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SUMMARY

Examination of future subsonic commercial aircraft propulsion trends begins with a brief review of the current NASA Energy Efficient Engine (E^3) Project. Included in this review are the factors that influenced the design of these turbofan engines and the advanced technology incorporated in them to reduce fuel consumption and improve environmental characteristics. In addition, factors such as the continuing spiral in fuel cost, that could influence future aircraft propulsion systems beyond those represented by the E^3 engines, are also discussed. Advanced technologies that will address these influencing factors and provide viable future propulsion systems are described. And finally, the potential importance of other propulsion system types, such as geared fans and turboshaft engines, is presented.

INTRODUCTION

Commercial airlines have suffered what can be described as a trauma in the last few years in attempting to respond to a situation in which fuel costs have become the dominant and ever-increasing fraction of their overall operating costs. The airlines have incorporated many fuel-saving operational approaches (reduced cruise speeds, reduced auxiliary power requirements, reduced aircraft weight, etc.) in order to hold down their fuel usage. Engine and airframe manufacturers have also responded to the challenge. More fuel-efficient models of the JT9D, CF6, and RB211 are entering the market, along with new engines such as the CFM56 and PW2037. These, coupled with new aircraft designs such as the Boeing 757 and 767, offer significant improvement in the fuel efficiency of the commercial fleet. Of vital interest today is the question of what direction will subsonic transport propulsion take in the future.

The National Aeronautics and Space Administration (NASA), through its Aircraft Energy Efficiency (ACEE) Program along with related research and technology efforts, is evaluating and developing the technology for a variety of current and future propulsion options. The three major propulsion projects of the ACEE Program are presented in figure 1. The Engine Component Improvement Project (reference 1), which is nearing completion, provides advanced component technology for reducing fuel consumption of those turbofan engines already in use by the airlines. The Energy Efficient Engine (E^3) Project is a longer range program aimed at providing advanced technology for future generations of fuel efficient turbofan engines (reference 2). The third program, the Advanced Turboprop Project (reference 3), is concerned with developing technology for high-speed turboprop (prop-fan) propulsion systems. It has the potential for the largest fuel saving gains (approximately 35 percent), but the technology readiness date is also the farthest downstream.

The advanced propulsion technology currently being developed under the Energy Efficient Engine Project and the Advanced Turboprop Project offers considerable potential for improving the fuel efficiency of future transport propulsion systems. These two projects are discussed below, and projections are also made regarding future transport propulsion trends and potential benefits, in view of expected continuing fuel price increases.

ENERGY EFFICIENT ENGINE PROJECT

While the prime emphasis in the E^3 Project is on fuel efficiency, acceptable commercial engines must also be economically attractive and environmentally compatible. The goals of the E^3 Project shown in figure 2 accordingly reflect this combination of factors. These goals represent performance of fully developed, flight qualified engines. Therefore, they include performance improvements that typically are achieved during normal commercial engine development efforts that would occur after the completion of the advanced technology efforts involved in the E^3 Project.

The project is being accomplished through contracted efforts with both of the large turbofan engine manufacturers: the Aircraft Engine Group of the General Electric Company (GE) and the Pratt & Whitney Aircraft Group (P&WA) of the United Technologies Company. Each has parallel efforts consisting of three major activities, as illustrated in figure 3. The first element of each contract pertains to generating flight propulsion system designs which serve as the basis for defining the technology advances to be evaluated in subsequent activities. These designs are also used for projecting performance benefits that could be attained in fully developed, flight-certified engines. The second element, component technologies, encompasses the design, fabrication, and test of most of the advanced components that comprise the engine designs. In addition, technology efforts are undertaken at the subcomponent level for the development of a design-base in these areas where the design base is deficient.

The third element of the contracted efforts involves integration of the advanced component designs into engine systems. The purpose of this effort is to experimentally assess the integrated performance of the components and the various advanced systems-technology features that can be evaluated only in system tests. The GE effort will include the integration of the high-spool components (high-pressure compressor, combustor, and high-pressure turbine) into a core-engine system test. Both contractors will conduct complete engine system tests which include the core engine components integrated with the low-spool components (fan, low-pressure compressor, and low-pressure turbine), referred to as ICLS (for Integrated Core-Low Spool), and the nacelle. The engine system tests are considered to be the primary means of demonstrating technology-readiness and will also serve as a reference for the final update (projection) of the flight propulsion system performance.

Cross-sections of each of the engine manufacturer's E^3 flight propulsion system designs illustrating the advanced technology features and configurational features are shown in figures 4 and 5. Both engines are two-spool configurations and take-off thrust ratings of both are about 160,000 Newtons (36,000 pounds). Additional details of the advanced technology features of the engines will be presented in the next section of this paper.

The cycle characteristics for the maximum cruise condition for each E^3 engine and those for their respective base (or reference) engine are shown in figure 6. A direct drive as opposed to a gear driven fan was chosen for both E^3 engines. This is the same approach as used in the baseline engine. Additional discussion of the factors that affect this selection is presented in a later section of this paper. Both engines employ core and bypass stream exhaust mixers whereas the baseline engines are both unmixed. Exhaust stream mixers can contribute as much as 3 percent in specific fuel consumption (SFC) improvement for the E^3-type engine cycle. Bypass ratios close to 7 are used in both E^3 designs, which is significantly higher than the baseline engines. The higher bypass ratio improves propulsive efficency. Another cycle characteristic related to increased fuel economy is the overall pressure ratio. For the E^3 designs, the overall pressure ratios are 50 percent and 20 percent greater than the baseline engines for the P&WA and GE engines, respectively. Both E^3 engines are designed for higher turbine inlet temperature for improved fuel economy. The maximum cruise turbine inlet temperature is about 200°F and 100°F higher than the baseline engines for the P&WA and the GE engines, respectively.

Estimates of the improvement in SFC over the baseline engines for both E^3 designs are between 14 percent and 15 percent. Thus, both of the engine designs are expected to exceed the 12 percent SFC improvement goal. Over half of the anticipated SFC improvements for both engines is a result of improvements in component efficiencies. The remainder of the SFC improvement is the result of about equal contributions from the engine cycles and the employment of mixer nozzles. In addition to meeting the fuel consumption goal, it is anticipated that the operating cost and environmental goals will be met by both of the engine designs.

ENERGY EFFICIENT ENGINE TECHNOLOGY

A listing of some of the E^3 advanced technology features is shown in Table I, along with the approach to achieving the feature. In the following discussion, each of the major component advanced technology features will be described.

Fans

The features incorporated into the fan designs for improved performance include tighter operating clearances between the blade tips and the fan casing, along with aerodynamic blade refinements. The efficiency and clearance improvements of the GE and P&WA fans are shown in figure 7. The GE single-stage fan operates at a design tip speed of 396 m/sec (1300 ft/sec) and has a target efficiency of 88.7%. The P&WA fan has a target efficiency of 87.3% and is designed to operate at 457 m/sec (1500 ft/sec). For comparison purposes, the shaded area in the figure represents the efficiency level of current technology operational fans. As can be seen, the E^3 designs represent a major gain in efficiency. A large part of the projected fan efficiency gains stems from the use of much tighter operating clearances. Figure 7 also illustrates the large improvement in tip clearance relative to the baseline engine fans. Also shown, for GE, is the relative tip clearance for the Engine Component Improvement (ECI) Project fan. It can be seen that the E^3 design even exceeds that of the advanced ECI fan.

Both fans employ solid titanium fan blades with a single mid-span damper. The dampers are located lower than usual on the blade span, and they are positioned towards the trailing edge of the fan blade. Both these factors contribute to improved fan efficiency.

Compressors

The advances incorporated in the E^3 high-pressure compressors of both engine manufacturers include: higher pressure per stage, higher efficiency, improved performance retention, and lower maintenance costs.

The higher pressure ratio capability per stage leads to fewer compressor stages and, therefore, a shorter and lighter compressor Shorter compressors are stiffer and therefore less subject to performance deterioration. The performance improvements sought are shown in figure 8. As indicated, the P&WA compressor is aimed at significantly higher efficiency than that for current technology compressors. The GE efficiency gain is more modest, but still represents a significant increase. The GE compressor is, however, primarily aimed at achieving a much higher pressure rise per stage. Thus, the GE compressor achieves a 23:1 pressure ratio in only 10 stages (figure 8). This choice of a shorter and lighter compressor was chosen at the expense of some reduction in efficiency. Both compressors will make use of active clearance control for improved efficiency, however.

Both compressors also employ lower aspect ratio blades and vanes. This design feature significantly reduces the number of airfoils, as shown in figure 9. The P&WA compressor design reduces the required airfoils to almost one half, as compared to the JT9D compressor. For GE, the reduction in number of airfoils over the baseline engine is not as large, but as previously mentioned the compressor develops a significantly higher pressure ratio (23 to 1) as compared to the reference CF6 compressor (13.2 to 1).

Combustors

The emphasis on advanced technology for the combustor includes: lower emissions, longer life, and shorter length. The goal of meeting the EPA 1981 emissions requirement has a major impact on the combustor design. In order to achieve these stringent requirements, it was necessary to depart from the standard combustor used in commercial engines today. The designs for both manufacturers evolved from the NASA Clean Combustor Program. The evolution of the combustors from current designs to the E^3 configurations is shown in figure 10. As can be seen, the E^3 configuration retains the two zone burning concept, as evolved in the Clean Combustor Program. In the case of P&WA, the two zones (pilot and main stage) are in series. For the GE configuration, the pilot and main stage zones are arranged in parallel. The pilot zone is used for lower power operation while both are used at high power. This combination provides reductions in emissions over the wide range of engine operating conditions from ground idle to take-off power. It can also be seen in figure 10 that the length of the combustor is progressively shorter in progressing from the baseline engines to the E^3 designs. The improvement in emissions over that for current engines is shown in figure 11. As can be seen, the anticipated E^3 combustor emissions are significantly lower than for today's engines.

Combustors are generally one of the shortest life span components, and, accordingly, one of the highest maintenance cost items for today's engines. In order to improve this situation, a new construction concept is being employed in the E^3 designs. As shown in figure 11, it is expected that a 3-fold increase in burner life can be obtained while using only half the cooling airflow. The major factor in increasing combustor life is the use of a segmented design. This concept is illustrated in figure 12. While this is the P&WA concept, the basic concept is the same in the GE design. The combustor liner is segmented both circumferentially and axially in order to reduce thermal stresses and consequently thermal fatigue. The segments are held in place (in the P&W design) by a frame structure that surrounds the outside of the combustor. The segmented concept also permits the use of cast turbine-type materials that have better high temperature durability characteristics than the current materials. The improved cooling effectiveness required in order to reduce the cooling flow results from the use of advanced forms of cooling (combination of transpiration, film, and impingement cooling).

