NASA Technical Memorandum 81507

(NASA-TM-81507) ADVANCED COMPONENT TECHNOLOGIES FOR ENERGY-EFFICIENT TURBOFAN ENGINES (NASA) 19 p HC A02/MF A01 CSCL 21E
N80-24316
Unclas
G3/07 20956

ADVANCED COMPONENT TECHNOLOGIES FOR ENERGY-EFFICIENT TURBOFAN ENGINES

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Prepared for the
Sixteenth Joint Propulsion Conference
cosponsored by the AIAA, ASME, and SAE
Hartford, Connecticut, June 30-July 2, 1980

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Abstract

NASA's Energy Efficient Engine (E^3) Project is a cooperative government-industry effort to develop the advanced technology base for future commercial development of a new generation of more fuel-conservative turbofan engines for airline use. This effort is being accomplished by two major domestic engine manufacturers: General Electric and Pratt & Whitney Aircraft. These companies have defined advanced engine configurations that are dependent upon technology advances in each major engine component, and they are currently designing and developing the advanced components. This paper describes each of the major engine components and the advanced technologies being developed for these components.

Introduction

One of the major elements in NASA's Aircraft Energy Efficiency (ACEE) Program is the Energy Efficient Engine (E^3) Project. This project is intended to provide the advanced technology base for a new generation of fuel-conservative engines that could be introduced into airline service by the late 1980s or early 1990s. The efforts in the E^3 Project are directed at advancing engine component and systems technologies to a point of demonstrating technology-readiness by 1984. If successful, commercial development of new engines could be subsequently initiated by the engine manufacturers in a timely manner to meet potential airline needs of the 1990s. Also, selected technologies could be incorporated by the engine manufacturers in derivative versions of their current engines, for possible introduction into airline fleets by the mid to late 1980s.

The prime emphasis of the E^3 Project is on the development of advanced technologies for reducing fuel consumption in future engines. However, future engines must be not only more fuel-efficient, but they also must be economically attractive to the airlines and environmentally acceptable to the public to be viable commercial products. Thus, engine design goals were established at the outset of the project to help guide the selection of engine cycles and configurations and to provide a focus for the project's component technology efforts. These goals are listed in Figure 1. These design goals address performance levels that can be expected in fully-developed flight-qualified engines. This includes performance improvements that typically are achieved during the 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 primarily through parallel contracts with the two U.S. manufacturers of large, high-bypass-ratio engines: the Aircraft Engine Group of the General Electric Company (GE) and the Pratt & Whitney Aircraft Group (P&WA) of the United Technologies Corporation. These organizations have developed preliminary designs of energy efficient engines that are predicted to meet or exceed the project's design goals, and they are currently developing the advanced component technologies to achieve the desired performance improvements. The early study efforts that led to these engine designs are summarized in Reference 1, and the preliminary engine designs are described in References 2 and 3.

Artist's conceptions of the initial E^3 configurations designed by each engine manufacturer are shown in Figures 2 and 3, and the cycle characteristics of both engines are summarized in Figure 4. Both engines employ a two-spool design with a total engine inlet airflow of about 1400 pounds per second and a core inlet airflow of about 120 pounds per second. Also, both engine configurations include long-duct nacelles and exhaust mixers to take advantage of the large performance advantages (i.e. - about 3% reduction in specific fuel consumption and reduced noise) of mixing the engine core and bypass air streams. For the experimental efforts conducted in the E^3 Project, both engines are sized to produce about 36,000 pounds of thrust at take-off; however, any future commercial versions of these engines could be scaled to other sizes if future airline requirements indicate a need for other thrust levels. Also, the advanced technologies being developed in the E^3 Project could be applied to derivative versions of current engines that operate at other thrust levels.

Both engines, if fully developed, are predicted to have at least 14% lower specific fuel consumption (SFC) at maximum cruise conditions than current turbofan engines selected as baselines for comparison (i.e. - the CF6-50C and the JT9D-7A engines). Most of this SFC improvement results from the performance improvements expected in each of the major engine components, as indicated in Figure 5. (Note: This figure illustrates the percent SFC improvements as compared to the respective engine used by each company as a baseline. Since the two baseline engines have different technology levels and SFC values, the absolute levels of SFC improvements are not directly comparable between GE and P&WA.) Thus, major emphasis in the E^3 Project is directed at developing improved engine components that incorporate aggressive advances in technology. Although the overall engine configurations and cycles for the two energy efficient engines are similar, each manufacturer is developing unique component designs with different technologies incorporated. So this paper presents an overview of the component configurations selected by each engine manufacturer, the prime performance improvements planned, and the advanced technologies being incorporated. Each component will be discussed individually starting with the fan and working rearward through the engine to the exhaust mixer.

Fans

In the fan section, the prime performance improvements that require the application of advanced technologies (i.e. - "technology-drivers") for both engine manufacturers' E^3 configuration are:

- increased bypass ratio
- higher efficiencies
- improved performance retention
- lower noise

The bypass ratios in these engine configurations have been increased from the levels of about 4 to 5 in current engines to a value of about 7 in the E^3 configurations. This translates to technology requirements for larger fans with lower-aspect-ratio blading and lighter-weight containment to minimize the weight increases associated with the larger fans. The greater efficiencies desired in the fans will result from improved aerodynamic designs of the airfoils and reduced clearances between the blade tips and the outer shrouds of the fan case.

Examples of the levels of performance improvements being sought are shown in Figure 6. The figure on the left shows the planned improvements in adiabatic efficiency as a function of rotor tip speeds for both engine manufacturers' current fan designs. The crossed-hatched area in the center of the figure indicates the levels of efficiency obtained in current-technology fans, and the two points at the top of the figure indicate the efficiency levels that have been established as goals for both E^3 designs. The GE fan design is targeted for about 88.7% adiabatic efficiency, and this is planned to be achieved with rotor tip speeds in the order of 1300 feet per second. The P&WA fan configuration has a goal of about 87.3% adiabatic efficiency, and this is planned to be achieved at tip speeds of about 1500 feet per second.

