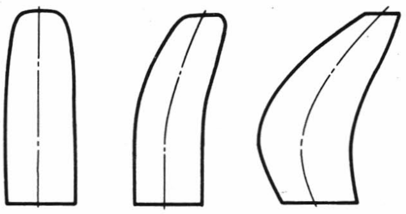


Figure 17. - Advanced turboprop (prop-fan) aircraft operating cost savings.



	SR-2	SR-1, 1M	SR-3
TIP SPEED, m/sec (ft/sec)	244 (800)	244 (800)	244 (800)
POWER LOADING, P/D^2, kW/m^2 (shp/ft^2)	301 (37.5)	301 (37.5)	301 (37.5)
NO. OF BLADES	8	8	8
TIP SWEEP ANGLE, deg	0	30	45
DESIGN EFF., %	77	79	81
DESIGN NOISE LEVEL, dB	143	143	137

Figure 18. - Design characteristics and planform of high-speed propeller models.

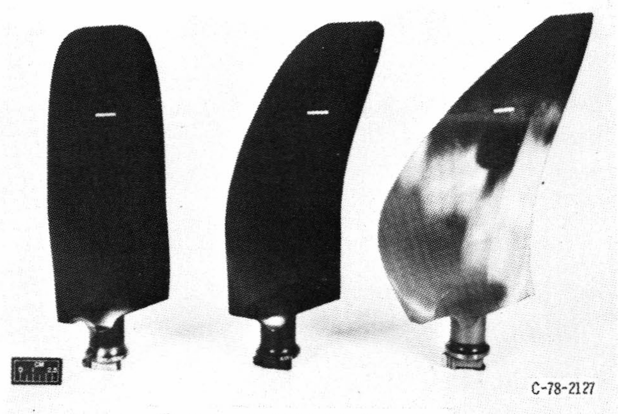
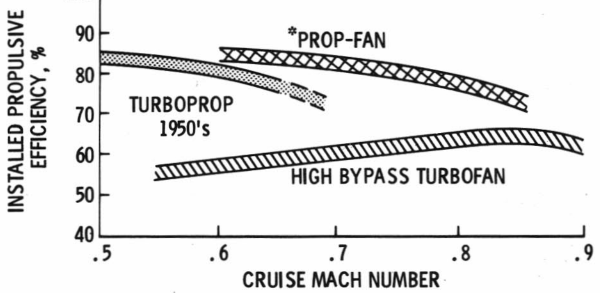


Figure 19. - High-speed propeller models.



*PROJECTION BASED ON 1976 MODEL WIND TUNNEL TESTS.

Figure 20. - Propulsive efficiency.

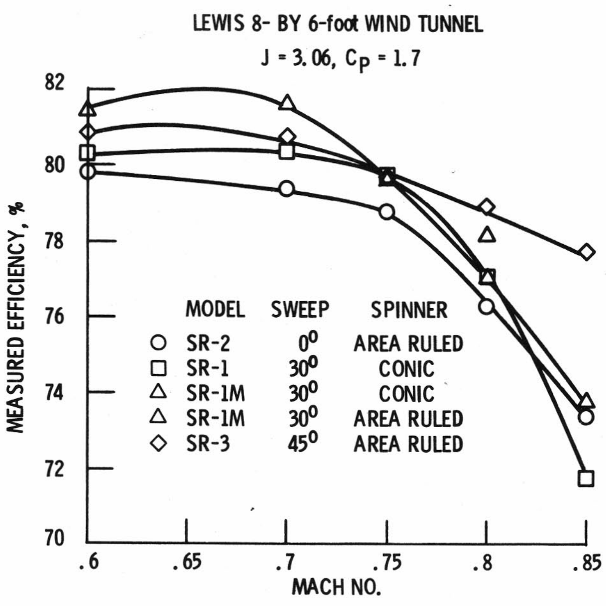


Figure 21. - High-speed propeller efficiency.

Figure 22. - Concept for high-speed propeller mounted on JetStar aircraft for in-flight acoustic tests.

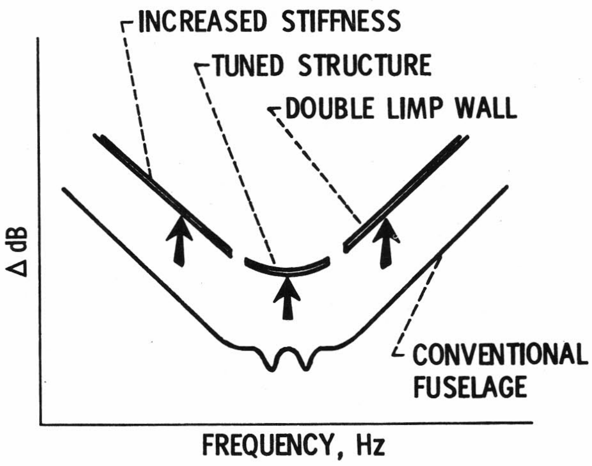


Figure 23. - Fuselage noise attenuation.

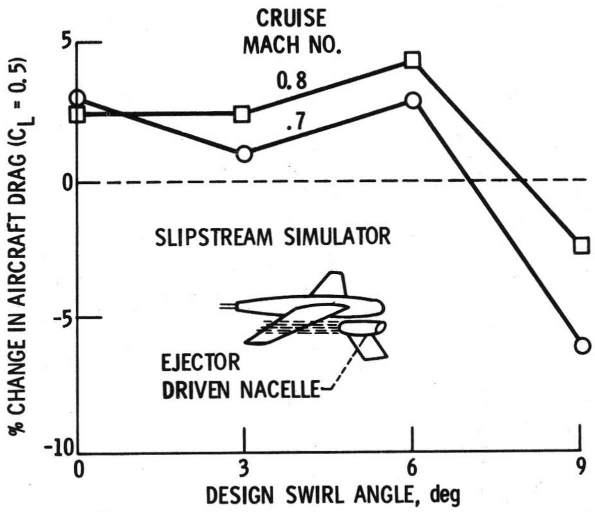


Figure 24. - Slipstream simulator results.