Turbines

The advanced technology in the turbines includes higher efficiencies, higher aerodynamic loading, higher temperature capability, and improved performance retention. The GE high-pressure turbine is a two-stage configuration which was selected to provide high efficiency, while the P&WA turbine is a highly-loaded single-stage selected for reducing the number of turbine airfoils and accordingly improving maintenance cost. Both turbines employ active clearance control, which is a major contributor to the improved efficiency. Aerodynamic refinements are also included in each design. As shown in figure 13, both turbines exceed current technology turbines in efficiency by at least a point. (A direct comparison between the efficiency of the one-and two-stage turbines should not be made because of the differences in the way turbine efficiency is calculated by the two companies. On a more directly comparable basis, the two-stage turbine is estimated to be about 1½ to 2 points higher than the one-stage turbine.)

In addition to the aerodynamic refinements, advanced turbine materials and improved cooling techniques are employed.

The expected efficiency of the low-pressure turbines is also shown in figure 13. The P&WA design is a four-stage configuration, while GE opted for a five-stage turbine. The four-stage turbine of P&WA is consistent with their approach to designing fewer stages and airfoils in the high-pressure turbine. The GE design loadings are higher. Both turbines employ the use of active clearance control for reducing the clearance between the turbine blades and case; this is accomplished by cooling the case during the cruise condition. In the case of P&WA, the low-pressure turbine is counter-rotating relative to the high-pressure turbine. This feature was selected because of the high degree of flow swirl in the gases coming from the single-stage, highly-loaded, high-pressure turbine. The advantage of this approach is a lessened amount of turning and, accordingly, lower losses associated with redirecting the flow for proper entry to the low-pressure turbine.

Exhaust Gas Mixers

Both engine configurations employ exhaust gas mixers for improved fuel economy. In order to accomplish the mixing, a "daisy-type" core nozzle mixer is employed, along with a long duct nacelle to allow for some length to accomplish the core and bypass stream mixing. The potential benefit to the E^3 designs is a 3% improvement in fuel economy with only a small penalty in weight.

In order to optimize the mixer for each E^3 design, a model mixer program was undertaken by each contractor. A number of mixer variables were investigated, as shown in figure 14. These variables were examined in order to arrive at the best combination of mixing efficiency, pressure loss, and length (hence weight). A photograph of one of the mixer models used in the investigation is shown in figure 15. The model size was 12% of full scale. In addition to measurements of mixer thrust and mixing effectiveness, flow visualization was employed to better understand the flow field. This is illustrated by the oil streaks in figure 15.

Improved Component Performance Retention

An important aspect of engine fuel economy is the ability of a given engine to retain its performance and not deteriorate. In order to address the engine deterioration problem, a number of design features aimed at improving performance retention were incorporated into both the E^3 designs. They were:

- Erosion-Resistant Coatings
- Thick-Leading-Edge Airfoils
- Reduced Rotor and Case Deflections Under Load
- Active Clearance Control
- Abrasive Blade Tips

FACTORS INFLUENCING ENERGY EFFICIENT ENGINE DESIGN

The Energy Efficient Engine cycles and basic configurations were established by late 1977, following a period of extensive trade studies (reference 4, 5). The specific cycle trade curves discussed below were developed by Pratt & Whitney. General Electric's cycle trades produced similar results, as evidenced by the quite similar design cycle conditions chosen by both contractors (figure 6). The cycle design point in each case was maximum cruise thrust at 10,700 m. (35,000 ft) and Mach 0.8.

The Pratt & Whitney trade studies isolated the impact of various cycle parameters on fuel burned and direct operating cost (DOC) as illustrated in figures 16-18. In figure 16, the fuel burned and DOC trends leading to Pratt and Whitney's selected turbine rotor inlet temperature of 1204°C (2200°F) are indicated. Below the selected temperature, definite fuel burned penalties are present because of increased specific fuel consumption (SFC) and engine weight. However, there is no DOC penalty because decreased maintenance cost associated with lower temperature more than offsets the fuel disadvantage. At higher temperatures, engine weight reductions are offset by small SFC increases so that fuel burned remains constant over a large temperature range. Direct operating cost is adversely affected at higher temperatures, as shown, because of increased maintenance costs.

The selected overall pressure ratio of 38.6:1 at the cruise design point results in near optimum DOC for the domestic and international aircraft as shown in figure 17. Higher pressure ratios result in further improvement in fuel consumption without severely affecting DOC, since the increasing procurement and maintenance cost effects are counteracted by lower fuel consumption. However, thermal/structural analysis of the rear of the compressor section and the high-pressure turbine indicated that the selected overall pressure ratio level represented a sufficiently aggressive design challenge when considering disk thermal control, maintaining tight rotor clearances, sealing of leakage paths, and especially thrust growth, which usually requires increased pressure ratios.

The fuel burned and DOC trends with bypass ratio are shown in figure 18. It should be noted that the choice of either direct fan drive (fan and low-pressure turbine rotate at same speed) or geared fan drive has a strong impact on optimizing bypass ratio. The curves presented in figure 18 assume a direct-drive engine. Geared engines were also studied and had somewhat higher optimum bypass ratios. For direct-drive engines, fuel burned is seen to bottom out with increasing bypass ratio, as improving SFC is offset by increases in the number of low-pressure compressor and low-pressure turbine stages, increased fan diameter, and increased nacelle size, with resulting increases in engine and nacelle weight as well as increased nacelle drag. Direct operating cost is a minimum at bypass ratios around 6.0 as the fuel burned advantages of higher bypass ratios are offset by higher engine and nacelle weights and costs. Installation penalties usually associated with larger nacelle diameters--such as landing gear length that increased airframe cost and hence DOC--also tended to favor lower bypass ratio engines. The selected bypass ratio of 6.5 appeared to provide the best combination of fuel burned and direct operating cost for the direct-drive engine.

Fuel burned vs DOC trades were also applied to individual components of the Energy Efficient Engines, in general resulting in some sacrifice of component efficiency potential in order to favorably influence DOC through reduced part counts, reduced maintenance costs, or increased part life by way of increased cooling airflow. Both contractors reflected this philosophy in their compressor and turbine designs, with Pratt & Whitney's single-stage high-pressure turbine being an obvious example. These design choices reflected the then (1977) prevailing relative impact of fuel cost and maintenance cost on DOC, and appeared to make sound economic sense at the time.

IMPACT OF INCREASING FUEL PRICES ON FUTURE PROPULSION SYSTEMS

As mentioned earlier, the E^3 cycles and basic configuration were established during the 1977 time period. The history of U.S. airline jet fuel prices for several years prior to and including this period is shown on figure 19. After the sharp upturn in prices in 1973-74 which forced increased emphasis on fuel consumption and which also provided the impetus for NASA's Aircraft Energy Efficiency Program, it can be seen that fuel prices remained relatively stable for several years. For the DOC tradeoffs discussed in the previous section of this paper, fuel prices of \$.09/liter (\$.35/gal) domestic and \$.12/liter (\$.45/gal) international (in constant 1977 dollars) were used. The implied assumption was that fuel prices beyond 1977 would vary with inflation, as they basically had been doing for the previous several years.

This general trend was dramatically altered during the 1979-80 period, as shown in figure 20. During these two years, airline jet fuel prices more than doubled, far exceeding the prevailing rate of inflation. (Fuel prices shown are from summarized Civil Aeronautics Board Form 41 data as presented in the periodic CAB Aircraft Operating Cost and Performance Reports.)

One result of these fuel price trends has been the increasing predominance of fuel cost as the critical component of airline direct operating costs. This is illustrated in figure 21, which is based on data from the same Civil Aeronautics Board reports cited above. The data presented represents summary values for domestic operations of all U.S. - based trunk airlines. By mid-1980, fuel and oil costs constituted more than 50 percent of DOC, and maintenance costs around 16 percent. For several years prior to 1974, each of these items had contributed around 25 percent to total DOC.

It can be anticipated that fuel costs will continue to dominate the DOC equation in the future and that the relative impact of fuel on DOC will continue to increase. Figure 22 is a projection of current DOC trends out to the year 2000. This projection assumes that fuel costs beyond 1980 will inflate at 20 percent per year, and the general inflation rate on all other costs is assumed to be 10 percent per year. (Note that this projection is <u>not</u> a forecast. It merely represents one of many scenarios that could be developed. However, also note that (1) fuel prices escalated over 30 percent per year from 1971 to 1981, (2) a decline in petroleum production, variously foreseen as occurring in the year 1990 to 2000, could begin to impact fuel prices in the time frame of this projection, and (3) the sensitivity of fuel prices to world-wide political uncertainties generally dictates the use of conservatism in predictions rather than optimism.) The short and medium range portion of the current domestic trunk aircraft fleet is represented in 1981 by JT8D powered aircraft such as the 727, 737, and DC-9, using about 60 percent of total aircraft fuel. The remaining 40 percent of the fuel is used by large long-range aircraft such as the 747, DC-10, and L-1011 powered by JT9D/CF6-50 type engines. This fleet mix is assumed to prevail until 1988, when a linear transition begins to a greatly improved fleet by the year 2000. During this transition, all short/medium range aircraft are replaced (in this projection) with aircraft embodying advanced aircraft and engine technology corresponding to the levels of the 757/767. All other aircraft are assumed to incorporate only improved engine technologies corresponding to the JT9D-7R4 or CF6-80 levels. When transition is complete, this represents a composite fleet fuel burned improvement of 30 percent. Even with this significant 30 percent improvement in fleet average fuel consumption by the year 2000, fuel cost is projected to be almost 82 percent of direct operating cost at that time. This value would of course vary up or down depending on the assumed inflation rates for fuel and the other DOC constituents, but it is probably safe to assume that fuel costs will dominate airline direct operating costs for the foreseeable future.

With the increasing impact of fuel costs relative to maintenance costs on airline DOC, some of the cycle parameters and component designs selected for the Energy Efficient Engines in 1977 would probably change if these engines were being designed in the current environment. There would be even more emphasis placed on absolute fuel savings and less emphasis on reduced maintenance costs.