Much of the efficiency improvements expected in these fans will result from the use of much tighter clearances between the fan-blade tips and the fan case. This is illustrated in the bar graph on the right of Figure 6 which indicates the degree of reduction in tip clearances expected in both fan designs. The three bars on the left side of this graph show comparisons for GE's designs. For E^3, the design goal is less than 50% of the tip clearances associated with CF6 engines. This is an even greater reduction than the tip clearance achieved in an advanced CF6 fan that was developed under the NASA-sponsored Engine Component Improvement (ECI) Project (Reference 4). For the P&WA engine configurations, the E^3 fan is planned to have tip clearances of about 55% of those currently obtained in JT9D engines. These reductions in tip clearances for E^3 are expected to contribute about 0.5% to the total reduction in engine SFC.

The prime features of the fan configurations selected by each engine manufacturer are shown in Figure 7. A cross-section of the GE configuration is shown on the left, while the P&WA configuration is shown on the right. Both configurations are single-stage fans with wide axial spacing between the blades and vanes. This wide spacing permits integration of the exit guide vanes and the structural struts that support the fan case without increasing the noise levels generated by the fan. Integration of vanes and struts helps reduce the number of airfoils required, and this reduces engine weight and cost. Both configurations have incorporated major advances in the strut design to improve the stiffness of the outer case and thereby assure improved performance retention in the fans. Also, both configurations utilize Kevlar/metal blade-containment systems in the outer fan cases to reduce the weight of the case and yet assure adequate safety for containment of any blade fragments that might occur as a result of fan ingestion of foreign objects.

The GE fan configuration utilizes solid titanium blades with one mid-span damper. This damper has been located lower than usual on the radial-span of the airfoils and near the trailing edge to reduce the aerodynamic losses that are normally associated with these dampers. The GE fan design also incorporates a unique quarter-stage booster just aft of the fan blades. This stage boosts the fan-stream pressure before entering the core, and it also provides a centrifuging action to reduce the amount of foreign particles that could enter the core stream. Any small particles entering the fan stream and going through the quarter-stage booster will tend to be centrifuged out into the engine bypass stream and thereby be prevented from entering the core compressor. This should greatly aid performance retention of the compressor by reducing the amount of erosion typically found on the leading edge of compressor blades.

The most advanced feature in the P&WA fan is the use of shroudless fan blades for increased aerodynamic performance. These blades will be produced from titanium foils and will be produced with hollow sections in the outer portion of the airfoils in order to reduce weight and to meet aeroelastic structural requirements. A unique airfoil design has been designed to meet both the aerodynamic performance and the aeroelastic stability requirements of these large fan blades. This unique configuration is shown in Figure 8. Note that four large hollow areas are incorporated which are separated by thin radial struts. Also, a thin chordwise strut is included to improve the structural stability of the blades. Finite element analysis of this blade configuration indicates that the blade should meet all of the operating requirements and withstand the aeroelastic forces that are expected under typical engine operating conditions.

Several types of fabrication processes were evaluated early in the E^3 Project to produce this type of unique blade. These fabrication processes included: (1) superplastic forming and diffusion bonding; (2) isothermal forging and diffusion bonding; and (3) lamination and diffusion bonding. After conducting some exploratory studies on each of these areas and assessing the potential production costs of each, it was decided that the lamination-and-diffusion-bonding process offered the best opportunity for meeting the goals of the project; therefore, this fabrication process was selected to be further developed under the E^3 Project. So P&WA currently has a subcontract with the TRW, Inc. to develop a lamination-and-diffusion-bonding process to fabricate these unique hollow fan blades, and the required manufacturing technology efforts are currently in progress.

Compressors

Major technology advances are planned by both engine manufacturers for their high pressure compressors. The prime technical-drivers here are:

- higher pressure and energy per stage
- higher efficiencies
- improved performance retention
- lower maintenance costs

The generation of higher pressure and energy in each stage is desired to keep the compressors as short and compact as possible. This compactness helps reduce engine weight and also leads to improved performance retention in the turbomachinery because of greater engine stiffness. Higher efficiencies are desired in order to reduce the fuel consumption of the total engine system.

The levels of performance improvements sought are indicated in Figure 9. The plot on the left shows the goals for compressor efficiency as a function of average stage energy coefficient. As indicated, the P&WA compressor configuration is aimed at a significant increase in polytropic efficiency above the current levels of technology, while a smaller gain in efficiency is planned by GE. The GE compressor is primarily aimed at achieving much higher pressure rise per stage in order to get much greater overall compression in the smallest number of stages possible. This is indicated in the plot on the right of Figure 9 which indicates that the GE compressor will try to achieve a pressure ratio of about 23:1 in only ten stages while the P&WA compressor is aimed at achieving a pressure ratio of about 14:1, also in ten stages. The remainder of the total compression in the P&WA engine will be generated by the four-stage low-pressure compressor shown in Figure 7. This split in compression system was necessary in this engine because P&WA selected a single-stage high-pressure turbine for their high-pressure spool. This limited the amount of compression that could be generated in the mating high-pressure compressor.

Cross-sections of the two high-pressure compressors are shown in Figure 10, with the GE configuration shown on the left and the P&WA configuration shown on the right. Both configurations are designed for high inlet tip speeds and have low-aspect-ratio blading incorporated throughout the ten stages of each compressor. Also, both configurations are dependent upon much tighter tip clearances between the blading and the outer compressor casing, as compared to the tip clearances in current engines. These reduced tip clearances will be achieved through a combination of better thermal matching of the materials involved in the rotor and case and also through the use of active-clearance-control systems applied to the cases. Although the specific designs of the active-clearance-control systems selected by each engine manufacturer are considerably different, they are both dependent upon controlled cooling of the outer cases during engine transient operations to help the case expand and shrink at rates similar to those of the rotor. Both of the configurations also involve use of shallow grooves (trenches) opposite the rotor tips to minimize aerodynamic losses during operation. Abradable rub strips are included in the base of the case trenches to minimize blade-tip wear if case rubs occur and also to prevent titanium-to-titanium contact in the stages where titanium blades and cases are used. In addition, the stator seals have been specially designed for tighter clearances to reduce the amount of leakage through these areas.

Some of the advances in the overall compressor designs for both manufacturers are indicated in Figure 11. This figure compares some design aspects of the E^3 compressors with those from the reference engines. Note that the aspect ratios for the E^3 compressor blades are considerably lower than those of the reference engines--this is particularly apparent for GE's compressor. This feature, coupled with higher tip speeds, aid the compressors in developing much higher pressure ratios per stage. These advances help generate the higher levels of total compression in fewer stages, and this results in a reduced number of airfoils in the compressors--particularly for P&WA's E^3 compressor.