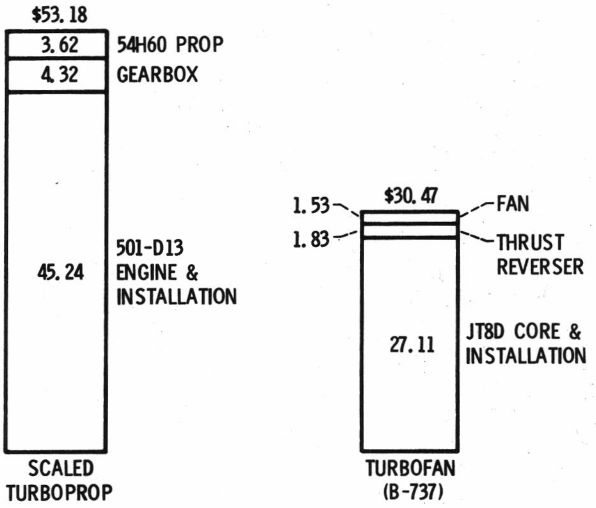


Figure 25. - Maintenance cost comparison for 1960-era turboprop versus turbofan. Fully burdened in 1976 dollars per flight hour.

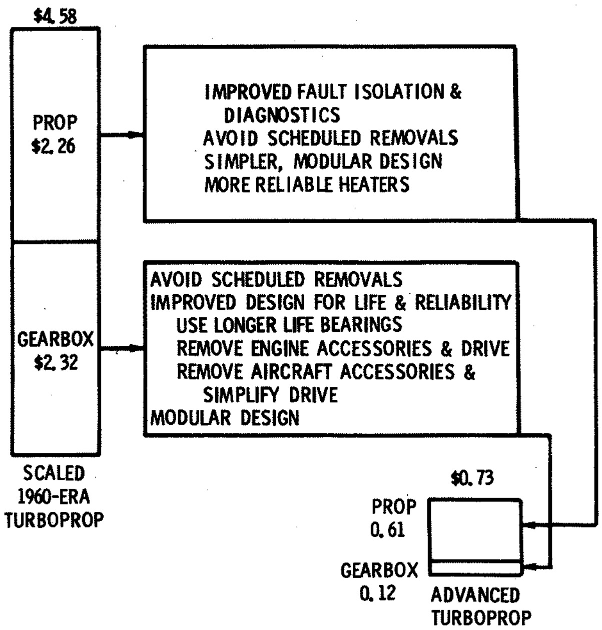


Figure 26. - Possible reductions in maintenance cost for propeller and gearbox. Unbroadened costs in 1976 dollars per flight hour.

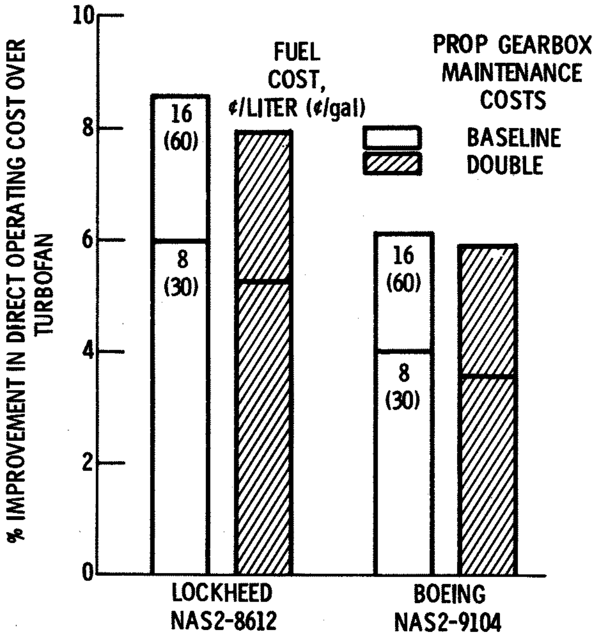


Figure 27. - Direct operating cost sensitivity to propeller and gearbox maintenance costs.

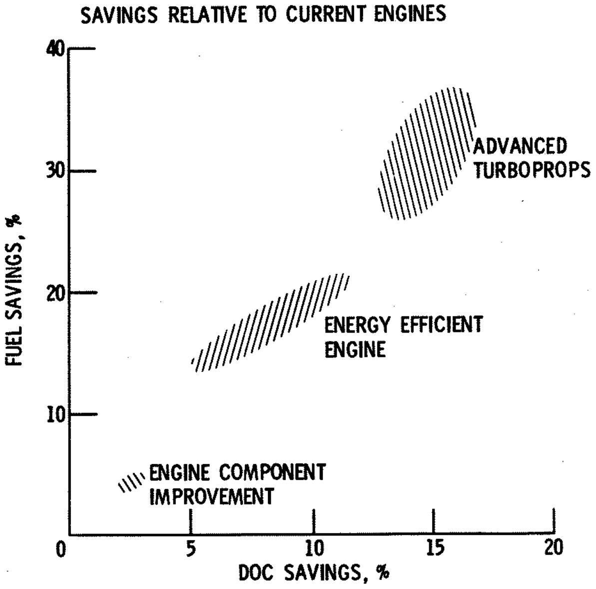


Figure 28. - Potential benefits of ACEE propulsion projects.