In figure 23, projected improvements in cruise specific fuel consumption for the current E^3 designs are presented and compared to estimates of SFC improvements that could be realized if these basic designs were modified so as to realize their full SFC reduction potential. Improvements in SFC are relative to the JT9D-7A/CF6-50C engines which are used as references in the E^3 program. Projected SFC improvements for the current E^3 designs are 14.8 percent for the Pratt & Whitney configuration and 14.2 percent for General Electric. Estimates of the full SFC potential of these designs, based on preliminary assessments by the contractors, range between 19 and 21.5 percent improvement. To realize this potential, both contractors anticipate that re-optimized E^3 cycles would specify slightly higher bypass ratios in the 7.0 to 7.5 range. Pratt & Whitney would anticipate adding an additional stage to both the high-pressure turbine and low-pressure turbine to realize significant efficiency improvements. General Electric has suggested an increased overall cycle pressure ratio (up to 45:1) and reduced turbine cooling requirements as major features of a re-optimized design. Each contractor also would anticipate several other changes of a more minor nature to improve efficiency and the cycle.

Although the Energy Efficient Engine design configurations would probably optimize somewhat differently today, this in no way diminishes the applicability to future engines of the advanced technology being developed under the E^3 Project. The modifications discussed above represent only a different application of the current E^3 technology, not radical departures.

ADVANCED CYCLES

The Energy Efficient Engine configurations, along with the newer large commercial engines and those currently under development, all represent variations of the conventional, direct-drive, high-bypass-ratio turbofan cycle. The increasing emphasis on aircraft fuel efficiency has directed attention to other cycles which promise greater fuel savings than direct-drive turbofans in similar applications (cruise Mach numbers between 0.7 and 0.85). The two advanced cycles that have emerged in recent years as meriting the most serious consideration are the prop-fan (or high-speed turboprop), which promises high propulsive efficiency at high subsonic cruise speeds, and the geared turbofan, which employs a set of reduction gears between the fan and its drive turbine to allow each to operate at its most efficient rotating speed. The potential of these advanced cycles is discussed in the following sections.

Geared Fans

During the cycle and configuration definition phase of the Energy Efficient Engine Project (reference 4,5), the geared turbofan cycle option received extensive consideration by both engine contractors along with their airframer subcontractors. Performance results from these evaluations are summarized in figure 24 for an average domestic mission. Each contractor identified an installed SFC advantage for their geared fan option relative to their optimized direct-drive configurations: 3.5 percent improvement for the Pratt & Whitney geared engine and 0.7 percent improvement for General Electric. Factors acting to improve SFC for the geared engines included cycle differences (higher bypass ratios and lower fan pressure ratios than feasible with direct drive) and improved low spool component efficiencies resulting from the combination of low fan tip speeds and high low-pressure-turbine speeds permitted by the reduction gear system. These SFC advantages were partially offset by gear power losses, reduced mixer efficiencies in the higher bypass ratio, increased diameter fan engines, and resulting higher drag of the larger nacelles. The fuel used projections (2.2 percent geared advantage from Pratt & Whitney, 1.9 percent penalty from General Electric) reflect these penalties along with the significantly higher propulsion system weights estimated for the geared engines relative to direct drive engines of equivalent cruise thrust. Pratt & Whitney's geared engine was 10 percent heavier than the corresponding direct-drive version, and General Electric's geared engine was 18 percent heavier. The DOC results, calculated at a fuel cost of 9¢/liter (35¢/gal) in constant 1977 dollars, were a 0.5 percent DOC advantage for the Pratt & Whitney geared engine and 2.1 percent penalty for the General Electric geared engine. Higher geared engine/nacelle acquisition costs and gearbox maintenance costs had a negative impact on DOC. The relative DOC values quoted at 26.4¢/liter ($1/gal) fuel costs (2.0 percent DOC improvement over direct-drive for the Pratt & Whitney engine and 0.6 percent penalty for General Electric's) are based on extrapolation of contractor generated trends and assume all other costs excepting fuel remain constant. The reduced noise for the geared engines relative to direct drive relfects the acoustic advantages of lower fan speeds and lower jet velocities.

In reference 5, Pratt & Whitney also assessed the relative risk involved in achieving the predicted performance of their direct drive and geared fan designs and concluded that the geared fan involved considerably more risk. They conducted an analysis to estimate geared fan performance on an equal probability of achievement basis with the direct-drive engine, and concluded that the relative SFC advantage of geared over direct drive would be reduced by a 1.4 percent increment (2.1 percent SFC improvement rather than 3.5 percent). Using trade factors, they further concluded that relative fuel burned (geared vs direct) on an average domestic mission would increase by a 1.6 percent increment to (-0.6 percent) and that the relative DOC's would increase by a 1.5 percent increment based on equal probabilities of achievement.

These general results from the Energy Efficient Engine geared turbofan evaluations are summarized in figure 25. The basic conclusion was that the potential economic benefits relative to equivalent direct-drive engines were not sufficiently attractive to justify a major product change, particularly when considering the technical unknowns and risks involved.

Prop Fans

Another future subsonic transport propulsion option which is proving to be considerably more attractive in terms of offering major improvements in fuel consumption and DOC is the high-speed turboprop, or prop-fan, configuration. The Advanced Turboprop Project at the NASA Lewis Research Center (another part of NASA's Aircraft Energy Efficiency (ACEE) Program) is providing the focus for a detailed examination of this promising concept and for advancement of the many interrelated technologies involved (reference 3).

The major features of an advanced high-speed turboprop propulsion system are shown in figure 26. The propeller blades themselves are required to be quite thin and highly swept in order to minimize compressibility losses and propeller noise during high speed cruise. The use of 8 or 10 blades with a high propeller power loading allows overall propeller diameter to be kept relatively small. An area-ruled spinner and integrated nacelle shape reduce compressibility losses in the propeller hub region. Finally, a large modern turboshaft engine and gearbox provide power to the advanced propeller.

The attractiveness of the advanced turboprop concept results from its potential for high propulsive efficiencies in the Mach 0.7 to 0.85 speed range, as shown in figure 27. Older model turboprops with relatively thick, unswept propeller blades were not efficient in this range, experiencing rapid increases in compressibility losses above Mach 0.6. Current high-bypass-ratio turbofans reach their peak propulsive efficiency of around 65 percent at cruise speeds above Mach 0.8. The advanced turboprop concept is estimated to be about 20 percent more efficient than high-bypass-ratio turbofans at Mach 0.8. At lower cruise speeds, the efficiency advantage of the advanced turboprop is even larger.

Before this promising potential can be realized, advances in a number of technical areas will be required. These important prop-fan technologies, summarized in figure 28, are all being addressed within NASA's Advanced Turboprop Project. The first major technical area (the propeller/nacelle) is concerned with propeller aerodynamics, acoustics, and structures. The second area involves the cabin environment. To encourage passenger acceptance of the prop-fan, a cabin comfort level (noise and vibration) comparable to that in modern turbofan-powered aircraft has been established as a technology goal. With a wing-mounted prop-fan, the fuselage will be in the direct noise field of the propeller and this propeller-generated noise must be attenuated by the cabin wall in order to provide a low-noise cabin environment. Also, the engine mounts, wings, and aircraft structure must be designed to reduce structural-borne noise and vibration transmitted to the cabin. The third major technical area (installation aerodynamics) addresses the accelerated, swirling, propeller slipstream flowing over the wing for a wing-mounted installation. The challenge here is one of integrating propeller design with wing design to achieve the best combination of propulsive efficiency and aircraft lift-drag ratio. Also, the impact of advanced turboprop engines on aircraft stability and control must be established and accounted for in the aircraft design. The fourth area involves the mechanical components of an advanced turboprop propulsion system: the engine drive, the gearbox, and the propeller construction. The development of advanced turboshaft engines and high-efficiency gearboxes constitutes a very important element of the prop-fan concept. Inlet-engine compatibility requirements will be addressed. Prop-fan inlet-compressor stability interactions may present problems and will require investigation. Further, all the mechanical components must be designed and packaged in such a way that maintenance and reliability will be much improved over that experienced by previous generations of commercial turboprop-powered aircraft. Since these four technical areas are so strongly interrelated, aircraft trade-off studies need to be performed periodically to obtain the match that will best achieve the goals of low fuel consumption, low operating cost, and passenger acceptance.

Two examples of potential future commercial aircraft configurations powered by advanced turboprops which have been evaluated in recent years are shown in the top part of figure 29: a medium-range wide-body transport with four turboprops mounted on the wing, and a shorter-range narrow-body transport with two turboprops mounted at the rear of the fuselage. Other types of subsonic aircraft being considered for prop-fan application include cargo airplanes and military patrol aircraft as shown at the bottom of figure 29.

The results of these and other aircraft studies to quantify the benefits promised by the Advanced Turboprop (reference 3) are generally summarized in figure 30. Block fuel savings relative to competing turbofan-powered aircraft were significant for all aircraft studied and vary with design range. Also, block fuel savings were seen to vary with cruise Mach number. The upper portion of the band in Figure 30 reflects a Mach 0.7 cruise speed, and the lower portion reflects a Mach 0.8 cruise speed. At the very short design ranges, with short-haul aircraft which consume a significant fraction of mission fuel during takeoff and descent, the turboprop fuel savings can be as high as 30 percent. Over a wide spectrum of medium to long range aircraft, fuel savings are 15 to 20 percent. For very long range aircraft, where most of the mission fuel is consumed during cruise, turboprop fuel savings of 17 to 30 percent are projected. Note that these fuel savings for the turboprop are relative to a turbofan-powered aircraft with the same level of component (i.e., core) technology. Thus, if a new turbofan engine would achieve a 15 percent fuel savings over a conventional turbofan in a new medium-range transport, a new turboprop with the same level of engine component technology could achieve a 30 to 35 percent fuel savings. It is this very large fuel savings potential that prompted NASA to include the Advanced Turboprop Project in its ACEE Program.

The Advanced Turboprop Project, as currently planned, consists of three phases organized and scheduled as shown in figure 31. The recently completed Phase I effort, described in detail in reference 3, helped establish a fundamental high-speed propeller data base through analysis and test of small-scale propellers. Key analytical and experimental investigations were also accomplished in fuselage acoustics and installations aerodynamics. In addition, Phase I also included mission studies for concept definition and preliminary design of systems and components to be developed by later phases.