Both compressor designs also incorporate various features to reduce foreign object damage and improve erosion resistance in the airfoils. In the case of the GE configuration, the quarter-stage booster in the fan section helps to centrifuge foreign particles away from the core stream. For the P&WA configuration, emphasis has been given to thickening the leading edge of the airfoils to make the blades more resistant to foreign object damage and erosion. Also, the number of compressor airfoils for P&WA's E^3 configuration has been reduced considerably from that in their current version of the JT9D engine. This results in reduced airfoil costs since there are fewer blades to replace and longer lives of these blades are expected.

Combustors

Several major technology advances have been incorporated in both E^3 combustors. The prime drivers of the technology advancements in these combustors are:

- lower emissions
- longer life
- higher pressures and temperatures
- shorter length

The most significant technology-driver in the E^3 combustors is the desire for lower emissions. This is illustrated in Figure 12, which shows the reductions that are desired for the E^3 combustors in carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC). The levels of these emissions from current engines are in the order of 6 to 12 points measured on the EPA parameter (EPAP) scale. However, the aggressive emission goals for the E^3 project require these levels to be reduced to the order of 0.4 to 3 points on the EPAP scale.

The other prime technology-driver is the need for longer life in combustors. Historically, combustors in aircraft engines have had relatively short lifespans; thus, combustors have been one of the prime contributors to high maintenance costs for engines. Therefore, the combustors for E^3 have been designed to meet a goal that would improve the life of the combustors by a factor of at least 3--as indicated in the right side of Figure 12. These desired improvements in combustor life are compounded by the fact that the E^3 engine cycles require the combustors to operate at much higher pressures and temperatures and also to achieve this increased life with about 50% less cooling flow through the combustor (to produce minimal impact on the engine SFC). Also, the E^3 combustors should be shorter in length in order to minimize the overall length and weight of the engines.

The prime features of both manufacturers' combustors are shown in Figure 13. Both of these configurations require two separate combustion zones to try to meet the very stringent emission goals set for the project. Two separate burning zones are needed in these combustors because the control of carbon monoxide and hydrocarbons must be done primarily at low operational speeds for the engines, while control of the nitrogen oxides must be done at high engine speeds. Therefore, the "pilot" burning zones are intended for operation at the low speeds of the engines to control CO and HC, and the "main" burning zones are intended for control of NO_x at the high-speed range of the engines. The arrangement and designs of these two separate burning zones are considerably different for each manufacturers' engine configuration. The GE combustor has the two zones located radially in parallel (i.e. - a double-annular configuration), while the P&WA combustor has the two different burning zones located axially in series (termed a "Vorbix" configuration). The need for these two different burning zones requires different types of fuel nozzles for each combustion zone and a very intricate fuel control system. Fortunately, E^3 engines will utilize full-authority digital electronic control (FADEC) systems which will be used in controlling the fuel-feed to each of the two combustion zones.

The desire for much longer life in these complex combustors has brought on the need for different types of liner configurations. Thus, both of the engine manufacturers have selected various forms of segmented liner configurations. These liner segments will be separately supported by a cooled support structure, and they will be free-riding to minimize the thermal stresses that build up during the rapid heating and cooling cycles encountered in normal combustor operations. Also, advance forms of cooling have been designed into the liners to take advantage of improved features of transpiration, film, and impingement cooling. These features allow the use of a much broader range of materials in the combustor liners. In addition, the inlet diffuser sections of both combustors have been improved over those in previous combustors because the higher pressures and shorter lengths of these combustors require very rapid diffusion of the compressor-exhaust in a very short length.

The relatively short lengths of the E^3 combustors are well illustrated in the combustor evolution diagram shown in Figure 14. This figure compares the E^3 combustors to those used in current engines (the JT9D-7A and CF6-50C engines) as well as the advanced combustor configurations that were developed through two previous NASA-sponsored efforts. All of these combustors are shown at the same scale for similar engine thrust sizes. The combustors in the central part of the figures were developed under an earlier NASA-sponsored program, termed the Experimental Clean Combustor Program (ECCP), to develop the combustors specifically for low emissions. These combustors were the first of their type to include two separate burning zones. The results of the ECCP program indicate that the two separate combustion zones were very effective in reducing emission levels, and this led to the confidence that the very stringent emission goals established for E^3 could be met with two-zone combustion systems. However, these initial two-zone combustors were relatively large and complex. Therefore, in the E^3 Project the combustion zones have been reduced considerably in length and some of the complexities that were originally incorporated in the ECCP combustors have been removed from the E^3 designs. The much smaller size of the E^3 combustors indicates the complexity of the problems that are being attacked in the E^3 combustors.

Turbines

The prime requirements for advanced technologies in the E^3 turbines are:

- o higher thermodynamic efficiencies
- o higher aerodynamic loading
- o higher temperatures
- o improved performance retention
- o lower maintenance costs

In approaching these needs, the engine manufacturers have taken different approaches in trying to satisfy them. For their E^3 high-pressure turbine, GE selected a two-stage turbine to achieve high efficiency while P&WA chose a single-stage turbine to reduce the number of turbine airfoils which reduces engine acquisition and maintenance costs. The efficiency goals for these turbines are indicated in Figure 15. GE is striving for an efficiency level of about 92.5% in their two-stage turbine--more than a full point increase in efficiency level over the two-stage turbines currently in operation today. For P&WA's single-stage turbine, the design goal is an efficiency level of 88.2%. Again this is at least a point higher than the efficiency levels developed in single-stage turbines with current technology levels. Considering the high degree of sophistication in the turbines operating in current aircraft, achievement of at least 1 point increase in turbine efficiency will require considerable advances in turbine technology.

For the low-pressure turbines, GE selected a five-stage turbine while P&WA chose a four-stage configuration. As indicated in Figure 15, the GE configuration is being designed to achieve an efficiency level of about 91.7% at a high level of stage loading--this represents an efficiency level that is nearly 2% higher than the current technology level. The P&WA low-pressure turbine is aimed at an efficiency level of about 91.5%, which is about a half-point advance over that achievable in current-technology turbines.