The initiation of Phase II earlier this year represents a shift in emphasis from small-scale model work to design, fabrication, and ground tests (static and wind tunnel) of a large-scale (2.4 to 3.0 m; 8 to 10 ft diameter) propeller. Following an extensive blade/disk technology program, the first large-scale propeller test assembly is expected to be available early in 1984. Initial static testing will use an existing ground-based propeller drive system. The propeller will then be installed on a gas-turbine propeller-drive system, which will be a modification of an existing turboshaft engine along with a new nacelle and modified gearbox. This propulsion system will then be used for check-out static tests, low-speed wind tunnel tests, and perhaps high-speed wind tunnel tests. Phase II also includes continuation of work in fuselage acoustics and installation aerodynamics. In addition, Phase II effort will be performed on defining requirements for an advanced high-speed turboprop gearbox and carrying out the preliminary design of such a gearbox. Requirement definition and preliminary design of an advanced propeller pitch change mechanism may also be addressed during this effort.

Phase III, currently scheduled to start in 1985, builds on the work of the previous phases and culminates in flight testing of an advanced propeller on a modified test-bed aircraft in 1988. (Note that the program block is shown as ending in 1988, but in actuality, the flight research would continue for several years beyond 1988). This flight research program would use the same propeller and propeller drive system used during the static and wind-tunnel tests of Phase II. Flight research will subject the advanced propeller to the complex flow field and propulsion system interactions not adequately simulated by ground tests. Flight research is further required to investigate fuselage and aircraft concepts for reducing passenger cabin noise and vibration levels. The major effort in installation aerodynamics will be accomplished by wind tunnel model tests, although this area will also be addressed during the flight tests to the extent feasible.

Phase III plans also include ground-based rig tests of an advanced gearbox and pitch change system suitable for an engine in the 15,000 SHP class. Such tests would establish feasibility of the design approach and would provide initial verification of design reliability and durability. Currently, these plans for Phase III are being assessed to establish the feasibility and desirability of accelerating the effort, with the goal of achieving flight research results by 1986. Such results, along with expanded efforts on turboshaft inlets and inlet-compressor stability, would provide earlier technology readiness than now planned. In view of the increasing impact of fuel prices on airline operations, the earliest possible application of prop-fan technology is, of course, highly desirable.

POTENTIAL IMPACT OF ADVANCED PROPULSION TECHNOLOGY

Advanced propulsion system technology as currently being developed in NASA's Energy Efficient Engine Project and Advanced Turboprop Project holds the promise of major improvements in fuel consumption and DOC for future subsonic commercial transport aircraft. In figure 32, the possible impact of this advanced technology on total fuel burned in domestic operations of the domestic trunk fleet is shown. Starting with the approximately 42 billion liters (11 billion gallons) used during 1980, and assuming no fleet efficiency improvements and a 4 percent per year growth in traffic and hence fuel use, domestic airline fuel use would be projected to more than double by the year 2000. Various levels of fuel efficient technology are then assumed to be introduced to proceed linearly until complete conversion is achieved in the year 2000. For curve 1, which is used as a reference, it was assumed as before (figure 22) that during the transition all short/medium range aircraft are replaced with aircraft embodying 757/767 aircraft and engine technology, and that all long range aircraft are assumed to incorporate engine technologies corresponding to the JT9D-7R4/CF6-80 levels. For point 2, it was assumed that current E^3 engine technology was introduced into all aircraft by the year 2000. This would produce a fuel savings of 5.3 billion liters (1.4 billion gallons) in the year 2000 alone, with obviously very large cumulative fuel savings, depending on the rate of introduction. Point 3 is based on the assumption that the short and medium-range portion of the domestic fleet, accounting for 60 percent of the fuel burned, is converted to prop-fan engines, with the conversion completed by the year 2000. Similarly, the long-range portion of the fleet using 40 percent of the fuel converts completely to E^3 technology engines over the same period. In this case, fuel savings in the year 2000 would be around 17.4 billion liters (4.6 billion gallons). Finally, for Point 4 it was assumed that by the year 2000 the domestic fleet would be made up entirely of prop-fan powered aircraft. This assumption results in fuel savings of around 25.4 billion liters (6.7 billion gallons) in the year 2000. Cumulative levels of potential fuel savings from advanced propulsion technology would of course vary with the assumed traffic growth rate, the date of introduction, and the rate of introduction, but regardless of the assumptions used there will be significant percentage reductions in fuel burned with the application of advanced propulsion technology.

In figure 33, this same series of assumptions is used to compare the value of domestic airline DOC in the year 2000. Complete conversion to engines with E^3 technology by that year would produce an overall DOC improvement of 7 percent relative to the 30 percent fleet improvement baseline. If the short-medium range segment of the fleet converts instead to prop-fan technology, the DOC improvement jumps to 22 percent, and complete conversion of the entire domestic fleet to prop-fans by the year 2000 would produce a 32 percent DOC improvement for that year. Thus there would be significant impact on airline operations from the fuel savings of advanced propulsion technology.

Finally, the projected impact of this advanced technology on the projected fuel-related DOC component is shown in figure 34. Curve 1 is from figure 22 and, as previously discussed, assumes an all new short/medium-haul domestic fleet with 757/767 aircraft and engine technology in place by the year 2000, and JT9D-7R4 or CF6-80 technology in the remainder, thus achieving a 30 percent overall fuel efficiency improvement over today's fleet. For this situation, fuel costs were still projected to make up almost 82 percent of DOC by the year 2000. If the entire fleet were assumed to incorporate new engine technology corresponding to projected Energy Efficient Engine levels (point 2), the fuel cost constituent of DOC would be reduced by an increment of about 1-1/2 percent. Point 3 assumes that the short/medium range portion of the fleet converts to prop-fan technology and the long-range portion to E^3 technology. In this case, the fuel cost constituent of DOC is reduced by an additional 4 percent. Complete converstion to all prop-fan technology (point 4) would result in an additional 3-1/2 percent reduction increment, so that fuel cost would comprise around 73 percent of DOC in the year 2000. Thus, even in this most optimistic application of advanced fuel saving technology to the future domestic fleet, fuel costs are projected to remain as the overwhelming constituent of DOC and are obviously the one item which will (and should) receive the largest technology attention.

CONCLUDING REMARKS

The future outlook for various facets of advanced subsonic transport propulsion is summarized in figure 35. Emphasis on minimizing fuel burned will almost certainly increase even further as fuel costs account for a larger and larger percentage of total direct operating costs. Installation effects will likely receive increased attention as the trend to larger turbofan bypass ratios produces larger nacelles and as increasing fuel costs put a larger premium on installed drag reduction. (Mixed exhaust systems will also most likely receive increased attention.) Steady improvements in engine component performance and cycle operating pressures and temperatures are anticipated in the future, but such advances will be relatively small--as compared to the past--as the higher cycle conditions make it increasingly difficult to maintain component efficiencies. In considering alternate propulsion concepts, the geared turbofan option does not appear to offer a clear economic advantage over similar-technology direct-drive turbofans, based on studies to date. The prop-fan concept, on the other hand, appears extremely attractive economically and will certainly receive major technology emphasis in coming years to attempt to bring it to commercial reality.

In summary, it is anticipated that Energy Efficient Engine-type turbofan technology will continue to evolve and find its way into the commercial fleet, producing steady improvements in overall fuel efficiency levels. While the future outlook for geared turbofans must be considered questionable, prop-fans offer such economic potential to commercial air transportation that they appear a major propulsion contender for the future. Through the Energy Efficient Engine Project and the Advanced Turboprop Project, NASA is currently developing the advanced technology required to achieve such future significant improvements in aircraft fuel efficiency.

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TABLE I. - ENERGY EFFICIENT ENGINE COMPONENT TECHNOLOGY IMPROVEMENTS

• IMPROVED COMPONENT AERODYNAMICS	• ENDWALL CONTROL • LOW-LOSS AIRFOILS
• REDUCED TIP CLEARANCES	• INTERNAL ACTIVE CLEARANCE CONTROL • THERMALLY MATCHED ROTORS AND CASES
• INCREASED COMPONENT WORK PER STAGE	• HIGHER TIP SPEEDS • IMPROVED AERODYNAMICS
• LOW-EMISSION, LONG LIFE COMBUSTORS	• IMPROVED STAGED COMBUSTION • SECTIONED, FLOATING COMBUSTOR LINERS
• REDUCED COOLING REQUIREMENTS	• IMPROVED COMBUSTOR LINER DESIGN • IMPROVED HPT COOLING AND MATERIALS
• ADVANCED MIXERS	• INCREASED MIXING EFFECTIVENESS • REDUCED PRESSURE LOSS
• IMPROVED COMPONENT PERFORMANCE RETENTION	• DESIGN • MATERIALS

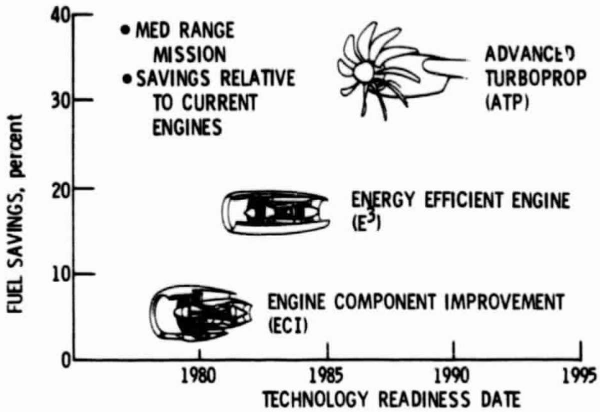


Figure 1. - ACEE propulsion projects. Projected fuel savings and technology readiness dates.

REDUCE FUEL USAGE

12% SPECIFIC FUEL CONSUMPTION (SFC)

50% PERFORMANCE DETERIORATION RATE

IMPROVE OPERATING COSTS

5% DIRECT OPERATING COST (DOC)

} RELATIVE TO CURRENT ENGINES (JT9D - 7A/CF6-50C)

MEET FUTURE ENVIRONMENTAL REGULATIONS

NOISE	FAR - 36 (1978)
EMISSIONS	EPA - 1981

Figure 2. - Energy Efficient Engine Project propulsion system design goals.

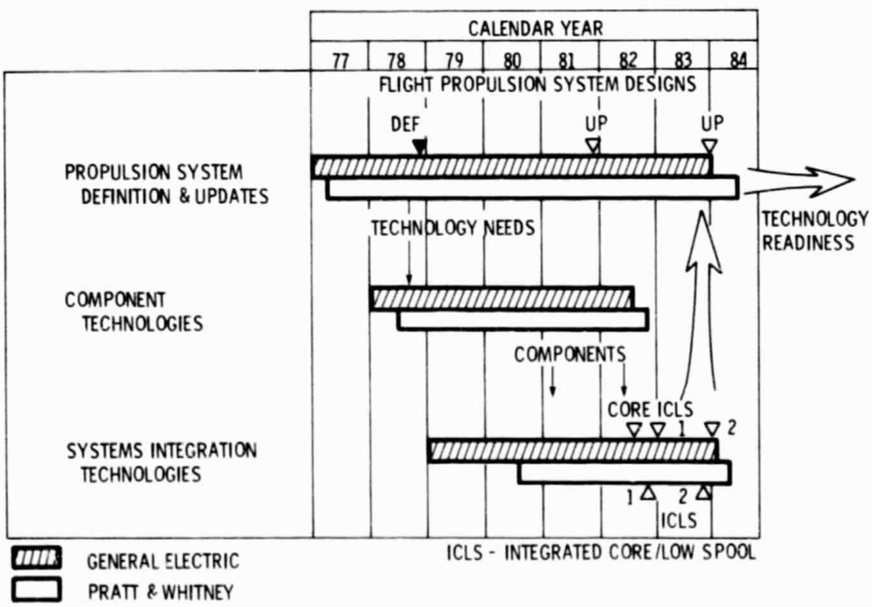


Figure 3. - Energy Efficient Engine Project summary schedule.

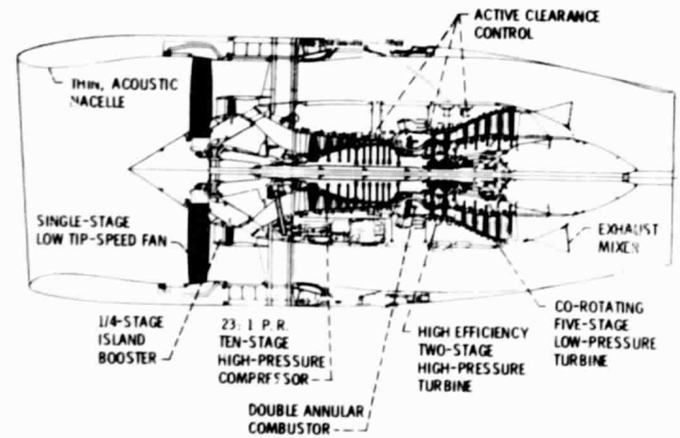


Figure 4. - Energy Efficient Engine configuration - General Electric.

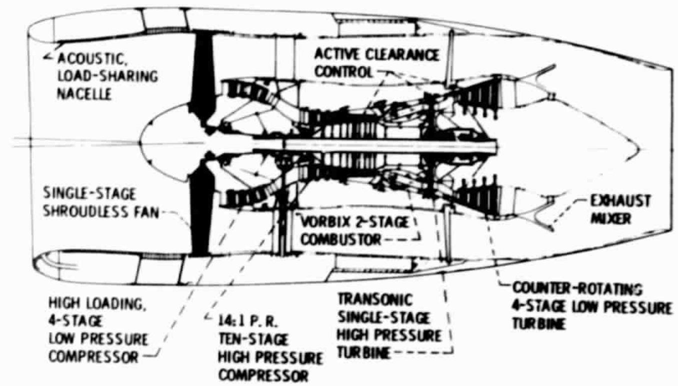


Figure 5. - Energy Efficient Engine configuration - Pratt and Whitney.

	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	6.61	6.9	4.3
FAN PRESSURE RATIO	1.58	1.71	1.61	1.73
COMPRESSOR PRESSURE RATIO	10	14	22.6	12.5
OVERALL PRESSURE RATIO	25.4	37.3	36.1	30.1
TURBINE TEMPERATURE (^{o}F)				
MAX. CRUISE	1990	2193	2170	2080
HOT-DAY TAKEOFF	2285	2484	2450	2400

Figure 6. - Cycles selected for E^3 designs (maximum cruise conditions).

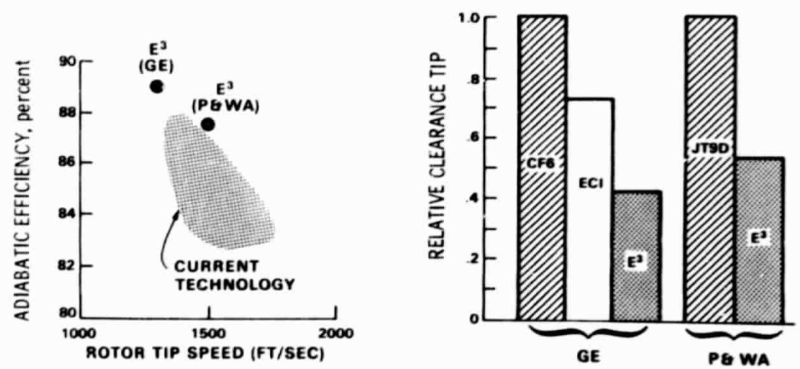


Figure 7. - Advances in fan performance.

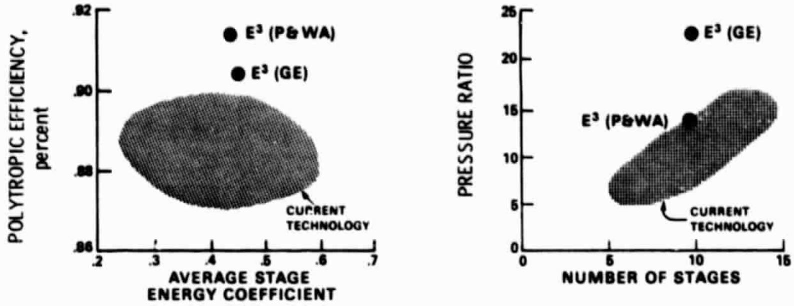
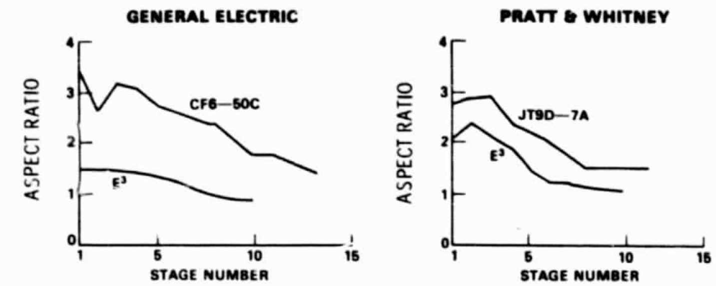


Figure 8. - Advances in compressor performance.



	PRESSURE RATIO	TIP SPEED	AIRFOILS
CF6-50C	13.2	1120	1747
E³	22.6	1495	1706

	PRESSURE RATIO	TIP SPEED	AIRFOILS
JT9D-7A	10	1003	2378
E³	14	1320	1320

Figure 9. - Advances in compressor design.

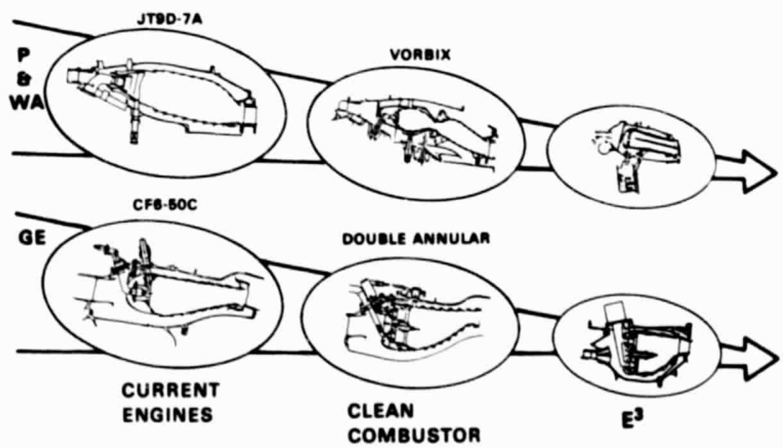


Figure 10. - Combustor evolution.

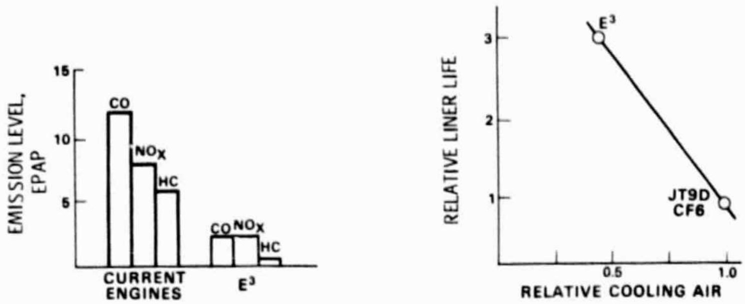


Figure 11. - Advances in combustor performance.

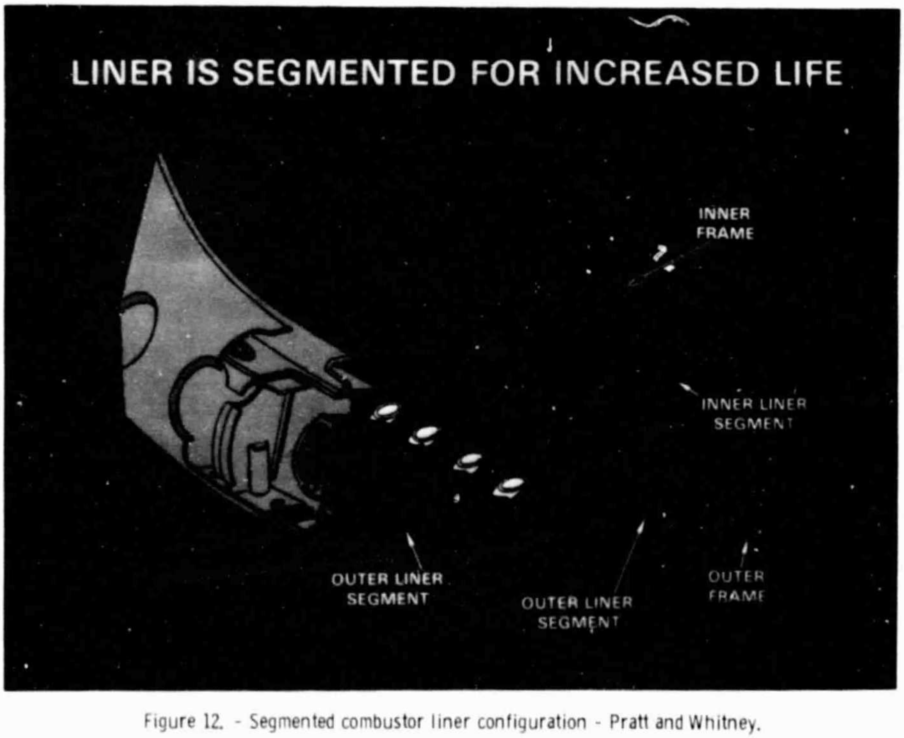


Figure 12. - Segmented combustor liner configuration - Pratt and Whitney.