The specific configurations selected by the engine manufacturers for the high-pressure turbines are shown in Figure 16. GE's two-stage configuration is shown on the left while P&WA's single-stage turbine is shown on the right. Both of these configurations involve significant advances in the aerodynamic and mechanical designs as well as the use of several advanced materials and manufacturing processes. Both turbine designs involve advanced airfoil designs and much tighter clearances between the rotor blade tips and the outer case shrouds to improve aerodynamic performance. These tighter clearances will be achieved through use of active-clearance-control systems on the case to help control the thermal expansion and contraction of the cases during various engine operating conditions. These tighter tip clearances are expected to be the major contributor to the expected turbine efficiency improvements. In addition, great care has been taken in designing the seals in these turbines to significantly reduce the amount of leakage through the various gaps between the rotating and static parts.

Historically, the repair or replacement of parts from the high-pressure turbine has been a major contributor to the total maintenance cost of engines. Thus, both engine manufacturers have directed considerable attention to designing means of reducing the maintenance costs of the E^3 turbines. One result of this is the large thickness of the hub-region in the rotor disks, as illustrated in Figure 16. Both turbine designs require rotors with very thick hub-regions to improve the fatigue life to meet the longer life requirements for the E^3 turbines. This results in relatively heavy disks, but the weight penalties are worth accepting to gain the significant life extensions predicted for these very expensive parts.

Another means of reducing turbine maintenance costs is the reduction of the number of hot-section parts. This is the prime advantage of the single-stage turbine approach selected by P&WA. As indicated in Figure 17, P&WA's E^3 single-stage turbine has only about one-fifth of the airfoils as compared to the two-stage turbine in their JT9D-7A engine. This reduction in airfoil number significantly increases the degree of work required of each airfoil, but it greatly reduces the initial and replacement costs of these expensive internally-cooled airfoils. Conversely, GE's two-stage E^3 turbine design, which aims at maximizing efficiency, has nearly the same number of airfoils as in the two-stage turbine in their CF6-50C engine. However, GE has given priority to designing for longer life in the hot-section parts--as indicated on the right side of Figure 17. They are striving to extend the lives of E^3 parts by factors of 4 to 5 over those typically achieved in current engines.

Several advanced materials and fabrication processes also are being incorporated in the E^3 turbines. Both engine manufacturers are basing their designs on the use of advanced turbine blade materials. GE's high-pressure turbine will use an advanced directionally-solidified nickel-base alloy (termed Rene' 150), while P&WA's turbine blades will utilize a second generation of single-crystal alloys (termed MERL-220). As indicated in Figure 18, these advanced alloys offer potential for about 50 to 100°F temperature advantage over the alloys being used in current engines. This temperature advantage is being used to reduce the cooling air required to internally cool the blades and to extend the life of the blades. P&WA is also planning to use a new fabrication process which will permit the single crystal turbine blades to be cast in two separate halves, as shown on the right side of Figure 18. These two blade halves will be bonded together to achieve one common single crystal. This approach permits the incorporation of much more complex, and more effective, cooling channels on the inside of these air-cooled blades.

Other advanced materials and manufacturing processes that are being incorporated in the E^3 turbines are ceramic oxides in the outer air seals and advanced powder-metallurgy alloys in the disks of both configurations. In addition, GE is incorporating an oxide-dispersion-strengthened alloy in their turbine vanes, and they are evaluating the potential of using ceramic thermal-barrier coatings on various parts of the turbine blades and vanes to reduce the amount of cooling air that may be required in the E^3 turbines.

The prime features of the E^3 low-pressure turbines being designed by both the engine manufacturers are shown in Figure 19. The GE five-stage low-pressure turbine is shown on the left, and the P&WA four-stage turbine is shown on the right. Both of these turbines will incorporate active-clearance-control systems to control the movement of the cases during various engine operating conditions. This permits the use of much tighter clearances between the blade tips and the outer air seals in these designs, and thereby increases the overall efficiency of the turbines. Considerable effort has also gone into the design of these low pressure turbines to reduce the amount of losses due to leakages by improving the platform overlaps and sealing of the small gaps near the seal areas. In addition, the number of airfoils selected for GE's low-pressure turbines has been based on an acoustic analysis of the noise-generation sources in the turbine. This tailored design should result in a reduction in the amount of noise generated by these turbines.

A significant difference in the two engine manufacturers' configurations for the low-pressure turbines is that P&WA's E^3 turbine rotates in the direction counter to their high-pressure turbine to recover the large amount of swirl in the airflow that is generated in their single-stage high-pressure turbine. Conversely, the GE configuration rotates in the same direction as their high-pressure turbine because much less swirl is generated in their two-stage high-pressure turbine. This rotational difference in the low-pressure spool causes several differences in design of the entrance and exit regions for the low-pressure turbines. For example, P&WA's E^3 design requires a transition duct between the two turbines and exit guide vanes at the exit of the low-pressure turbine. However, this permits use of a larger diameter low-pressure turbine which reduces the stage loadings and improves exhaust-gas mixing.

Exhaust Gas Mixers

The most apparent difference in the E^3 engines from those currently in use are that the E^3 engines will incorporate exhaust gas mixing. This requires use of mechanical mixers at the rear of the engine to mix the core and fan stream flows as well as use of a long-duct nacelle to provide a common tailpipe and nozzle for the mixed exhaust. Exhaust gas mixers have been incorporated in these designs because they offer the potential of about 3% reduction in specific fuel consumption for the total engine system. Thus, the mixers offer the largest increment of improvement in specific fuel consumption of any of the components in the engines. However, to achieve these attractive benefits, advanced mixer configurations must be developed that have high mixing effectiveness with low pressure losses. In addition, the mixers must be very light in weight. These technology advances are necessary to overcome the weight disadvantage of the long-duct nacelles required in this type of configuration.

The types of mixer performance advances desired in the E^3 Project are indicated in Figure 20. The goals for mixing effectiveness are shown on the graph on the left side of this figure. P&WA is striving for mixing effectiveness of about 85%, and GE is aiming for about 75% mixing effectiveness. Both of these levels are desired at very low mixing-length ratios in order to keep the mixing zones and long-duct nacelles as short as possible. The problem of trying to achieve the desired low pressure losses are shown in the right side of this figure. Both companies are striving for extremely low levels of pressure losses along with the high levels of mixing effectiveness. As indicated in this figure, considerable advances in technology levels are required to get from the current level of technologies that have been demonstrated in previous mixer model tests up to the levels desired in E^3.