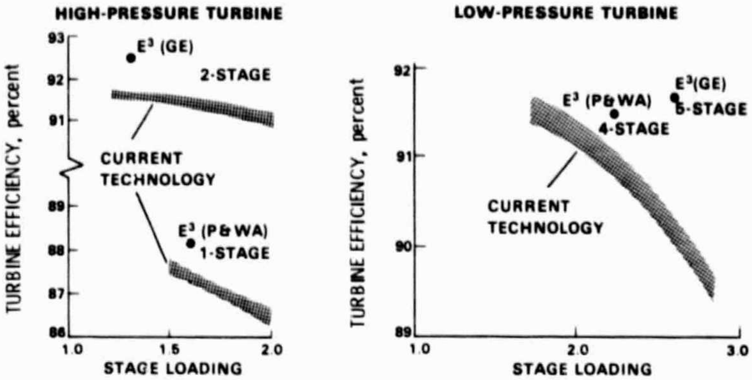


Figure 13. - Advances in turbine performance.

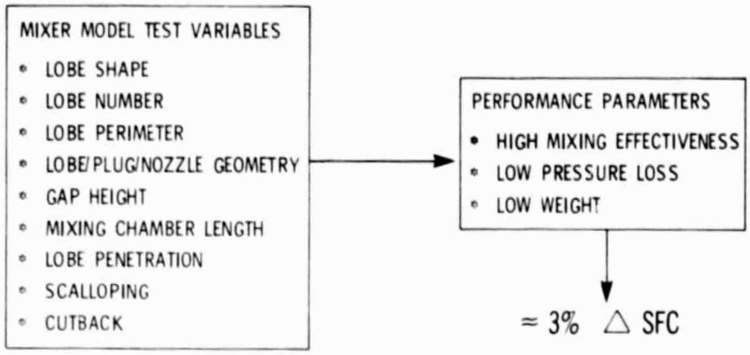


Figure 14. - Energy Efficient Engine mixer development.

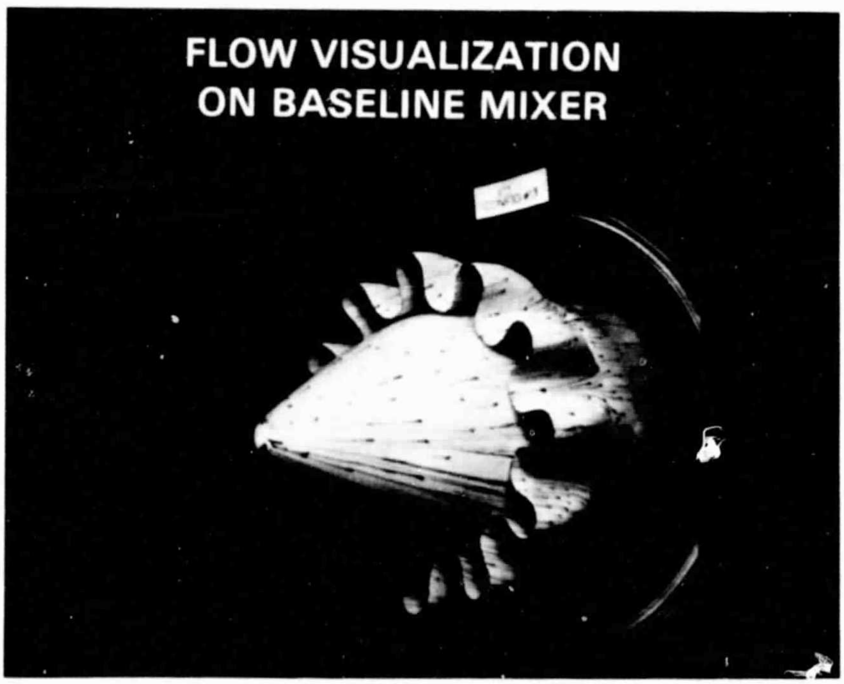


Figure 15. - Mixer model.

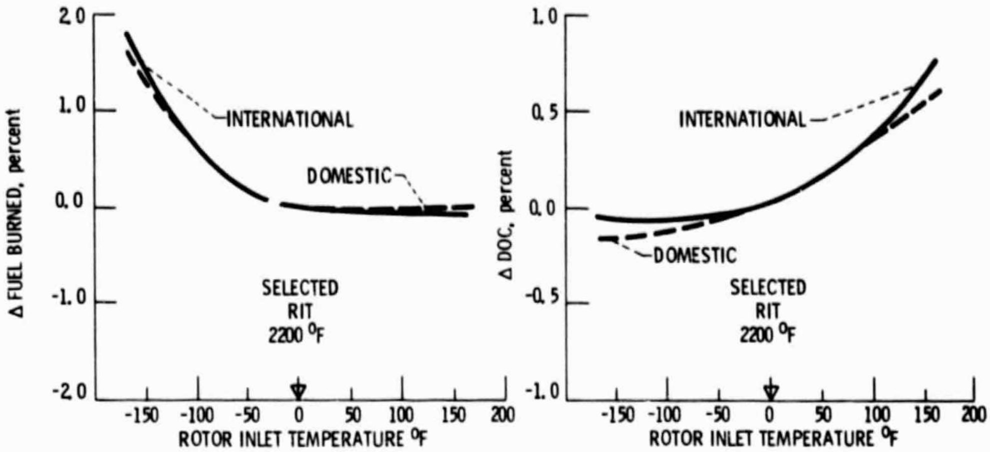


Figure 16. - Pratt and Whitney Energy Efficient Engine cycle trades.

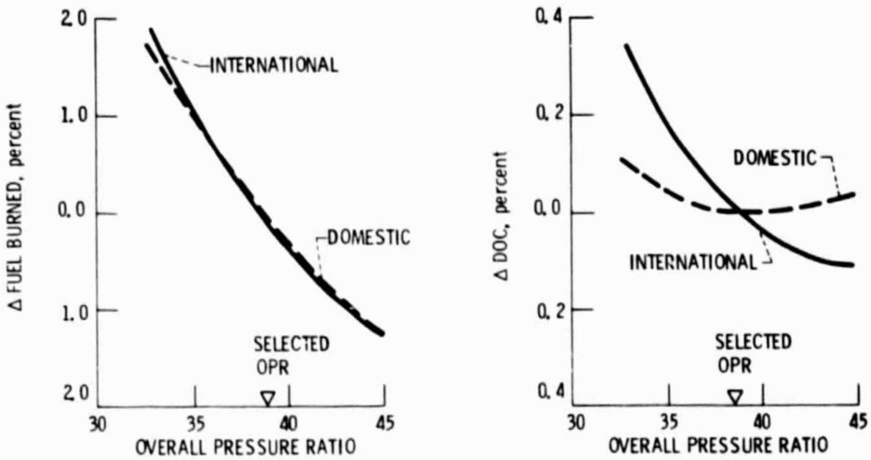


Figure 17. - Pratt and Whitney Energy Efficient Engine cycle trades.

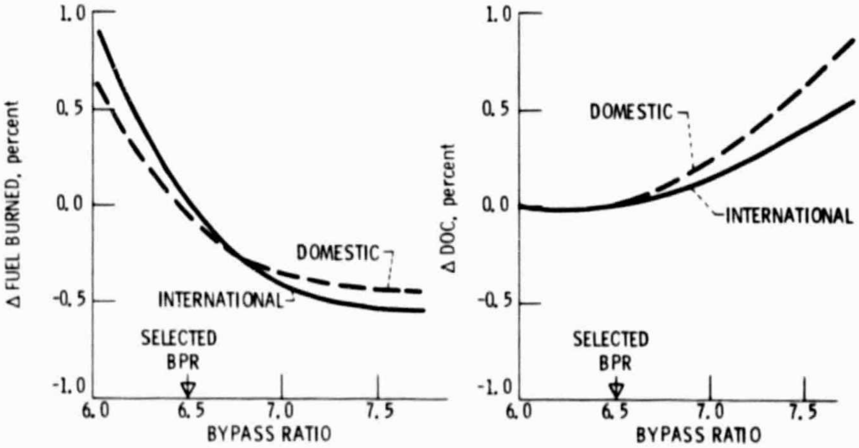
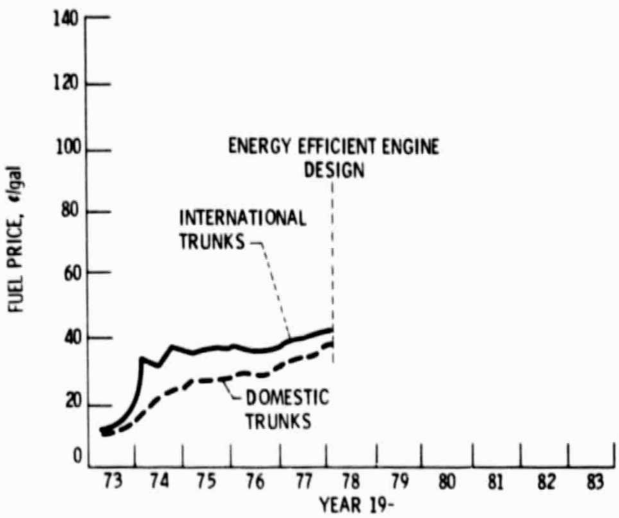
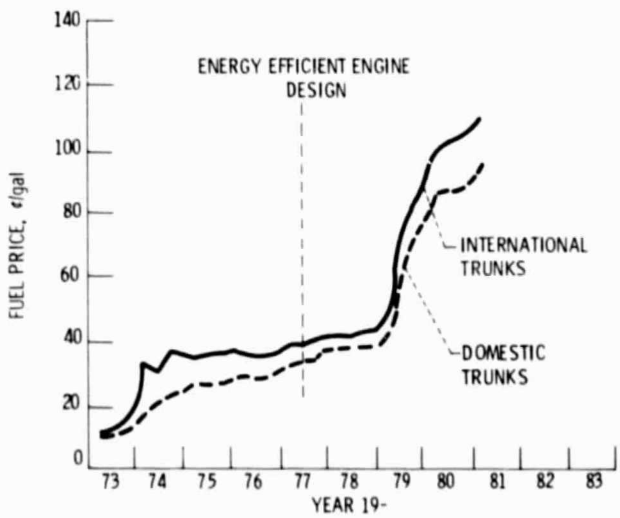


Figure 18. - Pratt and Whitney Energy Efficient Engine cycle trades.



SOURCE: SUMMARIZED CAB FORM 41 DATA

Figure 19. - U. S. airline jet fuel price (monthly averages).



SOURCE: SUMMARIZED CAB FORM 41 DATA

Figure 20. - U. S. airline jet fuel price (monthly averages).

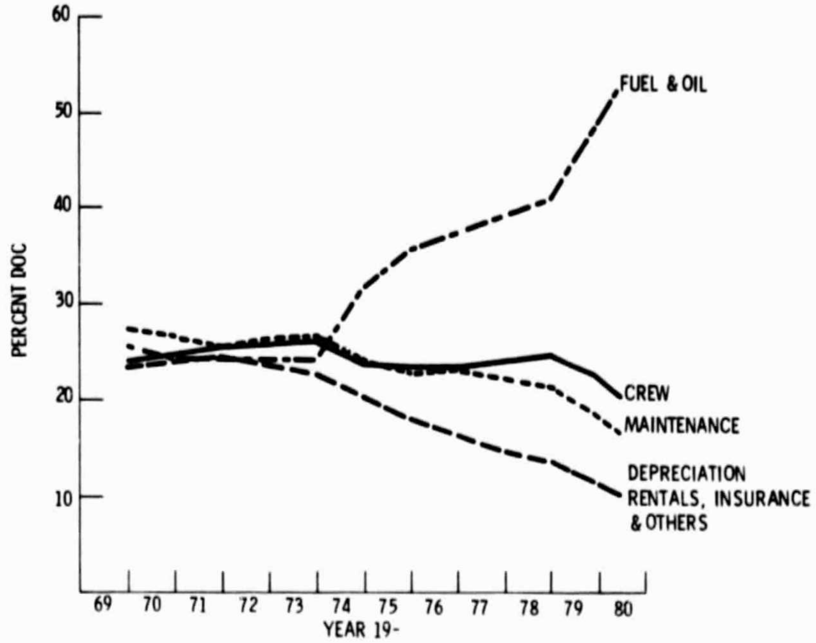


Figure 21. - DOC elements as a percent of total DOC. CAB Form 41 data.

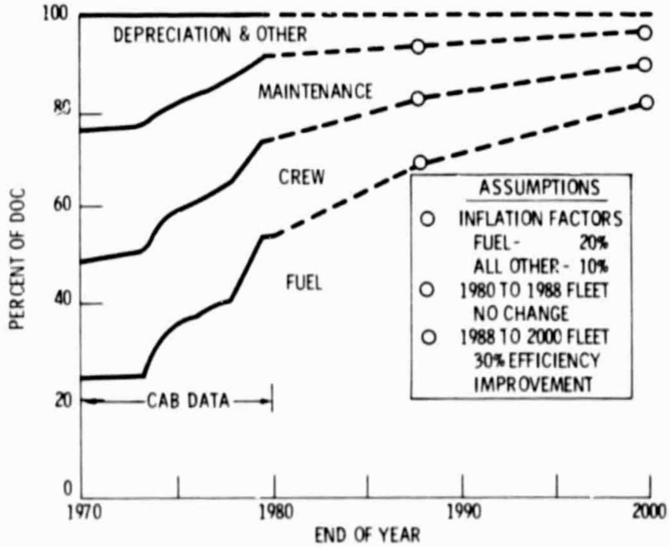


Figure 22. - DOC projections.

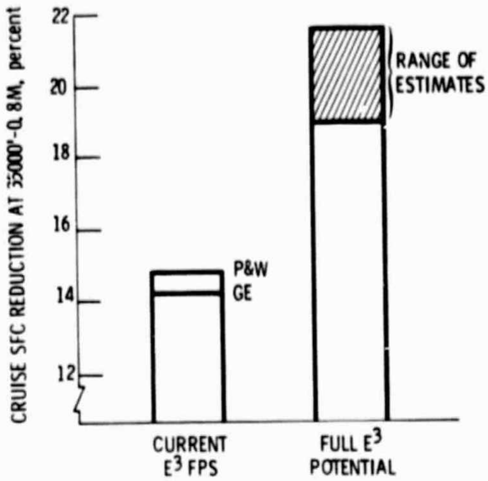


Figure 23. - Energy efficient engine potential performance improvement relative to JT9D-7A/CF6-50C.

	P&WA	GE
ΔSFC, INST., %	-3.5	-0.7
ΔFUEL USED, %	-2.2	+1.9
ΔDOC @35¢/ GAL, %	-0.5	+2.1
ΔDOC @ $1/ GAL, %	-2.0	+0.6
ΔNOISE, EPNdB	$(-2 \text{ TO } -5)^2$	$(0 \text{ TO } -2)^3$

NOTE
1. REF. NASA CR-135444 (GE); CR-135396 (PWA)
2. WITHOUT AIRCRAFT NOISE
3. WITH AIRCRAFT NOISE

Figure 24. - EEE preliminary design results - geared vs. direct drive turbofan. (Average domestic mission.)

- FUEL SAVINGS RELATIVE TO DIRECT-DRIVE TURBOFAN
  - SMALL TO NEGATIVE
  - IMPROVED SFC OFFSET BY INCREASED WEIGHT AND DRAG
- DOC IMPROVEMENTS RELATIVE TO DIRECT-DRIVE TURBOFAN
  - SMALL TO NEGATIVE
  - HELD DOWN BY HIGHER ENGINE/NACELLE COSTS AND MAINTENANCE COSTS
  - INCREASE SOMEWHAT WITH HIGHER RELATIVE FUEL PRICES
- CONSENSUS
  - RISK/PAYOFF COMBINATION NOT ATTRACTIVE

Figure 25. - Summary results - Energy Efficient Engine geared turbofan studies.

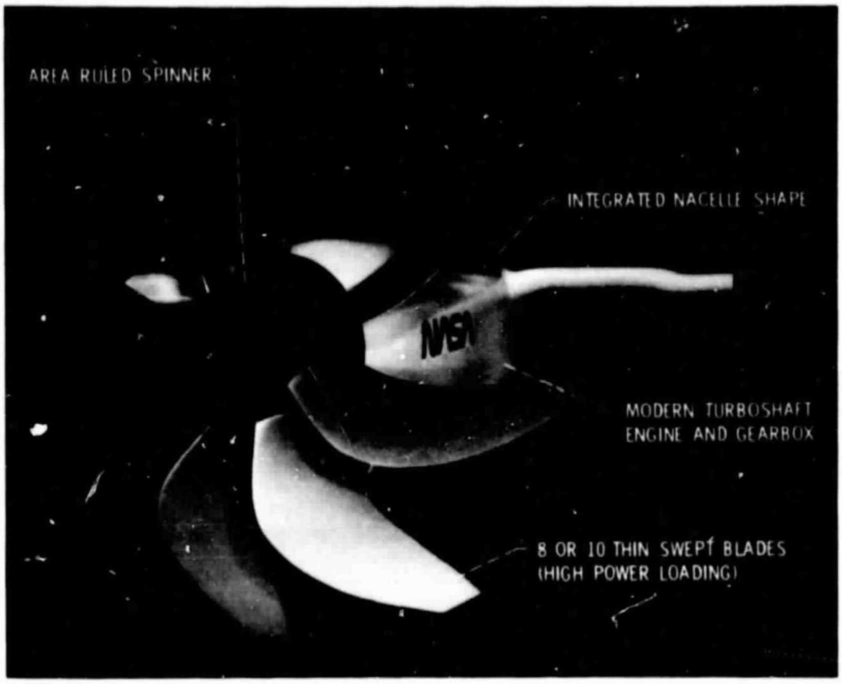


Figure 26. - Advanced turboprop propulsion system.

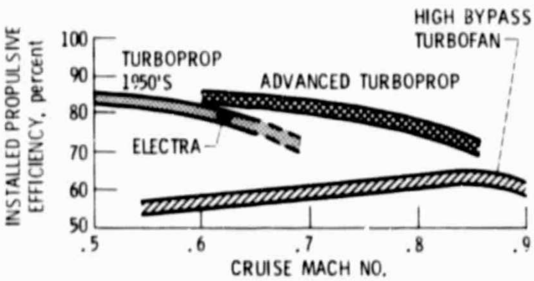


Figure 27. - Installed propulsive efficiency at cruise.

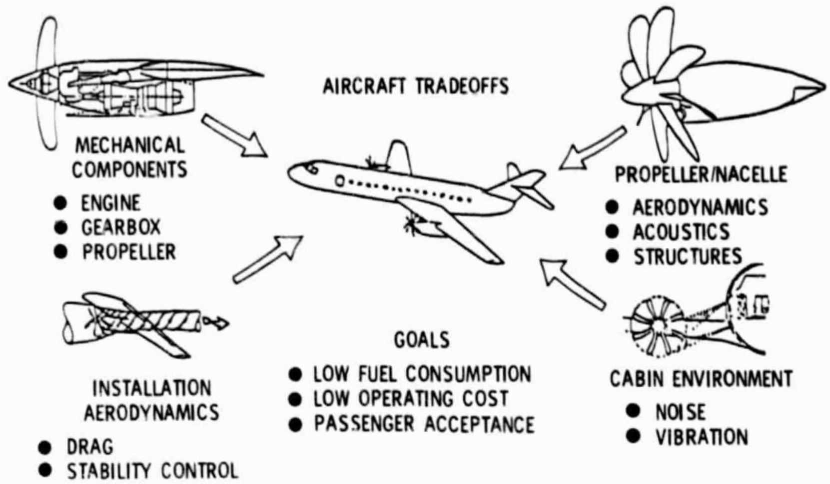


Figure 28. - Prop-fan technologies.