To achieve these very difficult performance advances will require very complex mixer configurations. The types of mixers that are currently being evaluated in the E^3 Project are illustrated in the artist's conception shown in Figure 21. Very short mixers, probably with some sort of scalloping, with various types of lobe configurations will be required to improve the mixing of the two exhaust streams. In addition, very short mixing chambers are desired to reduce the required length of the long-duct nacelles and to minimize weight of this entire section. Also, very light-weight materials will be required in these mixers--either titanium sheet or very thin sections of steel alloys will be used in the initial mixers. These thin sections could present difficult structural problems for mixers of these large sizes. Considerable effort is currently underway in the E^3 Project through both mixer model tests (subscale) and a limited amount of full-scale mixer testing to try to develop these required advances in mixing technology.

Concluding Remarks

Both engine manufacturers are currently involved in aggressive experimental efforts to develop the technology advancements that have been described in this paper. Some of the recent results of these technology efforts were recently described by the engine manufacturers in References 5 and 6. Although these component technology efforts have not yet been completed, the early results indicate high promise for achieving most of the goals established for the E^3 Project. Therefore, we are optimistic that the engine performance advantages projected in the initial E^3 design goals (shown in Figure 1) can be obtained with the design configurations that are currently incorporated in Energy Efficient Engine configurations.

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ENERGY EFFICIENT ENGINE PROJECT
PROPULSION SYSTEM DESIGN GOALS

REDUCE FUEL USAGE
  12% SPECIFIC FUEL CONSUMPTION (SFC)
  50% PERFORMANCE DETERIORATION RATE

IMPROVE OPERATING COSTS
  5% DIRECT OPERATING COST (DOC)

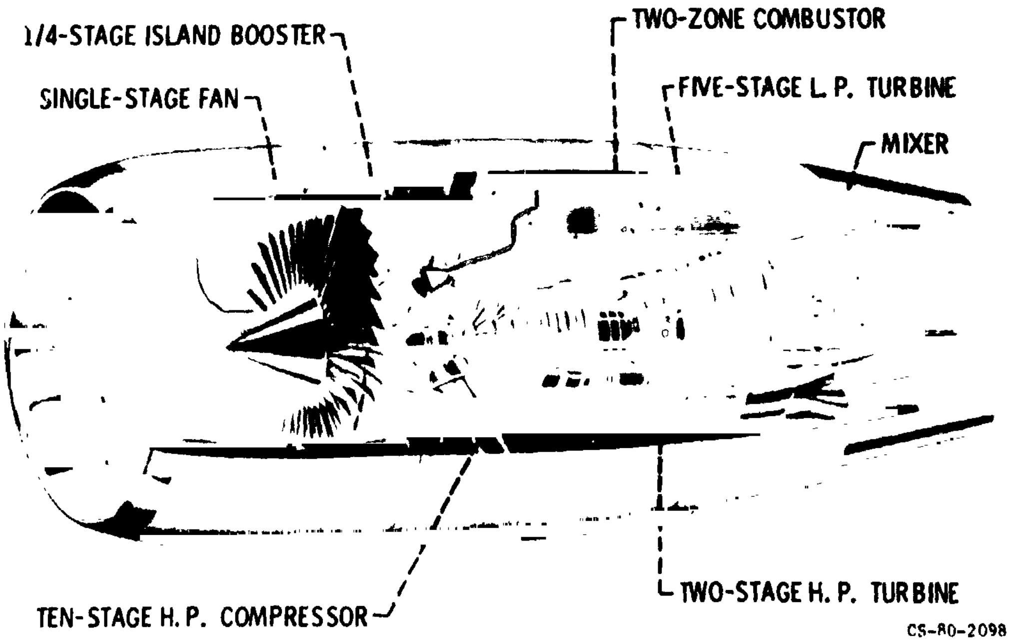
} RELATIVE TO CURRENT ENGINES (JT9D-7A/CF6-50C)

MEET FUTURE ENVIRONMENTAL REGULATIONS

NOISE	FAR-36 (1978)
EMISSIONS	EPA-1981

Figure 1.

ENERGY EFFICIENT ENGINE
GENERAL ELECTRIC CONFIGURATION



CS-80-2098

Figure 2.

ENERGY EFFICIENT ENGINE
PRATT & WHITNEY CONFIGURATION

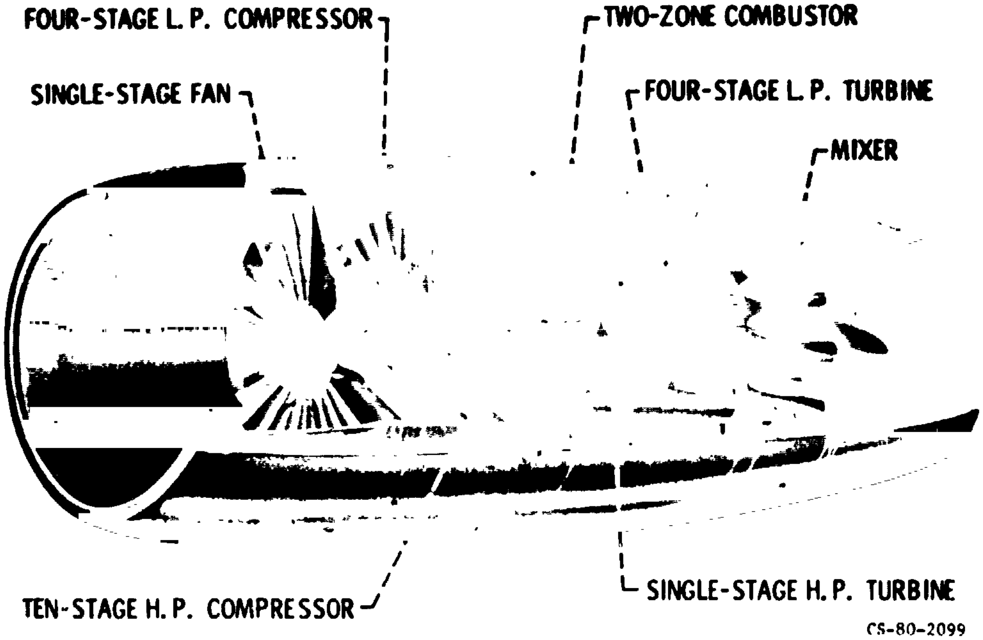


Figure 3.

CYCLE CHARACTERISTICS FOR ENERGY EFFICIENT ENGINES

	GE	P&WA
BYPASS RATIO	6.9	6.6
OVERALL PRESSURE RATIO	36.1	37.4
TURBINE TEMPERATURES:		
HOT-DAY TAKEOFF, °F	2450	2495
MAXIMUM CRUISE, °F	2170	2200
TAKEOFF THRUST, lb	36 500	36 600
INSTALLED SFC AT CRUISE, lbm/hr/lbf	0.572	0.576

Figure 4.

CONTRIBUTORS TO SFC IMPROVEMENTS
(RELATIVE TO CF6-50C/JT9D-7A)

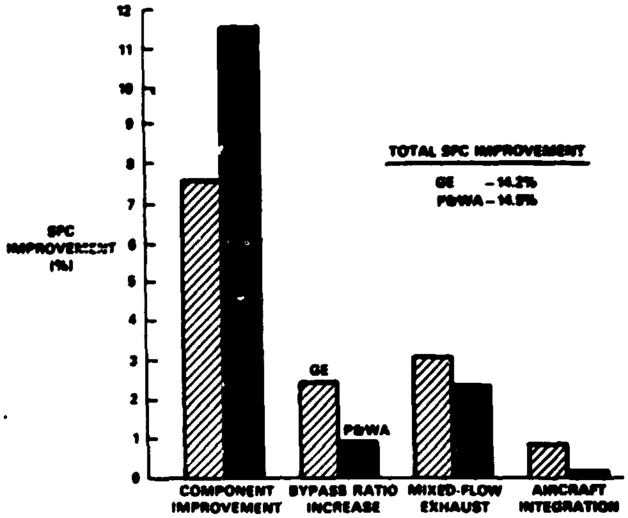


Figure 5.

ADVANCES IN FAN PERFORMANCE

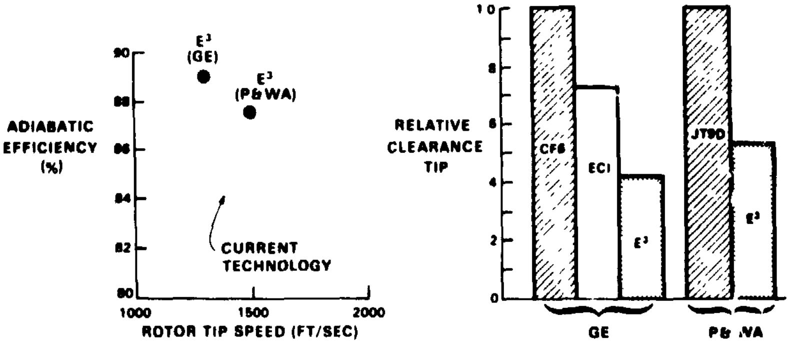
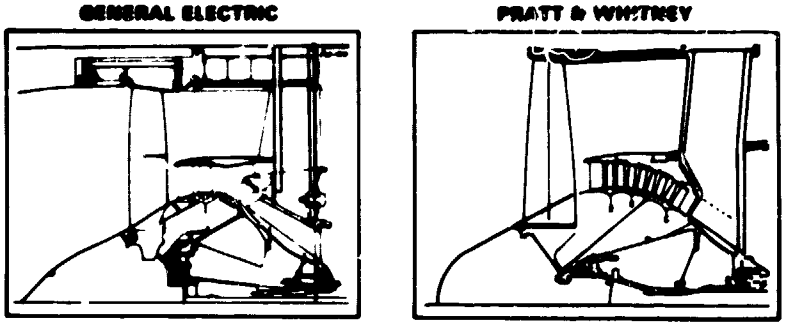


Figure 6.

FAN FEATURES



GENERAL ELECTRIC

PRATT & WHITNEY

Figure 7.

SHROUDLESS, HOLLOW TITANIUM FAN BLADES

PRATT & WHITNEY

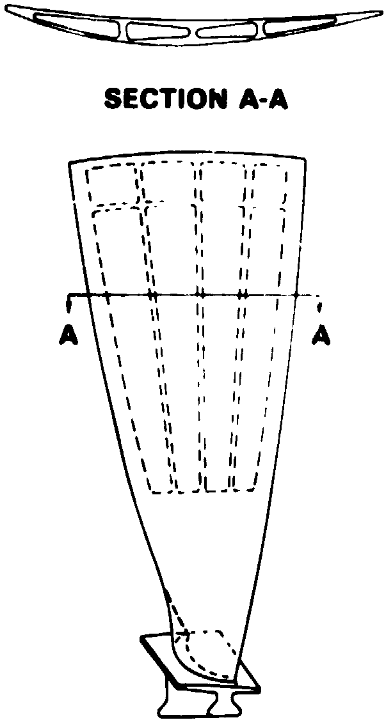


Figure 8.

ADVANCES IN COMPRESSOR PERFORMANCE

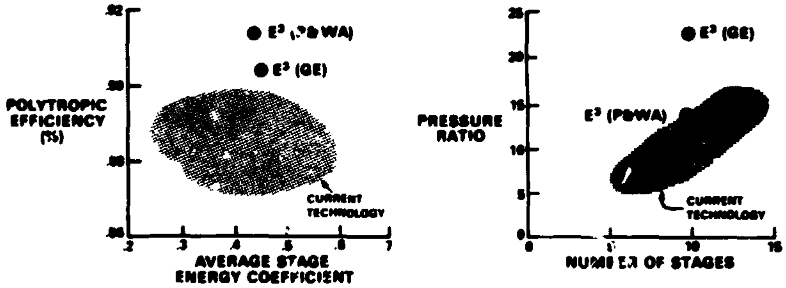
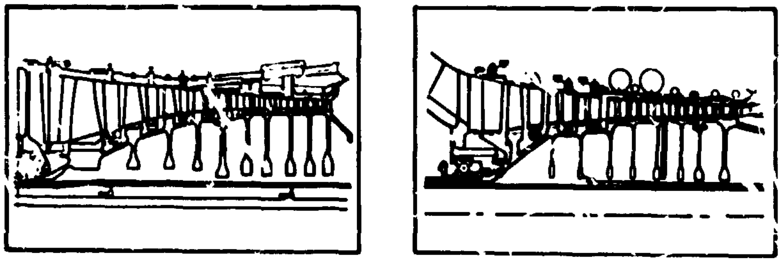


Figure 9.