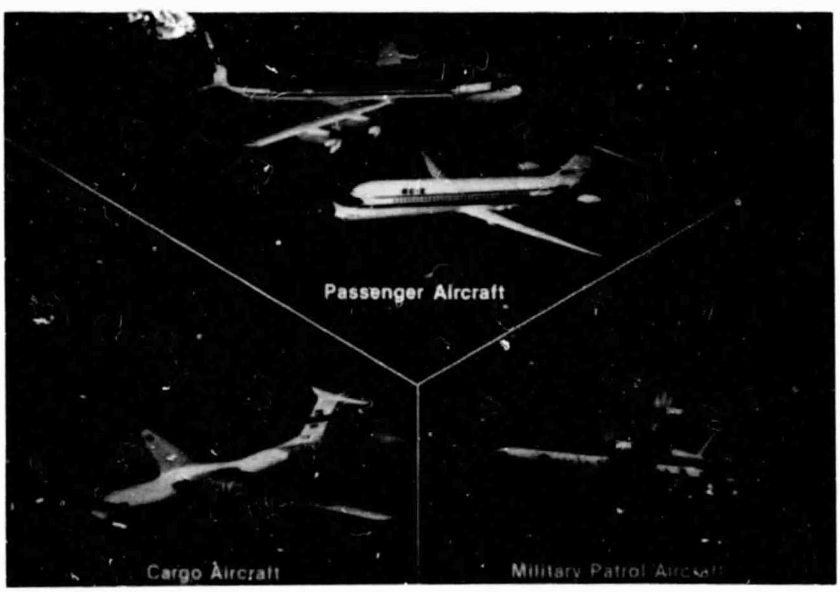


Figure 29. - Advanced turboprop aircraft concepts.

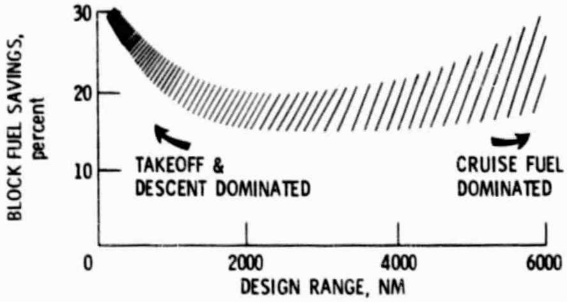


Figure 30. - Advanced turboprop fuel savings relative to turbofan-powered aircraft with same level of core technology.

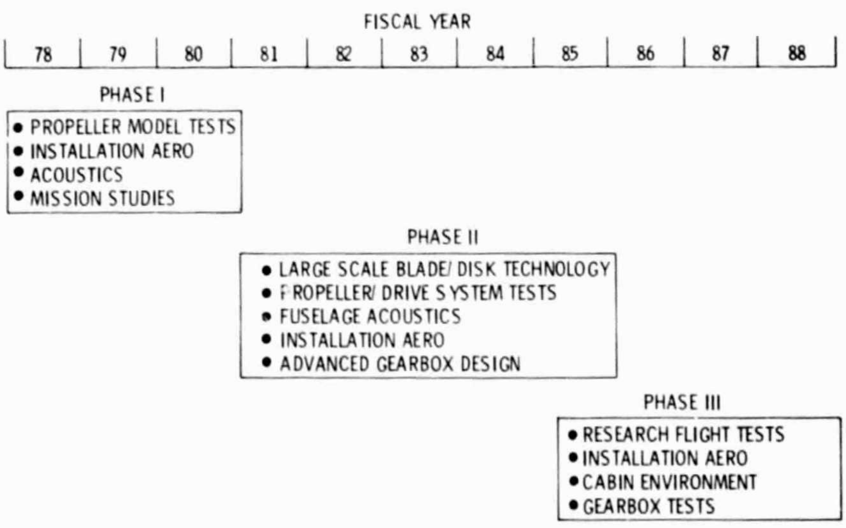


Figure 31. - NASA advanced turboprop program.

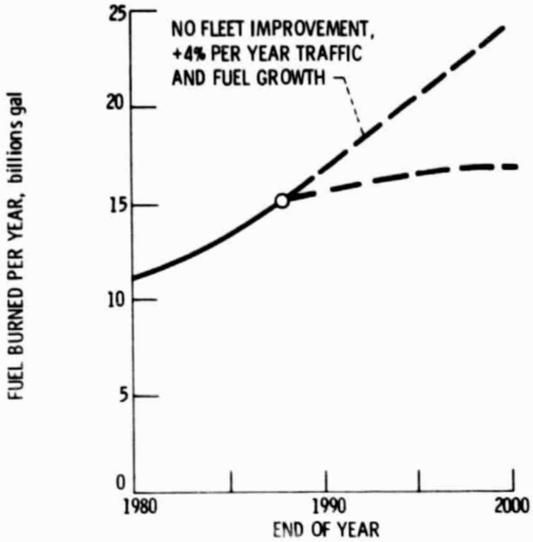


Figure 32. - Impact of advanced technology on fuel.

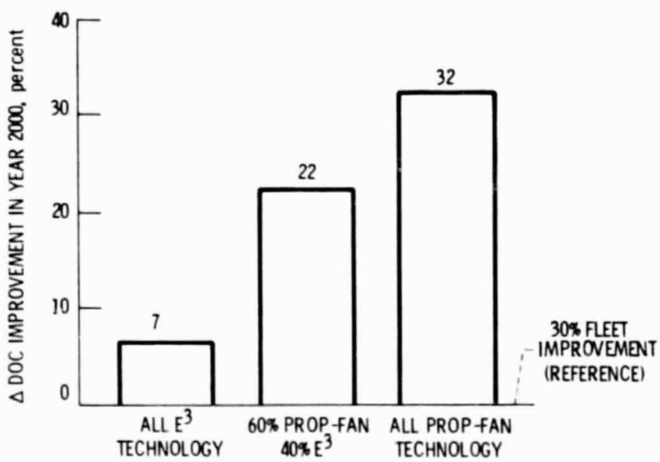


Figure 33. - Impact of advanced technology on DOC.

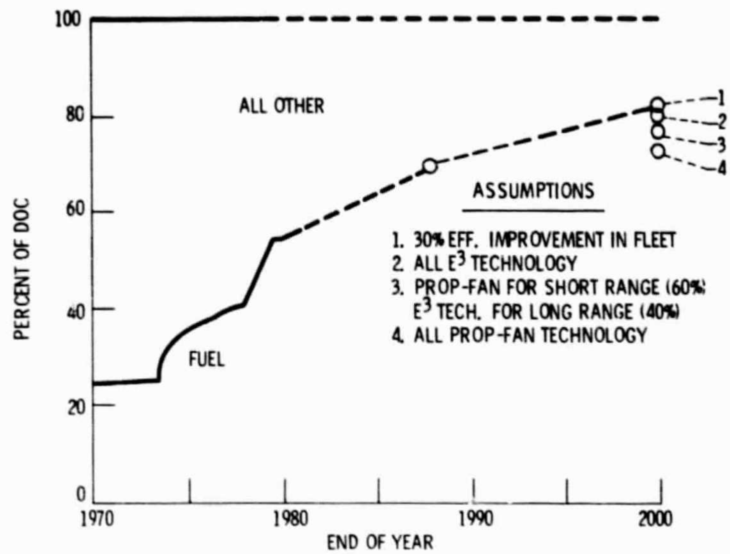


Figure 34. - DOC projections.

- MINIMIZE FUEL BURNED - - LARGEST IMPACT ON DOC
- INCREASED ATTENTION TO INSTALLATION EFFECTS
- SLOW INCREASES IN COMPONENT EFFICIENCY
- SLOW INCREASES IN OPERATING PRESSURE RATIO AND ROTOR INLET TEMPERATURE
  - BECOMES MORE DIFFICULT TO MAINTAIN COMPONENT EFFICIENCIES
    - INCREASED LEAKAGE LOSSES
    - INCREASED REQUIREMENTS FOR COOLING AIR
    - SMALLER COMPONENTS (e.g., HPC BLADING)
- GEARED FANS - QUESTIONABLE PAYOFF
- PROP - FANS - HIGH PAYOFF FOR ALL APPLICATIONS

Figure 35. - Future outlook for advanced subsonic transport propulsion.

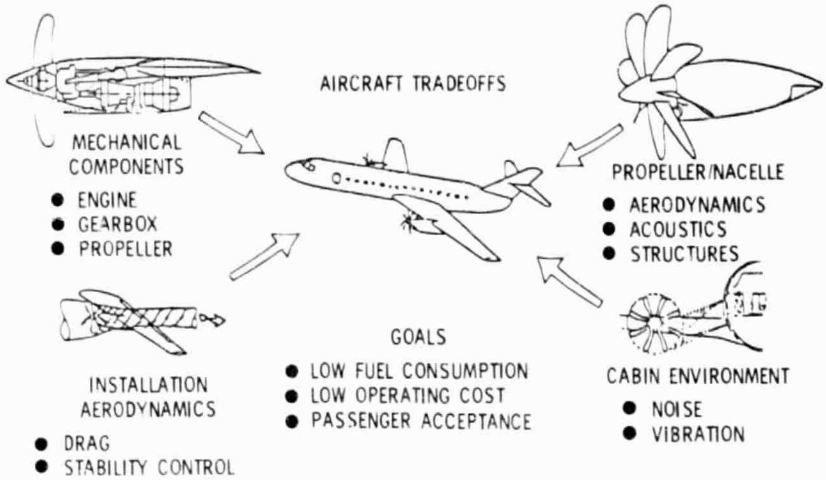


Figure 28. - Prop-fan technologies.

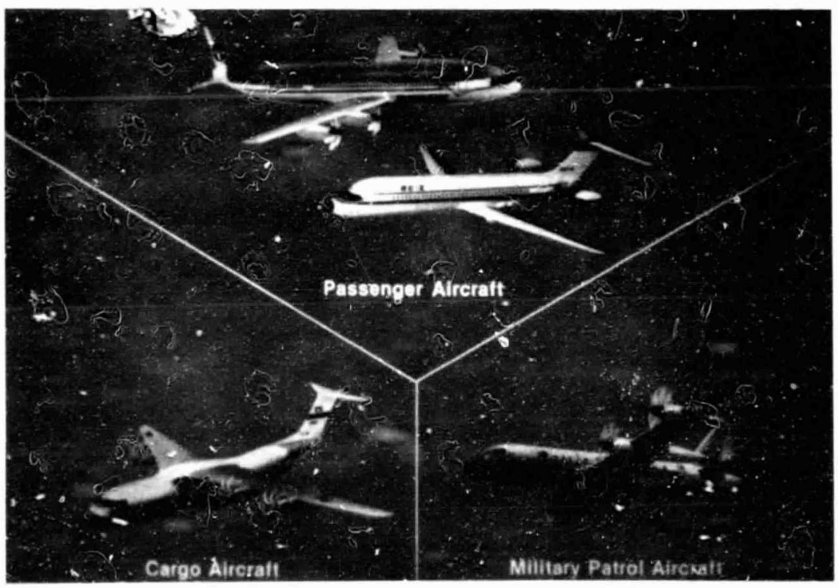


Figure 29. - Advanced turboprop aircraft concepts.