HIGH-PRESSURE COMPRESSOR FEATURES

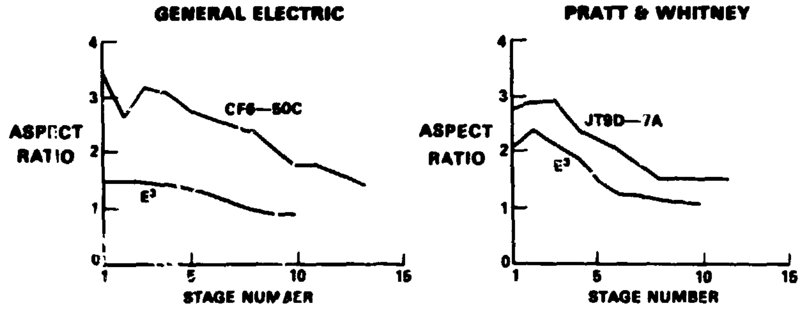


GENERAL ELECTRIC

PRATT & WHITNEY

Figure 10.

ADVANCES IN COMPRESSOR DESIGN


GENERAL ELECTRIC

PRATT & WHITNEY

	PRESSURE RATIO	TIP SPEED	AIRFOILS
CF6-50C	13.2	1120	1747
E^3	22.6	1495	1706

	PRESSURE RATIO	TIP SPEED	AIRFOILS
JT9D-7A	10	1003	2378
E^3	14	1320	1320

Figure 11.

ADVANCES IN COMBUSTOR PERFORMANCE

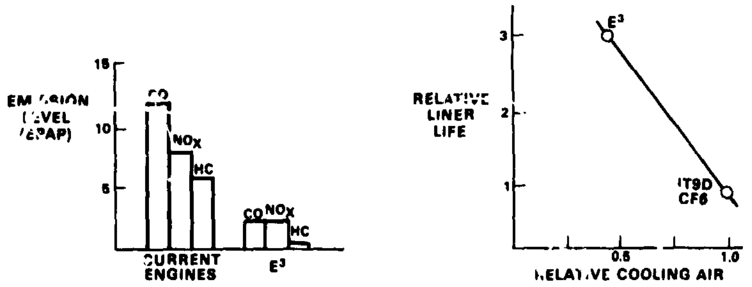
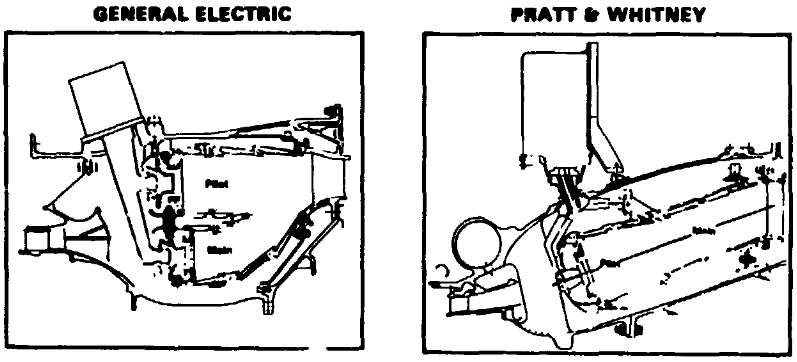


Figure 12.

COMBUSTOR FEATURES



GENERAL ELECTRIC

PRATT & WHITNEY

Figure 13.

COMBUSTOR EVOLUTION

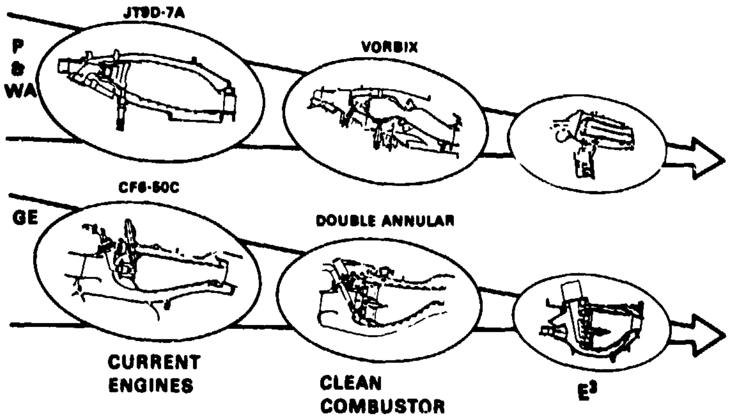


Figure 14.

ADVANCES IN TURBINE PERFORMANCE

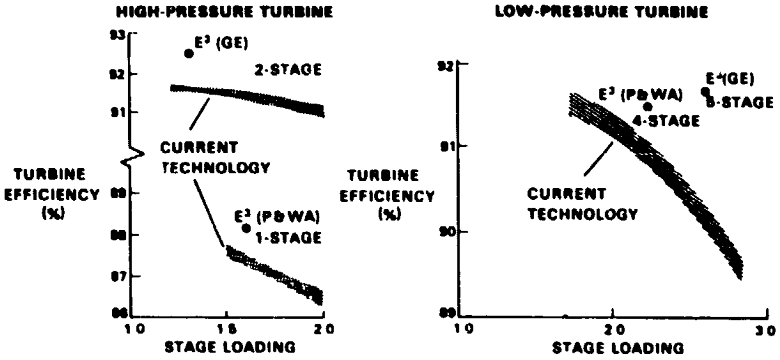


Figure 15.

HIGH-PRESSURE TURBINE FEATURES

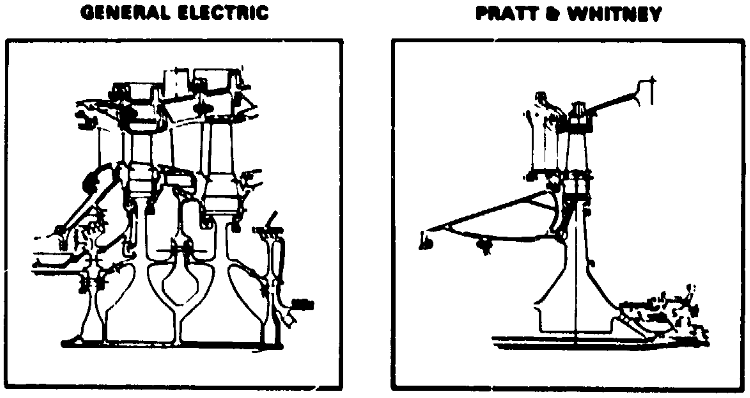


Figure 16.

APPROACHES TO REDUCING TURBINE MAINTENANCE COSTS

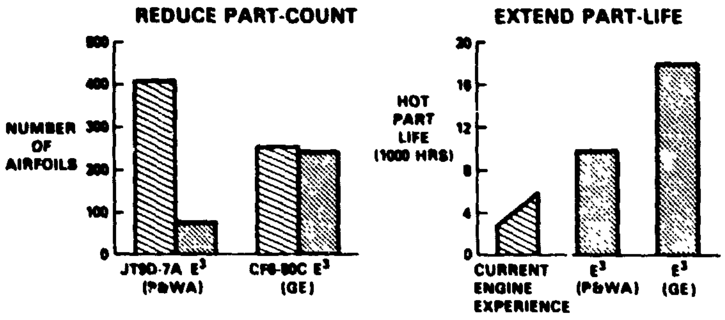


Figure 17.

ADVANCES IN TURBINE MATERIALS AND FABRICATION PROCESSES

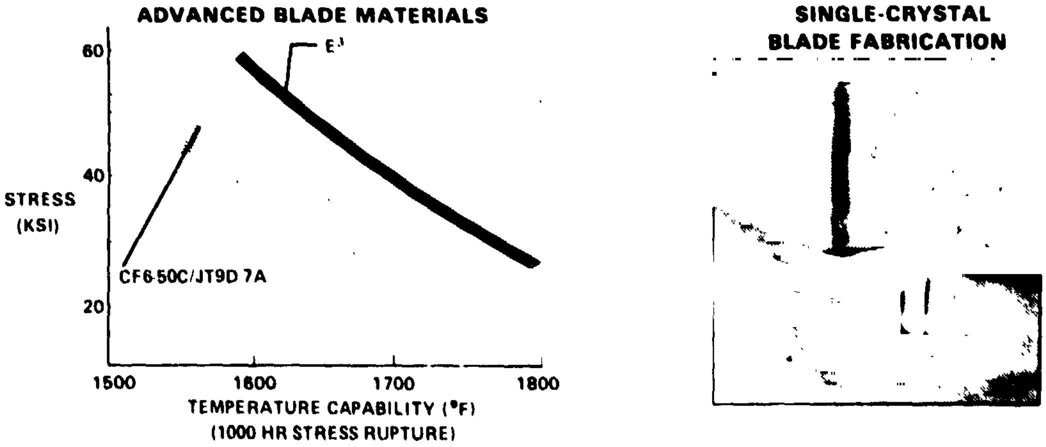


Figure 18.

LOW-PRESSURE TURBINE FEATURES

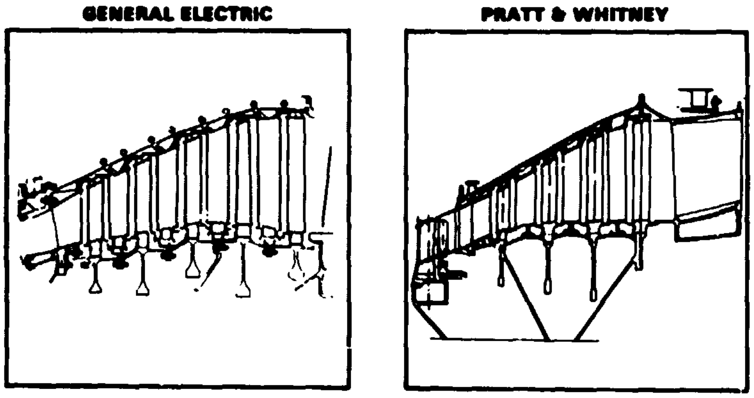


Figure 19.

ADVANCES IN MIXER PERFORMANCE

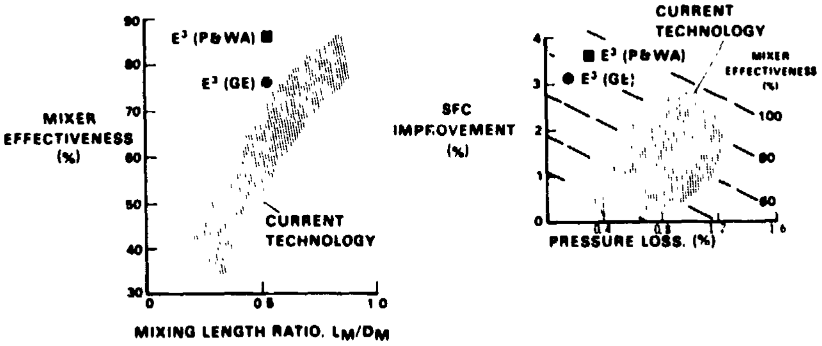


Figure 20.

MIXER FEATURES

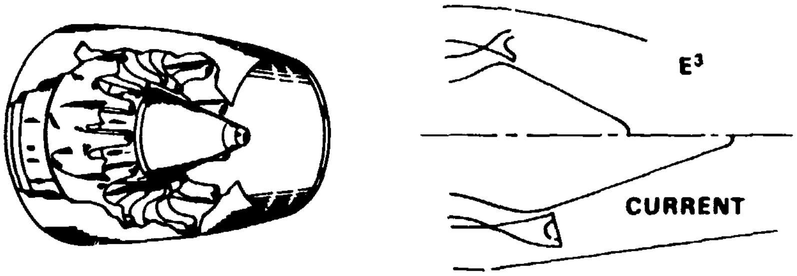


Figure 21.